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Effect of feedrate, depth of cut, tool material, and toolpath on dimensional accuracy and surface roughness of milled CFRP

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Effect of feedrate, depth of cut, tool material, and toolpath on dimensional accuracy and surface roughness of milled CFRP

Assem Almadani

Thesis submitted
to the Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University

In partial fulfillment of the requirements for the degree of

Master of Science in
Industrial Engineering

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Abstract

Effect of feedrate, depth of cut, tool material, and toolpath on dimensional accuracy and surface roughness of milled CFRP

Assem Almadani

This thesis investigates the effect of different factors on Carbon Fiber Reinforced Polymers (CFRP) milling, like feedrate, tool material, and cutting speed. CFRP offers excellent material properties, which led to the increase of the material in today's manufacturing industry. CFRP offers up to 2.25 times steel's modulus of elasticity at about a fifth of the weight and excellent thermal properties, which allow the use of this material in applications with high heat like automobiles. Many industries have implemented the use of CFRP in their applications, like airplanes and automobiles, which lead to a decrease in weight and increase in strength. A literature review was conducted to determine the research gap, which resulted in 132 articles, of which 72 were relevant. The literature review results showed no specific machine settings were recommended, and neither was the type of material to use. Almost all reviewed articles used different tool materials and machine settings, with little work done in comparing various tools and settings regarding surface roughness and dimensional accuracy. A CNC mill was used to make slots in a CFRP workpiece using different combinations of the factors listed above. An initial experiment was conducted to determine the optimal toolpath, using Autodesk Fusion 360, that achieves the highest accuracy and lowest surface roughness. The slots were then analyzed using a profiler and a digital caliper to determine which toolpath to use for the experiment. After determining the toolpath, the factor level determination was conducted. Four different tool coatings were tested at three different levels of feedrate and depths of cut on a Tormach PCNC 1100. Multiple bits were used to reduce the effect of tool wear. Data was then collected on the slots' accuracy and surface roughness using a digital caliper and the Dektak XT Stylus profilometer, respectively. The data obtained were then analyzed in JMP to determine the optimal settings to mill CFRP. The analysis showed feedrate, tool coating, depth of cut, and their interaction effects have a significant effect on dimensional accuracy and surface roughness.

Dedication

To my parents, **Hesham** and **Abeer**, thank you for all the support and inspiration. You are my role models.

To my partner, **Shereen**, I would not have become what I am if it wasn't for you. I am eternally grateful.

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List of Abbreviations

AlCrN	Aluminum Chromium Nitride
AlTiBN	Aluminum Titanium Boron Nitride
AlTiN	Aluminum Titanium Nitride
Ar	Aramid
CF	Carbon Fiber
CFRP	Carbon Fiber Reinforced Polymer/Plastic
CS	Case Study
CVD	Chemical Vapor Deposition
DIA-BNC	Diamond Coated
DIA-HBC4	Diamond Coated
DLC	Diamondlike Carbon
DoC	Depth of Cut
EXP	Experiment
Fr	Feedrate
GF	Glass Fiber
HSS	High Speed Steel
IPM	Inches per Minute
PCD	Polycrystalline Diamond
RF	Reinforcement
RMS	Root Mean Square
RPM	Revolutions per Minute
SiAlON	Silicon Aluminum Oxygen Nitrogen - Ceramic
TC	Tool Coating
Ti	Titanium
TiAlN	Titanium Aluminum Nitride
TiCN	Titanium Carbonitride
TiN	Titanium Nitride
UD	Unidirectional
UN	UNS A97075
WC	Tungsten Carbide
WoS	Web of Science
YG6	Tool Grade

1 Introduction

Manufacturing is an essential aspect of today's life. It plays a massive role in making our lives better by offering various products to improve it. It also has a significant effect on the economy. For every dollar spent on manufacturing, almost \$1.89 is increased in the country's economy.[82] Although there are various manufacturing processes, CNC machining allows low costs at low volumes, a good surface finish, and a tight tolerance.

Tolerance is a crucial aspect when making a product. The majority of manufactured parts are used as parts in other mechanisms or are interchangeable, requiring accurate dimensions to an extent. Therefore, ensuring that the manufacturing process leads to the lowest tolerance possible is vital in ensuring all parts fit correctly. Surface Roughness is another critical aspect of manufacturing. In some cases, surface roughness is vital to the use of a specific product. For example, in cars and airplanes, surface roughness can affect the vehicle's aerodynamics by increasing drag, requiring a smooth surface.

Carbon Fiber Reinforced Polymers (CFRP) are among the most known composites in the manufacturing industry for their high strength to weight ratio. CFRP is about a fifth the weight of steel and up to 2.5 times stronger. However, shown in the literature review, no settings and tool materials are recommended to be used. The articles found in the search show a large range of materials, feedrate, and cutting speeds used. The purpose of this thesis is to narrow down that range and show the most suitable settings and materials for successful machining. CFRP is made by adding carbon fiber laminates between layers of plastic and binding them together, as shown in Figure 1. It is being used in more and more machines around us like airplanes and Formula 1 race cars. Both Boeing and Airbus designed and built planes comprised of 50% composites, with carbon fiber being the most used.[73][77] CFRP is the addition of carbon fiber to plastic to increase its strength. The use of CFRP led to a huge reduction in airplanes' and vehicles' weight, which leads to a reduction in fuel costs. The use of composites will increase in the future as we understand more and more about how to manufacture them.

CFRP offers superior material properties compared to other traditional materials used like aluminum and steel. CFRP is considerably stronger than steel while only being about a fifth of the weight. The literature review clearly shows a gap in how to mill CFRP successfully. This proposal examines the recommended settings and tool materials for the highest accuracy and the lowest surface roughness. An experimental plan is also shown below, showing how the data will be interpreted and how the recommendation will be decided upon.

Figure 1: Layered structure of CFRP [83]

2 Research Gap

2.1 Introduction to Literature Review

The manufacturing industry is moving rapidly towards more intelligent and more advanced processes. This includes smarter, more data-driven, and sensor-based insights on the one hand, and advances in both processing technologies, e.g., additive manufacturing, and advanced materials, such as composites. An area where these advances of processing technology and materials interject is the processing of carbon fiber reinforced polymers (CFRP). These materials offer distinct advantages over traditional materials.

Carbon fiber has a high strength-to-weight ratio, a 20 percent weight reduction compared to steel.[76] On the other hand, as a material that possesses unidirectional properties and is anisotropic, they also present distinct challenges for the design and manufacturing engineer, such as degradation of the matrix due to heat, the fibers fracturing instead of being cut, and increased tool wear.[74][75]

CNC milling is one of the most used subtractive manufacturing processes. CNC milling is generally more economical when it comes to low quantity production than injection molding and other high-throughput processes. One of the many advantages of CNC milling is the ability to process CFRP parts. As mentioned before, CFRP parts are comparably durable and have many uses in the aerospace and automotive industries, among many others. CFRP is generally more expensive to process; however, this is acceptable given its superior strength and lightweight properties. According to Airbus, more than 50% of the A350 XWB model is CFRP.[73] CFRP is used for functional parts of the airplane, which allows it to carry more passengers and burn less fuel while being lighter, as shown in Figure 2. CFRP is also used in a lot of Formula 1's vehicles.[75]

Figure 2: Materials included in the Boeing 787 [77]

The same properties that make CFRP material the desired choice for selected applications, e.g., its increased strength, present a challenge for processing a CNC milling center. In addition, as an anisotropic material, the machining process must be carefully planned to avoid costly and dangerous quality problems during the manufacturing process. Therefore, setting the correct machine settings and parameters is crucial to successfully mill CFRP with minimal scrap and quality issues.

In this paper, we investigate the state of the art of CNC milling of CFRP to identify standard parameters and drivers that impact the process quality. Quality in this paper is defined as surface roughness and dimensional accuracy. Thus, this paper's overall research question is: What key parameters affect CFRP parts' quality during CNC machining?

The paper is structured as follows: Subsection 2.2 covers the research methodology, specifically the search string and the results. Followed by subsection 2.3 that shows the results obtained from the articles found in the search. subsection 2.4 discusses and compares the results of all reviewed articles. Finally, subsection 2.5 concludes the literature review by answering the research question and recommending future research areas.

2.2 Research Methodology

At the core of our literature review, we conducted a systematic search in the most prominent databases, compendex and WoS. The search query used keywords relevant to the research question on June 3rd, 2020, and filters were applied to ensure the returned article's scope fits the manufacturing domain. The initial search yielded 132 records, from which only 72 were relevant and available. The search string was: (milling OR Machining) AND ("Carbon fiber reinforced" OR "carbon fibre reinforced" OR "carbon-fiber reinforced" OR "carbon-fibre reinforced") AND polymer AND quality. The following filters were used: i) limit articles to the years 2009-present (June 3rd, 2020), ii) English language, iii) journal articles. Furthermore, we removed duplicates using compendex as the preferred database since most articles were available through compendex.

All records found in the initial search were screened to ensure they used the correct manufacturing process and focused mainly on the effect of machining on quality. Fifty articles were excluded by reading through titles and abstracts due to using a different manufacturing process than CNC milling. After reading all 73 available articles, one was excluded due to using a different process than CNC milling that was not specified in the title and abstract. The search breakdown is shown in Figure 3.

Figure 3: Systematic Search

2.3 Results

The objective of the results is to determine the factors that affect the quality of machined CFRP. The results reached by the articles found in the search are shown in this section in Table 1, and then each of the factors that affect CFRP quality is shown with how many articles concluded the same result.

Table 1: Article Parameters

#	RF	Fiber Wgt	Fiber Placement	# Layers	Workpiece Thickness (mm)	Layer Thickness (mm)	EXP or CS	Tool
1	CF	70%			10		EXP	TiAlN coated solid carbide drill
2	CF		0/90		10		EXP	TiAlN coated solid carbide drill
3	CF and GF		bidirectional				EXP	multiple
4	CF		[[((0,90)/(+45,-45))3/(0,90)]	14	3	0.2143	EXP	DIA-BNC (burr style) and DIA-HBC4 (herringbone style) diamond-coated carbide tools
5	CF		UD-(+45,0,+45,90,+45,0,-45,90,45,90)	26	5	0.1923	EXP	tungsten carbide
6	CF		UD- varying from 0-180 in 15 increments		5		EXP	carbide YG6
7	CF		UD-25% each 0, -45,45,90 and another with 50% 0		4 and 5		EXP	
8	CF	59%	UD-0/90/45/-45		10	0.14	EXP	SiAlON ceramic drills
11	CF	55%	UD-0/90	12	3	0.25	EXP	twist drill
12	CF	60%	[-45/45]		5		EXP	TiAlN-coated cemented carbide tool
13	CF	44.71%					CS	
14	CF		woven at 0 and second UD [45/45/0/90	10 and 24	2.2 and 3	0.22 and 0.125	EXP	
15	CF	44.71%		10	2.2	0.22	EXP	Uncoated helicoidal carbide
16	CF and UN	66%	UD-0/90/45/-45/45/-45		4.5 and 4.86		EXP	
17	CF	40% and 17.5%			5		EXP	
18			UD-0,90	32	4.224	0.132	CS	
19	CF		UD-0/45/90/-45		6		EXP	diamond coated and uncoated UDX twist drill
20	CF		UD				CS	
21	CF		UD	55	25	0.4545	EXP	seco sd205A-11.138-53-12r1-c1 special twist drill and tivolty 8236651 1000 end mill
22	CF		45/45/90/90/45/45/0/45	100	18.2	0.182	EXP	Sandvik corodrill R846 twist drill
23	CF	58%	UD-0/45/90/-45		4		EXP	carbide step drills

24	CF		Woven 0/90 tested at 0, -45,45,90	8	4	0.5	EXP	AlCrN-coated and HSS drills
25	CF and Ti	59%	UD-90, -45,0,45	80	20	0.26	EXP	AlTiN coated WC drills
27	CF	65%	UD- [0/0/0/ (135/0/45/90	24	3	0.125	EXP	
28	CF	60%	bidirectional	32	8	0.25	EXP	
29	CF	59%	UD-0/45/90/135	78	15	0.1923	EXP	diamond coated carbide
30	CF		UD-0 and 45				EXP	polycrystalline diamond (PCD)
33	CF	60%	woven	8	2	0.25	EXP	
34	CF	55%	woven- [(0,90)/ (30,60)/ (30,60)/ (0,90)/ (90,0)/ (60,30)/ (60,30)/ (90,0)]		4		EXP	AlTiN-coated solid carbide
35	CF		UD-0	40	5	0.125	EXP	tungsten carbide
36			UD-0	40	5	0.125	EXP	
37	CF	51%		32	4	0.125	EXP	WC tungsten carbide
38	CF	60%	weave 0/90 and 45/-45 thickness(25mm) and symmetric- 10 ply's 0/-45/90/45/0 and symmetric 20 ply's 0/45/90/45/0				EXP	
40	CF	60%	UD	40	5	0.125	EXP	PCD end mills
41	CF		UD				EXP	
42	CF	59%	UD-90/-45/0/45/90/-45/0/45	16	4.16	0.26	EXP	tungsten carbide
43		60%	UD		4.9		EXP	
45	CF	65%	UD		6		EXP	
46			Woven	35	6.35	0.1814	EXP	
47	CF		MD-plain weave	10	2.5	0.25	EXP	burr router bit
48			UD		4		EXP	
49	CF and Ar	65%	UD-0°,45°,90° and 135°				CS	
51	CF	64%	UD-90, -45,45,0,45, -45,45, -45,0, -45,45,90	24	4.44	0.185	EXP	CVD diamond coated carbide
52	CF	64%	[90°, -45°, 45°, 0°, 45°, -45°, 45°, -45°, 0°, -45°, 45°, 90°]	24	4.44	0.185	EXP	CVD diamond-coated carbide tool with six straight flutes
53	CF		UD- [0°/90°/45°/90°/45°/90°/-45°/90°/45°/90°/-45°/90°/0°]	114	25.4	0.22	EXP	2-flute tungsten carbide
54	CF	60%	0/90/45/-45		5		EXP	
56	CF	65%	UD sperate- 0,30,60,90,120,150		6.75		EXP	uncoated tungsten carbide
57	CF		UD-0 to 180	40	5	0.125	EXP	Polycrystalline diamond (PCD) end mills
58	CF	60%	UD-0	40	5	0.125	EXP	polycrystalline diamond (PCD) end mills
60	CF		[0/90]	16	2	0.125	EXP	three flute solid carbide milling tool with nano-copper coating
61	CF		UD- [0/90]	16	3.1	0.1938	EXP	polycrystalline diamond (PCD)

63	CF		UD-0 and MD-45/135/090		10		EXP	four-blade carbide
64	CF		UD-0		10		EXP	four-blade special solid carbide
65	CF		UD- [45/0/-45/90]	48	6	0.125	EXP	twist drill
67	CF				4.5		EXP	PCD double peek angle
68	CF	65%	45/90/-45/0	48	9.16	0.1908	EXP	CVD diamond-coated brad spur drill and uncoated tungsten carbide twist drill and uncoated solid carbide dagger drill
70	CF		Woven-0/90	40	10	0.25	EXP	WC, TiAlN coated, and diamond coated
71	CF		0/45				CS	
72			BD-0/90 and UD	35	5 and 4.5	0.14	EXP	

* 9,10,26,31,32,39,44,50,55,59,62,66,69 were removed from table for not providing enough parameters. Abbreviations are shown in List of Abbreviations.

As shown from the search, more than 80% of the articles written about the topic are experiments. The initial comparison was made to compare the workpiece used in each experiment, focusing mainly on the fiber orientation, fiber volume, number of layers, layer thickness, and tool used. The layer thickness varied between articles but was always between 0.125 mm and 0.5 mm per layer. Out of the 72 articles found, ten articles used a 0.125 mm layer thickness, and 5 used a 0.25 mm layer thickness. The remaining articles used a layer thickness between 0.132 mm and 0.5 mm. The most used layer thicknesses used for experiments were 0.125 mm and 0.25 mm. The number of layers used was usually between 14 and 48 layers. The maximum was 144 and a minimum of 8 layers. 6 articles set up their workpiece with 40 layers, from which 5 had a workpiece thickness of 5 mm and a layer thickness of 0.125. The table shows that setup was the most used one. The workpiece thickness was between 2 mm and 25.4 mm, where the typical thickness was on the lower end of that range, around 4 to 6 mm.

Another critical aspect is the fiber orientation, which is almost consistent across all the articles. Out of the 72 articles, only 53 documented the fiber placement. Out of those, 46 articles placed them in a unidirectional orientation, with each layer at a different angle. The angle placement is also consistent and is set at 0, 45, 90, and -45 degrees and then repeated for the number of layers used. Seven of the remaining articles chose a woven fiber placement at 0 and 90 degrees.

The fiber volume for all reported workpieces was between 40%-70%, except for one article that tested a workpiece at 17.5% in addition to the 40%. The average percentage of fiber volume used and the most common is 60%. There was no standard tool used in all the articles; however, five used diamond coated, 4 used tungsten carbide, and 6 used polycrystalline diamond (PCD) bits.

Two articles set up their experiment with multiple passes to reduce delamination in the workpiece. The first article made a small diameter hole first, and then the second cut was set to the required diameter hole, which avoided the damages done from the first cut. The second article used the same concept but in terms of depth of cut, not hole diameter. A comparison was made between a single pass with a depth of cut of 100 μm and multiple passes (two passes) with each depth of cut of 50 μm . Using the multiple pass method reduced the breakage length by 56.42% compared to the single-pass method. Another article compared single-step drilling to peck drilling and showed that single-step is better.

Four articles studied the effect of temperature on delamination and quality. Three of those studied the direct effect of heat on the workpiece, and the fourth studied the effect of heat on the drill, which causes tool wear, leading to lower surface roughness and higher delamination. Out of the 72 articles, only one article suggested a lower cutting speed and a larger depth of cut to increase surface quality.

Another setup used was cutting at different angles. One article tested their workpiece by performing inclination milling, and another tried cutting with an angle to the fiber orientation.

Another article gave conflicting results by showing that increasing the depth of cut leads to higher delamination, contradicting a previous article that suggested a higher depth of cut. This article also examines the effect of fiber orientation and rake angle on cutting force and delamination. Also, only one article used helical milling for hole making and suggested that optimum parameters were reached.

2.4 Discussion

For CNC milling, drilling into carbon-reinforced laminates increases tool wear, which tends to damage the workpiece. Throughout the articles included in the literature review, several different types of cutting tools (bits) were used to determine which is best suited to decrease delamination and tool wear. Multiple experiments showed that diamond-coated carbide bits reduce tool wear and increase surface quality, corroborated by a website on the challenges of CFRP and how to machine it successfully.[74]

Another critical factor for the good surface quality of milled CFRP parts is fiber placement. The results suggest that woven fiber placement leads to reduced delamination due to the fibers overlapping one another. Most of the experiments are set up with unidirectional fiber placement in which each layer is placed at a single angle of 0, 45, 90, and -45. This eliminates push-out delamination since each layer is not overlapping, and the angle placement increases strength. However, fiber placement affects cutting forces significantly due to the angle of contact.

To increase surface quality and reduce delamination, machine settings were set up to increase cutting speed and reduce feedrate. Reducing the feedrate also lowered the cutting forces. This, in turn, reduced tool wear and lead to better surface quality. Tool wear leads to uncut fibers, poor hole quality, and surface quality. The heat generated from contact between the tool and the workpiece leads to increased tool wear, and higher thrust forces both tend to increase delamination issues. Both feedrate and cutting speed influence heat generation during CNC milling of CFRP processing significantly. Although all reviewed articles except one [61] agree that a lower feedrate and higher cutting speed increase quality, a very high cutting speed would increase heat generation where the CFRP temperature would reach glass transition temperature and deform the material, leading to poor surface roughness.

Sharizal et al. compared single-step and peck drilling concluded that single-step drilling was more feasible due to the decrease in the time it takes to drill, and it reduced delamination by reducing exit delamination from peck drilling where the drill had to exit and enter multiple times.[53]

2.5 Identified Research Gap

The primary purpose of this article is to find the influencing factors for the quality of machined CFRP. The initial search conducted resulted in 132 articles, of which only 72 articles were available and relevant. The articles found in the search concluded that those factors are layer height, fiber placement, fiber weight, and machine settings.

There are many different setups to increase the quality of milling carbon fiber reinforced polymers; however, from the search done, it is shown that most experiments were set up with an 0.125 mm fiber layer thickness, 5 mm workpiece thickness, 60% fiber volume, and either a diamond-coated carbide drill, tungsten carbide drill or PCD (polycrystalline diamond) drill. Another one of the key factors to good quality is machine settings.

Future work could be narrowing the settings to near-optimal in terms of tool used, machine settings, workpiece properties, and toolpath. An experiment could be set up to compare different tool materials and their effect on CFRP quality. Other factors that could be included are depth of cut, feedrate, and toolpath type. None of the articles found in the search compared tool materials or investigated the effect of different toolpaths on dimensional accuracy and surface roughness. Also, only a few articles included depth of cut as a factor in their experiment; however, they did not truly show which is most suitable for milling CFRP.

3 Experimental Plan

3.1 Research Objective

This experiment's research goal is to determine optimal feedrates, tool coatings, and depths of cut to achieve lower surface delamination and higher dimensional accuracy in milling carbon-reinforced polymers by milling multiple slots using different combinations of the factors listed above and determining which are significant and which level is more suitable. The literature review (see section 2) concluded that machine settings, fiber weight, fiber orientation, and layer thickness were the most significant factors affecting milled CFRP surface roughness and dimensional accuracy. However, it also showed that little work is available investigating which specific feedrate, tool coating, or depth of cut has a higher effect on CFRP. In addition, little work has been done to investigate the impact of the toolpath type on those aspects. For this thesis, Autodesk Fusion 360 was used to design and generate the milling toolpath. Fusion 360 offers multiple toolpath types that allow better milling results depending on the design. However, numerous toolpaths available for slots, and none of the reviewed articles show which is more suitable. The toolpaths available have different cutting patterns, affecting the operation's surface quality, accuracy, and cost. The research objective of this thesis is to address this research gap.

The research approach to address this research gap aims at testing different tool coatings, feedrate, and depths of cut combinations to determine the optimal combination to achieve the highest surface quality and lowest delamination for CFRP composites. An initial experiment was conducted to determine the toolpath that leads to the lowest surface roughness and highest dimensional accuracy. For the factor level determination, four different tool coatings (Diamond, Diamondlike Carbon, TiCN, and TiN and TiAlN) will be used with varying feedrates (0.03, 0.1, and 0.15 mm/rev) and depths of cut (0.05, 0.075, and 0.15 in). The cutting speed is constant at 4500 RPM for all runs. A full factorial design with three replications was used to demonstrate the settings that lead to better results. The milled slots were then measured for dimensional accuracy and surface roughness using a digital caliper and mechanical profiler. After collecting all relevant data, a JMP analysis was conducted to indicate the significant factors that affect the two aspects this thesis focuses on, dimensional accuracy and surface roughness.

3.2 Experiments

3.2.1 Experimental Materials and Equipment

The workpiece used in this experiment was a 24x2x0.5 in block of CFRP composite. The fiber volume of the block was 53% with 0 and 90-degree alternating plies of unidirectional fibers. The layer thickness was 0.0066 in, and the surface layers are woven with 3K plain weave carbon fiber fabric. This is a standard block obtained from McMaster CARR and conforms to the needed parameters. The initial experiment (see section 3.2.2) performed to determine the suitable toolpath to be used was done using a 2x2 in block and 1/8 in AlTiBN square end mill cutting bits.

The remainder of the workpiece was cut into 2x2 in blocks and used for the factor level determination (see section 3.2.3). The tools used in this experiment are all 1/8 in carbide square end mills with different coatings. The four coatings used in this experiment are shown in Table 2 below. The bill of materials is shown in Table 3.

Table 2: Tool geometry

Tool Coating	Diameter (in)	# Flutes	Length (in)	Flute Length (in)
Diamond	0.125	4	1.5	0.5
Titanium Carbonitride	0.125	3	1.5	0.25
Diamondlike Carbon	0.125	4	1.5	0.625
Titanium Nitride and Titanium Aluminum Nitride	0.125	4	2	0.375

Table 3: Bill of Materials

Part	Quantity	Part #
Diamond Coated	3	3725A141
TiCN	3	8829A62
DLC	3	4119A15
TiN and TiAlN	3	2792N1
AlTiBN	8	B07FSJLMJ5
Carbon Fiber Bar	1	8194K143
Tormach PCNC 1100	-	-
Dektak XT Stylus Profiler	-	-

All parts are obtained from McMaster-Carr with their corresponding part # excluding the AlTiBN coated bits obtained from amazon.

All designs and toolpaths were done using Autodesk Fusion 360. The CNC milling machine used for this experiment was the Tormach PCNC 1100 located in ESB G85 at West Virginia University (WVU). The Tormach PCNC 1100 has a working area of 18 in x 9.5 in x 16.25 in, as shown in Figure 4. It offers a spindle speed of up to 5140 RPM; however, 4500 RPM was used in this research due to mechanical issues occurring at higher speeds. The milling machine has a maximum feedrate of 110 IPM in the x and y directions and 90 IPM in the z-direction.

Figure 4: Tormach PCNC 1100 located in ESB G85 at WVU

A Bruker Dektak XT Stylus profilometer provided in the cleanroom at West Virginia University was used to measure each slot's surface roughness. The machine offers nanometer resolution and a work area of 6 in. The Dektak profilometer, shown in Figure 5, measures surface roughness by moving a 2 μm diameter stylus on the part's surface in one direction. The machine then mechanically measures the difference in heights between the starting and ending points, as shown in Figure 6. The profiler then calculates the average roughness of the profile. The machine settings listed in Table 4 were unchanged for all measurements.

Figure 5: Dektak XT Stylus profilometer located in the cleanroom at WVU

Figure 6: Data output from Dektak profilometer.

Table 4: Dektak profilometer measurement settings

Scan Type	Standard Scan
Range	6.5 μm
Profile	Hills & Valleys
Stylus Type	Radius: 2 μm
Stylus Force	10 mg
Length	2000 μm
Duration	10 sec

After completing the milling operation, results were determined based on the accuracy/tolerance of the slot and the surface roughness using metrology equipment and surface imaging machines, respectively. Machining time for each machine settings combination was calculated to determine machining cost. The data obtained were then entered into JMP to determine the near-optimal settings for milling CFRP. Extra material was considered for milling more slots if needed.

3.2.2 Toolpath Determination Setup (Pre-Experiment)

The initial experiment's main objective was to determine which toolpath available in Fusion 360 leads to higher accuracy and lower surface roughness. The design used for this experiment consisted of 14 slots on a 2x2 in block of CFRP. There were seven toolpath types available that were used for milling the slots:

1. 2D Adaptive
2. 2D Contour
3. 3D Pencil
4. 3D Pocket
5. 3D Adaptive
6. 3D Contour
7. 2D Pocket

Each toolpath type was used to mill two slots. In addition, each toolpath was milled using a different bit to reduce the effect of tool wear and allow future studies of the tool wear effect of different toolpaths. Figure 7 shows the design used for the toolpath determination.

Figure 7: Design used for Toolpath Determination

The numbers shown on the workpiece in Figure 7 correspond to the toolpath used, listed above. All slots were identical in dimensions to allow comparison. Each slot had a length of 0.475 in, a width of 0.25 in, and a depth of 0.15 in. The center slot was used as a test to determine if the chosen feedrate and cutting speed are suitable and would not damage either the bit or the material. An AlTiBN bit was used to mill the slots. Each toolpath type was milled with a new bit to reduce tool wear. The machine settings shown in Table 5 were used for all toolpaths.

Table 5: Machine Settings used for Toolpath Determination

Setting	Value
Cutting Speed	4500 RPM
Feedrate	26.5748 in/min
Depth of Cut	0.15 in

The slots designed for this experiment were milled at the edge to allow the mechanical profiler to measure the surface roughness. There was an optical profiler available; however, it relies on light to measure surface roughness. The material created too many interferences during the readings, which led to incorrect measurements.

3.2.3 Factor Level Determination Setup

This experiment aims to determine the near-optimal feedrate, depth of cut, and tool coating to mill CFRP successfully. Three bits will be used for each coat to reduce the tool wear effect on the experimental results. Each bit will be used to mill twelve slots for a total of 36 slots per coating. In addition, there will be three different feedrates and depths of cut tested for a total of 144 slots. The design to be milled is shown in Figure 8, and the machine settings are shown in Table 6. Overall, there are 36 slots milled per coating, 48 slots per depth of cut, and 48 slots per feedrate. By milling multiple slots using different combinations of the levels listed, the settings that lead to better results can be determined. This experiment shows which combination mills CFRP better and which individual settings are recommended.

Figure 8: Design used for Factor Level Determination

The feedrates used below in Table 6 were chosen based on the literature review. These were the ranges in which all the surveyed articles decided to conduct their experiment. Since none of the articles found compared multiple depths of cut, those values were chosen to demonstrate the effect of multiple passes on dimensional accuracy. They are explicitly chosen to mill the slot in either one, two, or three passes. The CFRP block has a thickness of 0.5 in with a layer thickness of 0.0066 in and a surface thickness of 0.125 in. Each epoxy layer was roughly 0.0002 in thick. With a slot depth of 0.15 in, 4 layers of epoxy and 5 layers of CFRP, including the surface weave, are cut during the operation. The slot depth is about 0.0044 in into the fifth layer of CFRP. This ensures that the surface roughness measurement is on a CFRP layer instead of an epoxy layer which would lead to inconclusive results.

Table 6: Machine settings used for the experiment

Cutting speed is set to 4500 RPM		Feedrate (in/min)[mm/rev]			
		5.3150 [0.03]	17.7165 [0.10]	26.5748 [0.15]	88.5827 [0.5]
Depth of Cut (in)	0.05				
	0.075				
	0.15				

4 Experimental Results

Data were collected on each slot for each experiment using a digital caliper for dimensional accuracy and a mechanical profiler for surface roughness. After collecting each slot's width, length, and height, the equation below was used to calculate RMS. The Dektak XT profilometer was used to measure the surface roughness.

$$RMS = \sqrt{\frac{(\frac{Width - 6.35}{6.35})^2 + (\frac{Length - 12.06}{12.06})^2 + (\frac{Height - 3.81}{3.81})^2}{3}} * 100$$

4.1 Toolpath Determination (Pre-Experiment)

Autodesk Fusion 360 offers many types of toolpaths to achieve the designed shape. There were a total of 7 available toolpaths that mill slots. Each toolpath was used to mill two slots at a constant feedrate and depth of cut of 26.5748 in/min and 0.15 in, respectively. After machining the part, machining time, cost, dimensional accuracy, and surface roughness were determined. The toolpath that led to higher dimensional accuracy and lower surface roughness was then used to complete the remainder of the experiment.

Each toolpath type performs the milling operation differently, which leads to different machining times, which correspond to different costs. The machining time and cost for one slot for each toolpath type are shown in Table 7. Each toolpath removes material by moving in a different pattern. For example, both 2D and 3D Adaptive Clearing toolpaths move in a semi-circular or circular pattern. 2D Contour, 3D Contour, and 3D Pencil toolpaths move in a line that performs one pass along the edge of the slot, while 2D and 3D Pocket toolpaths move in a spiral to remove material. Examples of each toolpath removal pattern are shown in Figure 9.

Table 7: Machining cost per type of toolpath

Toolpath Type	Machining Time per slot (sec)	Machining Time per slot Cost (\$)
2D Adaptive Clearing	42	\$0.28
2D Contour	5	\$0.03
2D Pocket	5	\$0.03
3D Pencil	2	\$0.01
3D Pocket	24	\$0.16
3D Adaptive Clearing	46	\$0.31
3D Contour	12	\$0.08

Figure 9: Material removal pattern for each toolpath

The Contour, Pocket, and Adaptive Clearing toolpaths each have a 2D and 3D option. While they both remove material in the same manner, the machining times are different. This is due to the direction and speed the bit approaches the material for each type. For example, in 2D Pocket, the bit moves down away from the stock material and then approaches from the side of the block and removes material. In contrast, 3D Pocket toolpaths bore into the slot and remove the material, which leads to the extra 19 seconds used. Figure 10 demonstrates how each toolpath approaches the stock material.

Figure 10: (a) 2D Pocket. (b) 3D Pocket

2D Contour, 3D Contour, and 3D Pencil toolpaths are only suitable for milling slots with a width of two times the bit diameter. Since these toolpaths remove material along the edge of the slot only, material is left in the middle when the width is larger than two times the bit, as shown in Figure 11. The slot below has a width of 0.6 in, while the bit is only 0.125 in in diameter, therefore leaving a large piece of material not removed in the middle. For this slot to be successfully milled using one of the three toolpaths mentioned, an 0.3 in diameter bit should be used. For this experiment, an 0.125 in diameter bit was used; therefore, an 0.25 in wide slot was designed to compare the different toolpaths.

Figure 11: Example of a slot larger than two times the bit diameter

The milled stock consists of 14 identical slots and one center slot used as a test run to ensure all settings are achievable. The part machined is shown in Figure 12.

Figure 12: Milled part used for toolpath determination

The surface roughness was measured along the center of each slot. The width of the slot was approximately the same size as the Dektak's measuring arm to ensure an accurate reading. Due to the different cutting pattern for each toolpath type, different parts of the slot could be rougher than others. As shown in Figure 13, 2D adaptive (a) and 2D Pocket (c) have multiple passes to ensure all material is removed, however for 2D Contour (b) there is only one pass which could lead to a rougher surface in the center if the bit diameter is not 0.125 in exactly. None of the roughness measurements were outliers and were within the range calculated for all slots.

Figure 13: Surface roughness measurement location. (a) 2D Adaptive (b) 2D Contour (c) 2D Pocket

The length, width, and height of each slot was measured using a caliper. Multiple measurements were taken to check if there are different results in different parts of the slot, however, the discrepancies were nonexistent. Due to the shape of the slot, the length was difficult to measure and required multiple tries to get an accurate reading from the top of the arc to the bottom of the slot. There were also no outliers in the dimensional data. The location of each measurement is shown in Figure 14. There were multiple equations that can be used to measure the deviation from the design dimensions, however, Root Mean Square (RMS) was chosen based on previous work.

Figure 14: Dimensional data measuring locations

After conducting the initial experiment at a constant feedrate, depth of cut and cutting speed, and varying toolpath types, a digital caliper was used to measure each slot's width, length, and height. The surface roughness was then collected using the Bruker Dektak XT Stylus profilometer. The data obtained for each measurement is shown in Table 8.

Table 8: Data obtained for each toolpath

Toolpath	Width (mm)	Length (mm)	Height (mm)	RMS (mm)	Surface Roughness (μm)
2D Adaptive	6.32	12.02	3.62	2.90	1.420
2D Adaptive	6.29	12.12	3.58	3.54	1.517
2D Contour	6.27	12.16	3.58	3.59	1.099
2D Contour	6.18	12.22	3.63	3.23	1.537
2D Pocket	6.25	11.14	3.90	4.70	1.348
2D Pocket	6.27	11.46	3.95	3.64	1.370
3D Pencil	6.26	12.30	3.33	7.41	1.000
3D Pencil	6.22	12.38	3.30	7.97	1.087
3D Pocket	6.30	11.90	3.37	6.73	1.233
3D Pocket	6.33	12.01	3.44	5.61	1.833
3D Adaptive	6.39	11.88	3.57	3.76	1.097
3D Adaptive	6.36	11.99	3.78	0.57	1.257
3D Contour	6.20	11.84	3.76	1.88	1.432
3D Contour	6.18	12.06	3.82	1.55	1.427

4.2 Factor Level Determination

The initial feedrates used were 0.03, 0.15, and 0.5 mm/rev. However, the 0.5 mm/rev feedrate was too high during the first run and broke the bit. Therefore, a lower feedrate, 0.10 mm/rev, was chosen to avoid further damage to the bits and material. The selected new feedrate was within the range of feedrates used in the literature review. All slots were milled using the 2D Contour toolpath, which was determined in the initial experiment. After performing the milling operation using the Tormach PCNC 1100 mill, the Dektak XT stylus profilometer used in the initial experiment was used to gather the surface roughness measurements for each slot. A total of 8 blocks were milled with 18 slots per block. Figure 15 demonstrates one of the milled blocks.

Figure 15: Milled block

This experiment was designed as a full factorial with three replications to ensure enough data to demonstrate which combination leads to better results. The factorial design was generated in JMP and randomized to reduce the tool wear effect on the operation. The number of slots was divided equally and randomly among the number of bits to eliminate the tool wear effect further. The dimensional accuracy and surface roughness data collected are shown in Table 9.

Table 9: Data obtained for each slot.

Slot #	RMS (mm)	Surface Roughness (μm)	Slot #	RMS (mm)	Surface Roughness (μm)	Slot #	RMS (mm)	Surface Roughness (μm)
1	1.44	0.964	49	2.27	1.064	97	2.73	0.679
2	2.23	0.908	50	2.55	0.810	98	2.48	1.095
3	1.79	0.604	51	1.74	1.102	99	2.35	0.532
4	1.63	0.728	52	1.71	1.201	100	2.06	0.919
5	1.88	0.857	53	1.05	1.453	101	3.35	1.001
6	4.19	1.116	54	3.97	1.398	102	3.78	0.860
7	3.77	0.859	55	4.22	1.695	103	3.36	1.349
8	3.69	0.966	56	4.02	1.412	104	4.09	0.816
9	2.55	1.035	57	2.92	1.410	105	3.48	0.904
10	5.18	1.147	58	3.98	1.335	106	4.26	1.280
11	7.87	1.689	59	3.03	1.443	107	2.80	1.182
12	7.43	1.744	60	2.28	0.689	108	2.83	1.137
13	4.16	0.854	61	2.49	0.589	109	3.98	0.979
14	2.87	0.431	62	2.12	1.033	110	2.26	0.851
15	3.73	0.656	63	2.20	0.882	111	3.05	0.918
16	2.75	0.708	64	3.09	1.229	112	2.67	0.758
17	3.01	1.315	65	4.35	1.330	113	3.87	1.113
18	2.27	1.219	66	2.00	1.329	114	4.29	0.876
19	13.63	0.836	67	2.27	1.539	115	2.98	1.213
20	12.57	1.335	68	2.50	1.775	116	4.27	0.983
21	12.36	1.113	69	2.28	1.566	117	2.05	0.830
22	3.89	1.138	70	3.42	1.136	118	3.11	0.877
23	3.68	0.692	71	2.71	1.302	119	3.61	0.932
24	1.68	1.195	72	3.29	1.110	120	3.07	1.078
25	3.44	0.796	73	3.45	0.707	121	2.84	1.013
26	1.51	1.061	74	2.48	1.313	122	2.93	1.004
27	1.73	0.984	75	2.10	1.027	123	2.46	0.822
28	3.55	1.338	76	3.63	1.330	124	1.14	0.891
29	3.32	1.089	77	2.40	0.968	125	2.89	0.840
30	3.66	1.404	78	2.94	1.230	126	2.04	0.911
31	3.48	0.913	79	3.01	0.767	127	4.45	0.941
32	3.49	1.145	80	2.98	1.150	128	3.84	0.777
33	2.96	1.016	81	3.20	1.074	129	4.18	1.148
34	3.16	0.561	82	2.68	1.650	130	3.90	1.005
35	3.24	1.233	83	2.84	1.168	131	4.53	0.815
36	3.12	0.802	84	3.21	1.126	132	4.36	0.683
37	3.82	1.006	85	3.00	1.173	133	3.47	0.757
38	3.63	1.022	86	3.25	1.016	134	3.14	0.667
39	2.54	1.277	87	2.21	0.936	135	2.90	0.866
40	3.18	1.521	88	2.65	1.039	136	4.89	0.915
41	3.01	1.786	89	2.39	0.793	137	4.58	1.104
42	3.05	1.239	90	3.94	0.706	138	3.09	1.138
43	3.01	0.781	91	3.83	0.891	139	3.81	0.842
44	2.71	1.780	92	3.82	1.084	140	3.77	0.593
45	2.24	1.083	93	4.30	1.192	141	3.90	0.994
46	3.66	1.347	94	3.83	0.816	142	2.91	1.171
47	3.61	1.545	95	3.71	0.756	143	3.18	0.757
48	3.68	1.441	96	3.56	1.140	144	3.04	0.933

Each slot's surface roughness was measured separately using the Dektak XT Stylus profilometer. For each slot, a surface roughness value and profile were obtained, as shown in Figure 16.

Figure 16: Surface roughness value and profile for slot 5

The 2 μm diameter stylus was used to measure a 2 mm portion of the slot at a speed of 200 $\mu\text{m/s}$. Figure 17 shows the stylus placement on the part's surface.

Figure 17: CFRP surface roughness measurement

5 Discussion

This section interprets and discusses the results obtained to determine the optimal settings to use when CNC milling CFRP to increase dimensional accuracy and reduce surface roughness. Two experiments were set up, the first to determine which toolpath type leads to better results and the second to determine the combination of tool coating, feedrate, and depth of cut, using the toolpath type found in the first experiment, which leads to higher dimensional accuracy and lower surface roughness. The dimensional and roughness data to determine which toolpath type to use were shown in section 4.1. Section 4.2 then shows the data collected by running an experiment with varying feedrates, depths of cut, and tool coatings. Section 5.1 discusses the results obtained in the initial experiment and includes the effect of cost when choosing a toolpath type. Section 5.2 goes over the results from the factor level determination and shows which factor levels lead to better results.

5.1 Toolpath Determination (Pre-Experiment)

The initial experiment determined which toolpath type leads to better dimensional accuracy and surface roughness while minimizing cost was determined to be the 2D Contour toolpath. A 2D Contour toolpath was eligible to be used because the slot width did not exceed two times the bit diameter. This toolpath was chosen based on surface roughness, dimensional accuracy, and cost. Although the cost for this experiment was not a significant factor, in manufacturing in general, the cost is very important and affects the manufacturing capabilities available for a product. Although 3D toolpaths were included in the experiment, they can not be used for the factor level determination due to the inability to adjust the depth of cut. However, they were added to show the capabilities of those toolpaths for future work.

A JMP analysis was performed to identify which of the toolpath types are significant factors affecting dimensional accuracy and surface roughness. Concerning surface roughness, none of the toolpath types had a significant effect; however, for dimensional accuracy, the toolpath type did affect the milled slot. Both 3D Adaptive and 3D Contour toolpaths had a significant effect on the accuracy of the slot, and 3D Pencil toolpaths had some significant effect. All other toolpath types do not have a significant effect on dimensional accuracy. The JMP profiler shows that 3D Pencil is the best 3D toolpath and 2D Contour is the best 2D one. Table 10 shows the ranking of each toolpath in terms of dimensional accuracy and surface roughness when the cost is excluded and included.

Table 10: Ranking of each toolpath

	Excluding Cost		Including Cost
1	3D Pencil		3D Pencil
2	3D Contour		2D Contour
3	2D Contour		3D Contour
4	2D Adaptive		2D Pocket
5	2D Pocket		3D Pocket
6	3D Pocket		2D Adaptive
7	3D Adaptive		3D Adaptive

5.2 Factor Level Determination

The toolpath type determined in the initial experiment, 2 Contour, was then used to generate toolpaths using three levels of feedrates, three levels of depths of cut, and four tool coatings. After milling each of the 144 slots and obtaining the dimensional accuracy and surface roughness data, a JMP analysis was conducted to determine which combination leads to better accuracy and surface roughness.

An issue that arises with milling CFRP is delamination due to chipping during the operation. Due to the nature of the material, having fibers placed in a matrix, instead of the bit cutting the material, it can either chip, peel up or push out the fibers, as shown in Figure 18 and Figure 19. There are multiple ways to reduce delamination during milling, the most common issue is incorrect machine settings. Delamination can occur if the feedrate is too high and the cutting speed is too low. To ensure that the material is cut correctly, the bit needs to be spinning at very high speeds and low feedrates. In the literature review, most articles used cutting speeds around 12000 RPM; however, for this experiment, a cutting speed of 4500 RPM was used due to the limitations of the available CNC mill. To offset that decrease in cutting speed, lower feedrates were chosen to ensure that the material is cut correctly. Fiber peel-up and push-out mainly occur during drilling CFRP due to low cutting speeds or wore out cutting bits. Worn-out cutting bits can also cause delamination at the edges or surface of the milled part due to being dull and not cutting the fiber correctly, increasing surface roughness.

Figure 18: Peel up and push out delamination in CFRP. [84]

All slots had delamination at the edges. As shown in Figure 19, the slot does not appear to be damaged at the edges; however, at the nanoscale, there is some damage in slot 7 and a lot of damage in slot 5. Although this kind of delamination does not affect the results of this experiment, in mechanical uses, this part could fail due to damaged material. Therefore, ensuring that delamination doesn't occur or is minimized is crucial to the part's structural integrity.

Figure 19: Chipping on slot edges. (a) slot 5 (b) slot 7

After collecting all the data, another JMP analysis was performed using feedrate, tool coating, and depth of cut as the main factors. The interaction effect of feedrate and depth of cut and tool coating and depth of cut were added to show the impact of the different combinations. The interaction effect feedrate and tool coating led to an error that miscalculated the tool coating effect. Therefore it was removed from the analysis due to insufficient degrees of freedom.

Figure 20: JMP model fitting.

All factors were analyzed with respect to dimensional accuracy and surface roughness. Tables 11-14 show the significant factors and levels on dimensional accuracy and surface roughness. Feederate was the only significant factor for both criteria, which agrees with the literature review that feederate is one of the most critical factors when milling CFRP. Tool coating is a significant factor on surface roughness and somewhat significant on dimensional accuracy. This could be because better/stronger coatings cut CFRP fibers completely and cause less delamination, resulting in better roughness. The depth of cut has some significant effect on surface roughness but none on dimensional accuracy. The interaction effect feederate and depth of cut is somewhat significant in terms of dimensional accuracy; while, tool coating and depth of cut are more significant concerning dimensional accuracy. Both interaction effects are not an important factor on surface roughness.

Table 11: Effect tests on dimensional accuracy

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Feedrate	3	2	49.810581	14.6492	<.0001*
Tool Coating	3	3	18.170111	3.5625	0.0162*
Depth of Cut	2	1	5.809504	3.4171	0.0669
Feedrate*Depth of Cut	6	5	25.833172	3.0390	0.0127*
Tool Coating*Depth of Cut	6	6	39.376198	3.8602	0.0014*

Table 12: Significant effects on dimensional accuracy

Term	Prob> t
Intercept	<.0001*
Feedrate[0.03]	<.0001*
Feedrate[0.15]	0.5179
Feedrate[0.5]	0.0466*
Feedrate[0.1]	0.1244
Tool Coating[Diamond]	0.0045*
Tool Coating[Titanium Carbonitride]	0.3183
Tool Coating[Diamondlike Carbon]	0.0274*
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]	0.8103
Depth of Cut[0.05]	0.2809
Depth of Cut[0.075]	0.0148*
Depth of Cut[0.15]	0.8655
Feedrate[0.03]*Depth of Cut[0.05]	0.7931
Feedrate[0.03]*Depth of Cut[0.075]	0.0105*
Feedrate[0.03]*Depth of Cut[0.15]	0.3524
Feedrate[0.15]*Depth of Cut[0.05]	0.1996
Feedrate[0.15]*Depth of Cut[0.075]	0.0003*
Feedrate[0.15]*Depth of Cut[0.15]	0.6729
Feedrate[0.5]*Depth of Cut[0.05]	0.7707
Feedrate[0.5]*Depth of Cut[0.075]	1.0000
Feedrate[0.5]*Depth of Cut[0.15]	0.7707
Feedrate[0.1]*Depth of Cut[0.05]	0.8117
Feedrate[0.1]*Depth of Cut[0.075]	0.2835
Feedrate[0.1]*Depth of Cut[0.15]	0.7887
Tool Coating[Diamond]*Depth of Cut[0.05]	0.0196*
Tool Coating[Diamond]*Depth of Cut[0.075]	<.0001*
Tool Coating[Diamond]*Depth of Cut[0.15]	0.0134*
Tool Coating[Titanium Carbonitride]*Depth of Cut[0.05]	0.3789
Tool Coating[Titanium Carbonitride]*Depth of Cut[0.075]	0.1131
Tool Coating[Titanium Carbonitride]*Depth of Cut[0.15]	0.4739
Tool Coating[Diamondlike Carbon]*Depth of Cut[0.05]	0.4219
Tool Coating[Diamondlike Carbon]*Depth of Cut[0.075]	0.0224*
Tool Coating[Diamondlike Carbon]*Depth of Cut[0.15]	0.1322
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]*Depth of Cut[0.05]	0.4528
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]*Depth of Cut[0.075]	0.2867
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]*Depth of Cut[0.15]	0.7493

Table 13: Effect tests on surface roughness

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Feedrate	3	2	1.2734975	10.0271	<.0001*
Tool Coating	3	3	2.6109013	13.7049	<.0001*
Depth of Cut	2	1	0.3158138	4.9732	0.0275*
Feedrate*Depth of Cut	6	5	0.3815797	1.2018	0.3123
Tool Coating*Depth of Cut	6	6	0.2781252	0.7300	0.6263

Table 14: Significant effects on surface roughness

Term	Prob> t
Intercept	<.0001*
Feedrate[0.03]	<.0001*
Feedrate[0.15]	0.1118
Feedrate[0.5]	0.0003*
Feedrate[0.1]	0.0189*
Tool Coating[Diamond]	0.0431*
Tool Coating[Titanium Carbonitride]	0.5675
Tool Coating[Diamondlike Carbon]	<.0001*
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]	0.0007*
Depth of Cut[0.05]	0.0532
Depth of Cut[0.075]	0.2259
Depth of Cut[0.15]	0.1555
Feedrate[0.03]*Depth of Cut[0.05]	0.2996
Feedrate[0.03]*Depth of Cut[0.075]	0.0691
Feedrate[0.03]*Depth of Cut[0.15]	0.0628
Feedrate[0.15]*Depth of Cut[0.05]	0.1608
Feedrate[0.15]*Depth of Cut[0.075]	0.7416
Feedrate[0.15]*Depth of Cut[0.15]	0.2137
Feedrate[0.5]*Depth of Cut[0.05]	0.1457
Feedrate[0.5]*Depth of Cut[0.075]	1.0000
Feedrate[0.5]*Depth of Cut[0.15]	0.1457
Feedrate[0.1]*Depth of Cut[0.05]	0.1514
Feedrate[0.1]*Depth of Cut[0.075]	0.1468
Feedrate[0.1]*Depth of Cut[0.15]	0.4403
Tool Coating[Diamond]*Depth of Cut[0.05]	0.8936
Tool Coating[Diamond]*Depth of Cut[0.075]	0.9469
Tool Coating[Diamond]*Depth of Cut[0.15]	0.9467
Tool Coating[Titanium Carbonitride]*Depth of Cut[0.05]	0.8465
Tool Coating[Titanium Carbonitride]*Depth of Cut[0.075]	0.8070
Tool Coating[Titanium Carbonitride]*Depth of Cut[0.15]	0.6605
Tool Coating[Diamondlike Carbon]*Depth of Cut[0.05]	0.1365
Tool Coating[Diamondlike Carbon]*Depth of Cut[0.075]	0.7201
Tool Coating[Diamondlike Carbon]*Depth of Cut[0.15]	0.2561
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]*Depth of Cut[0.05]	0.1227
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]*Depth of Cut[0.075]	0.9648
Tool Coating[Titanium Nitride and Titanium Aluminum Nitride]*Depth of Cut[0.15]	0.1328

The 0.5 mm/rev (88.5827 in/min) feedrate initially chosen was able to mill 2 slots, however, it broke during the cutting of the third slot. It was then replaced with the 0.1 mm/rev (17.7165 in/min) feedrate. Although the bit used was diamond coated, due to the high feedrate the cutting forces were too high and led to the broken bit. This shows that high feedrates when milling CFRP damages the bit and the material which corresponds to the articles found that lower feedrates lead to better milled CFRP by reducing cutting forces therefore reducing delamination and tool wear.

The JMP profiler was used to determine the most desirable operating conditions for each factor and choosing the most suitable level depending on the expected outcome of the milling operation. When dimensional accuracy and surface roughness are equally important, a feedrate of 0.03 mm/rev, TiN and TiAlN tool coating, and a depth of cut of 0.05 in lead to better results. Based on the literature review, low feedrate and diamond coated tools were said to cut CFRP better; however, this experiment showed that feedrate does need to be low, but a TiN and TiAlN tool coating has better results. Not enough information was given in previous work on the depth of cut, but this experiment shows that depth of cut is somewhat important and does not need to be too low. In this case, the slot milled in 3 passes led to the best results.

While this configuration is best when dimensional accuracy and surface roughness are important, the operating conditions change if only one aspect is important. Surface roughness uses the same operating conditions listed whether or not dimensional accuracy is important. On the other hand, when dimensional accuracy is more important, a Diamondlike Carbon tool (DLC) coating and a depth of cut of 0.075 in are more suitable for better results. When cost is an equally important factor, which it usually is, a higher feedrate of 0.15 mm/rev is better to mill the slot in less time, reducing machining cost. When only dimensional accuracy and surface roughness are important, at best operating conditions, an average dimensional accuracy of 2.49% and average surface roughness of 0.628 μm can be obtained at the cost of \$0.25 per slot or \$14.71/ in^3 . When cost is included, the dimensional accuracy decreases to 3.20% and surface roughness to 0.882 μm at the cost of \$0.09 per slot or \$5.29/ in^3 .

A coolant was used during the milling operation to reduce the heat generated. Based on the literature review, heat generation causes delamination in the material and damages the tool used. An example of the setup is shown below in Figure 21. There was no visible damage to the material or the tools. Air pressure was also used to remove the milled chips from the block while being cut to ensure that they do not interfere with the cutting.

Figure 21: Milling operation.

This analysis determined the desirable outcome using a slot two times the diameter of the bit which led to 2D Contour. However, if milling a slot that bigger or smaller than two times the diameter then 2D Contour, 3D Contour and 3D Pencil cannot be used, therefore 2D Adaptive clearing would lead to better results. During the analysis, a correlation between the cutting pattern and the dimensional accuracy and surface roughness was observed. 2D Adaptive, 3D Adaptive, 2D Pocket and 3D Pocket toolpaths had the lowest dimensional accuracy and surface roughness, while 3D Pencil, 2D Contour, 3D Contour had the best. The lower four toolpaths have a longer cutting pattern where they move back and forth multiple times to mill the slot while the better three only do one pass around the slot. This could be because the more movement the bit performs during the operation the higher the delamination is in the material leading to worse results.

Figures 17-19 show the effect of different levels of the factors on surface roughness. All the profiles were exported from the Dektak XT Stylus Profilometer. Figure 22 shows the effect of the three levels of feedrate on surface roughness. The 0.03 mm/rev (blue line) has the lowest overall step height, which corresponds to the analysis and literature review that a lower feedrate leads to better surface roughness. Figure 23 compares the different tool coatings. While Titanium Nitride and Titanium Aluminum Nitride is the best tool coating tested for dimensional accuracy and surface roughness, Diamond coated tools are better for surface roughness, and Diamondlike Carbon coated tools lead to the roughest surface. Depth of cut also follows the same trend as feedrate, that a lower level leads to better surface roughness, as shown in Figure 24.

Figure 22: Effect of feedrate on surface roughness

Figure 23: Effect of tool coating on surface roughness

Figure 24: Effect of depth of cut on surface roughness

6 Conclusion

6.1 Conclusion

In conclusion, the use of CFRP in the manufacturing industry has skyrocketed in recent years, leading to the need to manufacture CFRP given its difficulties successfully. Although many manufacturing methods can produce parts made with CFRP, CNC Milling offers low costs at low volumes, a good surface finish, and a tight tolerance.

Determining which toolpath type, tool coating, feedrate, and depth of cut to use is vital in machining CFRP. Therefore, this thesis conducted an experiment and determined which toolpath, machine settings, and tool materials among the tested achieve the most desirable outcome. Two experiments were designed to determine the optimal levels to use when milling CFRP. The factors tested were chosen based on insufficient information found in previous work during the conducted literature review. Little work is done on the impact of the toolpath type or the effect of different levels of the factors listed above on the operation. This research gap is addressed in this thesis.

The first experiment compared the dimensional accuracy and surface quality of the toolpath types available on fusion 360. Seven toolpaths were used to mill slots at a constant depth of cut and feedrate using a Tormach PCNC 1100. The slots were then measured with a caliper and the Dektak XT Stylus Profilometer, a mechanical profiler. The data collected was then analyzed in JMP. The analysis determined that 3D Pencil was the best 3D toolpath in terms of dimensional accuracy and surface roughness and 2D Contour is the best 2D toolpath type.

The second experiment tested different combinations of three levels of feedrate, three levels of depth of cut, and four levels of tool coatings using the 2D Contour toolpath type determined in the initial experiment. Three replications were used to reduce the effect of tool wear on the results. The main effects, as well as their interaction effects, were analyzed. The experiment showed that feedrate, tool coating, and depth of cut are crucial factors in milling CFRP successfully. The analysis results showed that selecting a low feedrate (0.03 mm/rev) and depth of cut (0.05 in) with a Titanium Nitride and Titanium Aluminum Nitride leads to better milled CFRP parts.

6.2 Limitations and Future Work

This thesis did not include the effect of heat generation or tool wear on the milled part's dimensional accuracy and surface roughness due to the unavailability of the required devices to measure both aspects.

Further work could be done to compare different fiber placements or matrix weights. An experiment could be conducted to determine the effect of fiber weight, fiber placement, or layer thickness on dimensional accuracy, surface roughness, or material strength. Another experiment that could be conducted is to compare dimensional accuracy and surface roughness among different materials using the same factor combinations across all materials. Heat generation and tool wear affect CFRP delamination and could be inspected in a future experiment to choose a feedrate and tool coating that reduces their effect.

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Appendix

Appendix A: Tormach PCNC 1100 Software and Equipment

Figure A.1: Tormach PCNC 1100

Figure A.2: Work Area

Figure A.3: Tool Holders

Figure A.4: Referencing

Figure A.5: Zeroing

Figure A.6: CNC Mill file upload

Figure A.9: Toolpath

Figure A.10: Work Area with Stock

Appendix B: Dektak XT Stylus Profilometer Software and Equipment

Figure B.1: Dektak XT Stylus Profilometer

Figure B.2: Workpiece

Figure B.3: Machine Settings

Figure B.4: Surface Roughness Measurement

Appendix C: Data Tables

Table C.1: Factor combinations for the Factor Level Determination.

Slot Number	Pattern	Feedrate (mm/rev)	Tool Coating	Depth of Cut (in)	Width (mm)	Length (mm)	Height (mm)
1	111	0.03	Diamond	0.15	6.20	12.04	3.78
2	112	0.03	Diamond	0.05	6.21	12.10	3.69
3	112	0.03	Diamond	0.05	6.25	12.12	3.71
4	113	0.03	Diamond	0.075	6.18	11.96	3.82
5	113	0.03	Diamond	0.075	6.20	11.79	3.81
6	211	0.15	Diamond	0.15	5.91	11.81	3.83
7	211	0.15	Diamond	0.15	5.98	11.85	3.72
8	212	0.15	Diamond	0.05	6.07	11.91	3.98
9	212	0.15	Diamond	0.05	6.11	11.79	3.83
10	312	0.5	Diamond	0.05	5.87	12.64	3.79
11	313	0.5	Diamond	0.075	5.64	12.92	3.69
12	313	0.5	Diamond	0.075	5.63	12.59	3.97
13	111	0.03	Diamond	0.15	6.08	12.76	3.82
14	111	0.03	Diamond	0.15	6.16	12.54	3.81
15	112	0.03	Diamond	0.05	6.14	12.71	3.76
16	113	0.03	Diamond	0.075	6.12	12.30	3.72
17	211	0.15	Diamond	0.15	6.02	12.08	3.80
18	212	0.15	Diamond	0.05	6.15	12.19	3.73
19	213	0.15	Diamond	0.075	6.06	9.32	3.98
20	213	0.15	Diamond	0.075	6.02	9.59	4.01
21	213	0.15	Diamond	0.075	6.07	9.54	3.87
22	311	0.1	Diamond	0.15	6.00	11.79	3.69
23	311	0.1	Diamond	0.15	6.03	11.83	3.68
24	312	0.1	Diamond	0.05	6.19	11.94	3.77
25	111	0.03	Diamond	0.15	5.98	12.21	3.81
26	112	0.03	Diamond	0.05	6.21	12.20	3.78
27	113	0.03	Diamond	0.075	6.20	12.06	3.88
28	211	0.15	Diamond	0.15	6.02	12.30	3.71
29	212	0.15	Diamond	0.05	6.11	12.42	3.69
30	213	0.15	Diamond	0.075	6.04	12.32	3.68
31	311	0.1	Diamond	0.15	6.01	12.16	3.71
32	311	0.1	Diamond	0.15	6.05	12.35	3.70
33	312	0.1	Diamond	0.05	6.14	12.34	3.69
34	312	0.1	Diamond	0.05	6.04	12.22	3.73
35	313	0.1	Diamond	0.075	6.09	12.19	3.67
36	313	0.1	Diamond	0.075	6.10	12.12	3.67
37	131	0.03	DLC	0.15	6.03	11.95	3.65
38	131	0.03	DLC	0.15	6.07	12.10	3.64
39	133	0.03	DLC	0.075	6.12	11.90	3.73
40	232	0.15	DLC	0.05	6.09	12.07	3.67
41	232	0.15	DLC	0.05	6.12	11.87	3.68
42	233	0.15	DLC	0.075	6.10	11.87	3.69
43	233	0.15	DLC	0.075	6.04	12.17	3.87

44	332	0.1	DLC	0.05	6.10	12.34	3.85
45	332	0.1	DLC	0.05	6.12	12.11	3.86
46	332	0.1	DLC	0.05	6.12	12.62	3.72
47	333	0.1	DLC	0.075	6.07	12.53	3.73
48	333	0.1	DLC	0.075	6.08	12.63	3.83
49	131	0.03	DLC	0.15	6.16	12.34	3.77
50	132	0.03	DLC	0.05	6.26	12.54	3.76
51	132	0.03	DLC	0.05	6.32	12.23	3.91
52	133	0.03	DLC	0.075	6.18	12.21	3.80
53	133	0.03	DLC	0.075	6.30	12.18	3.76
54	231	0.15	DLC	0.15	5.99	11.91	3.67
55	231	0.15	DLC	0.15	5.97	12.05	3.65
56	231	0.15	DLC	0.15	5.98	11.80	3.69
57	331	0.1	DLC	0.15	6.06	11.88	3.75
58	331	0.1	DLC	0.15	6.01	11.78	3.67
59	331	0.1	DLC	0.15	6.06	11.79	3.86
60	333	0.1	DLC	0.075	6.18	12.08	3.70
61	131	0.03	DLC	0.15	6.10	11.85	3.80
62	132	0.03	DLC	0.05	6.17	11.94	3.73
63	132	0.03	DLC	0.05	6.16	11.93	3.73
64	133	0.03	DLC	0.075	6.09	12.39	3.73
65	231	0.15	DLC	0.15	5.93	12.36	3.71
66	232	0.15	DLC	0.05	6.17	12.24	3.86
67	232	0.15	DLC	0.05	6.15	12.07	3.72
68	233	0.15	DLC	0.075	6.11	12.04	3.73
69	233	0.15	DLC	0.075	6.11	12.16	3.84
70	331	0.1	DLC	0.15	6.05	12.19	3.68
71	332	0.1	DLC	0.05	6.18	12.40	3.71
72	333	0.1	DLC	0.075	6.14	12.44	3.68
73	121	0.03	TiCN	0.15	6.07	11.95	3.66
74	123	0.03	TiCN	0.075	6.13	11.85	3.88
75	123	0.03	TiCN	0.075	6.16	11.90	3.75
76	221	0.15	TiCN	0.15	5.98	11.88	3.88
77	222	0.15	TiCN	0.05	6.14	11.80	3.76
78	222	0.15	TiCN	0.05	6.17	11.55	3.80
79	222	0.15	TiCN	0.05	6.08	11.71	3.84
80	223	0.15	TiCN	0.075	6.05	11.82	3.79
81	321	0.1	TiCN	0.15	6.02	11.85	3.84
82	322	0.1	TiCN	0.05	6.09	12.27	3.76
83	322	0.1	TiCN	0.05	6.10	12.14	3.70
84	323	0.1	TiCN	0.075	6.10	12.48	3.74
85	121	0.03	TiCN	0.15	6.13	12.28	3.68
86	121	0.03	TiCN	0.15	6.16	12.33	3.65
87	122	0.03	TiCN	0.05	6.27	12.36	3.71
88	123	0.03	TiCN	0.075	6.11	12.36	3.78
89	123	0.03	TiCN	0.075	6.18	12.37	3.74
90	221	0.15	TiCN	0.15	5.99	12.36	3.70
91	222	0.15	TiCN	0.05	6.24	12.80	3.74
92	223	0.15	TiCN	0.075	6.17	12.78	3.82

93	321	0.1	TiCN	0.15	6.04	12.70	3.74
94	322	0.1	TiCN	0.05	6.22	12.82	3.80
95	323	0.1	TiCN	0.075	6.16	12.74	3.78
96	323	0.1	TiCN	0.075	6.15	12.66	3.88
97	121	0.03	TiCN	0.15	6.13	11.74	3.88
98	122	0.03	TiCN	0.05	6.12	11.80	3.84
99	122	0.03	TiCN	0.05	6.14	11.82	3.86
100	122	0.03	TiCN	0.05	6.14	12.22	3.81
101	221	0.15	TiCN	0.15	6.01	12.25	3.87
102	221	0.15	TiCN	0.15	5.97	12.38	3.81
103	223	0.15	TiCN	0.075	6.04	12.44	3.80
104	223	0.15	TiCN	0.075	6.03	12.38	3.97
105	321	0.1	TiCN	0.15	5.98	12.16	3.86
106	321	0.1	TiCN	0.15	5.90	12.27	3.77
107	322	0.1	TiCN	0.05	6.07	12.21	3.75
108	323	0.1	TiCN	0.075	6.07	12.32	3.81
109	141	0.03	TiN and TiAlN	0.15	6.03	11.57	3.90
110	142	0.03	TiN and TiAlN	0.05	6.17	11.74	3.79
111	143	0.03	TiN and TiAlN	0.075	6.10	11.68	3.75
112	143	0.03	TiN and TiAlN	0.075	6.11	11.74	3.81
113	143	0.03	TiN and TiAlN	0.075	6.17	11.40	3.91
114	241	0.15	TiN and TiAlN	0.15	6.00	11.50	3.88
115	341	0.1	TiN and TiAlN	0.15	6.03	11.97	3.84
116	341	0.1	TiN and TiAlN	0.15	6.00	11.89	3.99
117	342	0.1	TiN and TiAlN	0.05	6.14	11.91	3.80
118	343	0.1	TiN and TiAlN	0.075	6.09	12.16	3.94
119	343	0.1	TiN and TiAlN	0.075	6.13	12.47	3.96
120	343	0.1	TiN and TiAlN	0.075	6.10	12.49	3.81
121	141	0.03	TiN and TiAlN	0.15	6.13	12.48	3.82
122	141	0.03	TiN and TiAlN	0.15	6.12	11.74	3.72
123	142	0.03	TiN and TiAlN	0.05	6.27	11.57	3.81
124	142	0.03	TiN and TiAlN	0.05	6.26	12.01	3.86
125	241	0.15	TiN and TiAlN	0.15	6.08	12.04	3.91
126	242	0.15	TiN and TiAlN	0.05	6.16	12.01	3.74
127	243	0.15	TiN and TiAlN	0.075	6.10	11.26	3.81
128	243	0.15	TiN and TiAlN	0.075	6.10	11.42	3.78
129	243	0.15	TiN and TiAlN	0.075	6.14	11.30	3.76
130	341	0.1	TiN and TiAlN	0.15	6.12	11.38	3.84
131	342	0.1	TiN and TiAlN	0.05	6.18	11.18	3.77
132	342	0.1	TiN and TiAlN	0.05	6.13	11.26	3.77
133	141	0.03	TiN and TiAlN	0.15	6.08	11.55	3.82
134	142	0.03	TiN and TiAlN	0.05	6.12	11.75	3.93
135	143	0.03	TiN and TiAlN	0.075	6.16	11.69	3.91
136	241	0.15	TiN and TiAlN	0.15	5.97	12.63	3.95
137	241	0.15	TiN and TiAlN	0.15	5.95	12.64	3.82
138	242	0.15	TiN and TiAlN	0.05	6.11	12.46	3.88
139	242	0.15	TiN and TiAlN	0.05	6.10	12.66	3.88
140	242	0.15	TiN and TiAlN	0.05	6.09	12.66	3.77
141	243	0.15	TiN and TiAlN	0.075	6.03	12.60	3.82

142	341	0.1	TiN and TiAlN	0.15	6.09	12.27	3.90
143	342	0.1	TiN and TiAlN	0.05	6.14	12.46	3.92
144	343	0.1	TiN and TiAlN	0.075	6.10	12.30	3.92

Appendix D: Toolpath Determination JMP Output

Response RMS

Figure D.1: Actual by Predicted Plot

Figure D.2: Residual by Predicted Plot

Figure D.3: Studentized Residuals

Table D.1: Summary of Fit

RSquare	0.891826
RSquare Adj	0.799105
Root Mean Square Error	0.982555
Mean of Response	4.077143
Observations (or Sum Wgts)	14

Table D.2: Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	55.714386	9.28573	9.6184
Error	7	6.757900	0.96541	Prob > F
C. Total	13	62.472286		0.0043*

Table D.3: Parameter Estimates

Term	t Ratio	Prob> t	AdjPower0.05
Intercept	15.53	<.0001*	1.0000
Toolpath[2D Adaptive]	-1.33	0.2244	0.0736
Toolpath[2D Contour]	-1.04	0.3342	0.0500
Toolpath[2D Pocket]	0.14	0.8893	0.0500
Toolpath[3D Adaptive]	5.62	0.0008*	0.9764
Toolpath[3D Contour]	-3.67	0.0079*	0.7131
Toolpath[3D Pencil]	-2.97	0.0207*	0.5106

Table D.4: Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Toolpath	6	6	55.714386	9.6184	0.0043*

Figure D.4: Residual by Row Plot

Figure D.5: Residual Normal Quantile Plot

Table D.5: Parameter Estimate Population

Term	Estimate	t Ratio	Orthog Coded	Orthog t-Ratio	Prob> t
Intercept	4.07714	15.5261	4.07714	15.5261	<.0001*
Toolpath[2D Adaptive]	-0.85714	-1.3326	-0.78842	-3.0024	0.0199*
Toolpath[2D Contour]	-0.66714	-1.0372	-0.39656	-1.5101	0.1748
Toolpath[2D Pocket]	0.09286	0.1444	-0.03164	-0.1205	0.9075
Toolpath[3D Adaptive]	3.61286	5.6167	1.16547	4.4382	0.0030*
Toolpath[3D Contour]	-2.36214	-3.6723	-1.10997	-4.2269	0.0039*
Toolpath[3D Pencil]	-1.91214	-2.9727	-0.78063	-2.9727	0.0207*

Table D.6: Correlations of Estimates

Intercept	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Toolpath[2D Adaptive]	0.0000	1.0000	-0.1667	-0.1667	-0.1667	-0.1667	-0.1667
Toolpath[2D Contour]	0.0000	-0.1667	1.0000	-0.1667	-0.1667	-0.1667	-0.1667
Toolpath[2D Pocket]	0.0000	-0.1667	-0.1667	1.0000	-0.1667	-0.1667	-0.1667
Toolpath[3D Adaptive]	0.0000	-0.1667	-0.1667	-0.1667	1.0000	-0.1667	-0.1667
Toolpath[3D Contour]	0.0000	-0.1667	-0.1667	-0.1667	-0.1667	1.0000	-0.1667
Toolpath[3D Pencil]	0.0000	-0.1667	-0.1667	-0.1667	-0.1667	-0.1667	1.0000

Table D.7: Transformation to make uncorrelated

Intercept	3.80809	0	0	0	0	0	0
Toolpath[2D Adaptive]	0	2.03551	1.01775	1.01775	1.01775	1.01775	1.01775
Toolpath[2D Contour]	0	0	1.7628	0.5876	0.5876	0.5876	0.5876
Toolpath[2D Pocket]	0	0	0	1.66199	0.4155	0.4155	0.4155
Toolpath[3D Adaptive]	0	0	0	0	1.60921	0.32184	0.32184
Toolpath[3D Contour]	0	0	0	0	0	1.5767	0.26278
Toolpath[3D Pencil]	0	0	0	0	0	0	1.55465

Figure D.6: Normal Plot

Response Surface Roughness

Figure D.7: Actual by Predicted Plot

Figure D.8: Residual by Predicted Plot

Figure D.9: Studentized Residuals

Table D.8: Summary of Fit

RSquare	0.542996
RSquare Adj	0.151278
Root Mean Square Error	0.206143
Mean of Response	1.332643
Observations (or Sum Wgts)	14

Table D.9: Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	0.35343771	0.058906	1.3862
Error	7	0.29746550	0.042495	Prob > F
C. Total	13	0.65090321		0.3370

Table D.10: Parameter Estimates

Term	t Ratio	Prob> t	AdjPower0.05
Intercept	24.19	<.0001*	1.0000
Toolpath[2D Adaptive]	1.01	0.3476	0.0500
Toolpath[2D Contour]	-0.11	0.9166	0.0500
Toolpath[2D Pocket]	0.20	0.8507	0.0500
Toolpath[3D Adaptive]	-1.15	0.2866	0.0500
Toolpath[3D Contour]	0.72	0.4962	0.0500
Toolpath[3D Pencil]	-2.14	0.0694	0.2576

Table D.11: Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Toolpath	6	6	0.35343771	1.3862	0.3370

Figure D.10: Residual by Row Plot

Figure D.11: Residual Normal Quantile Plot

Table D.12: Parameter Estimate Population

Term	Estimate	t Ratio	Orthog Coded	Orthog t-Ratio	Prob> t
Intercept	1.33264	24.1885	1.33264	24.1885	<.0001*
Toolpath[2D Adaptive]	0.13586	1.0067	-0.01724	-0.3129	0.7635
Toolpath[2D Contour]	-0.01464	-0.1085	-0.05640	-1.0237	0.3401
Toolpath[2D Pocket]	0.02636	0.1953	-0.02646	-0.4802	0.6457
Toolpath[3D Adaptive]	-0.15564	-1.1533	-0.08202	-1.4888	0.1802
Toolpath[3D Contour]	0.09686	0.7177	0.02015	0.3657	0.7254
Toolpath[3D Pencil]	-0.28914	-2.1426	-0.11804	-2.1426	0.0694

Table D.13: Correlations of Estimates

Intercept	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Toolpath[2D Adaptive]	0.0000	1.0000	-0.1667	-0.1667	-0.1667	-0.1667	-0.1667
Toolpath[2D Contour]	0.0000	-0.1667	1.0000	-0.1667	-0.1667	-0.1667	-0.1667
Toolpath[2D Pocket]	0.0000	-0.1667	-0.1667	1.0000	-0.1667	-0.1667	-0.1667
Toolpath[3D Adaptive]	0.0000	-0.1667	-0.1667	-0.1667	1.0000	-0.1667	-0.1667
Toolpath[3D Contour]	0.0000	-0.1667	-0.1667	-0.1667	-0.1667	1.0000	-0.1667
Toolpath[3D Pencil]	0.0000	-0.1667	-0.1667	-0.1667	-0.1667	-0.1667	1.0000

Table D.14: Transformation to make uncorrelated

Intercept	18.1508	0	0	0	0	0	0
Toolpath[2D Adaptive]	0	9.70199	4.85099	4.85099	4.85099	4.85099	4.85099
Toolpath[2D Contour]	0	0	8.40217	2.80072	2.80072	2.80072	2.80072
Toolpath[2D Pocket]	0	0	0	7.92164	1.98041	1.98041	1.98041
Toolpath[3D Adaptive]	0	0	0	0	7.67009	1.53402	1.53402
Toolpath[3D Contour]	0	0	0	0	0	7.51513	1.25252
Toolpath[3D Pencil]	0	0	0	0	0	0	7.41002

Figure D.12: Normal Plot

Figure D.13: Prediction Profiler

Appendix E: Factor Level Determination JMP Output

Table E.1: Effect Summary

Source	LogWorth		PValue
TC	7.051		0.00000
Fr	5.711		0.00000
TC*DoC	2.839		0.00145
Fr*DoC	1.896		0.01270
DoC	1.560		0.02754 ^

Table E.2: Singularity Details

Term	Details
Intercept	$= \text{Fr}[0.03] + \text{Fr}[0.15] - 3*\text{Fr}[0.5] + \text{DoC}[0.05] + \text{DoC}[0.075] - \text{Fr}[0.03]*\text{DoC}[0.05] - \text{Fr}[0.03]*\text{DoC}[0.075] - \text{Fr}[0.15]*\text{DoC}[0.05] - \text{Fr}[0.15]*\text{DoC}[0.075] + 3*\text{Fr}[0.5]*\text{DoC}[0.05] + 3*\text{Fr}[0.5]*\text{DoC}[0.075]$

Response Surface Roughness

Figure E.1: Actual by Predicted Plot

Table E.3: Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	18	1.4687683	0.081598	1.3503
Pure Error	106	6.4056039	0.060430	Prob > F
Total Error	124	7.8743722		0.1728
				Max RSq
				0.5218

Figure E.2: Residual by Predicted Plot

Figure E.3: Studentized Residuals

Table E.4: Summary of Fit

RSquare	0.412204
RSquare Adj	0.322139
Root Mean Square Error	0.251998
Mean of Response	1.043833
Observations (or Sum Wgts)	144

Table E.5: Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	19	5.522072	0.290635	4.5767
Error	124	7.874372	0.063503	Prob > F
C. Total	143	13.396444		<.0001*

Table E.6: Parameter Estimates

Term	Scaled Estimate		Prob> t	Lower 95%	Upper 95%
Intercept	1.2124759		<.0001*	1.1120994	1.3128525
Fr[0.03]	-0.310663		<.0001*	-0.423211	-0.198116
Fr[0.15]	-0.09108		0.1118	-0.203627	0.0214671
Fr[0.5]	0.5407569		0.0003*	0.2505482	0.8309657
Fr[0.1]	-0.139013		0.0189*	-0.254685	-0.023342
TC[Diamond]	-0.077246		0.0431*	-0.15204	-0.002452
TC[TiCN]	-0.020946		0.5675	-0.093254	0.0513628
TC[DLC]	0.2249986		<.0001*	0.15269	0.2973073
TC[TiN and TiAlN]	-0.126807		0.0007*	-0.199116	-0.054498
DoC[0.05]	-0.161809		0.0532	-0.325881	0.0022629
DoC[0.075]	0.0368783		0.2259	-0.023096	0.0968525
DoC[0.15]	0.124931		0.1555	-0.04809	0.2979516
Fr[0.03]*DoC[0.05]	0.0955592		0.2996	-0.086007	0.2771255
Fr[0.03]*DoC[0.075]	0.0778092		0.0691	-0.006168	0.1617862
Fr[0.03]*DoC[0.15]	-0.173368		0.0628	-0.356102	0.0093645
Fr[0.15]*DoC[0.05]	0.1294134		0.1608	-0.052153	0.3109797
Fr[0.15]*DoC[0.075]	-0.014024		0.7416	-0.098001	0.0699529
Fr[0.15]*DoC[0.15]	-0.115389		0.2137	-0.298122	0.0673437
Fr[0.5]*DoC[0.05]	-0.360026		0.1457	-0.846781	0.1267279
Fr[0.5]*DoC[0.075]	0		1.0000	0	0
Fr[0.5]*DoC[0.15]	0.3600263		0.1457	-0.126728	0.8467805
Fr[0.1]*DoC[0.05]	0.1350536		0.1514	-0.050139	0.3202462
Fr[0.1]*DoC[0.075]	-0.063785		0.1468	-0.150256	0.0226855
Fr[0.1]*DoC[0.15]	-0.071268		0.4403	-0.253476	0.1109386
TC[Diamond]*DoC[0.05]	-0.007151		0.8936	-0.112732	0.0984289
TC[Diamond]*DoC[0.075]	0.0036348		0.9469	-0.104258	0.1115274
TC[Diamond]*DoC[0.15]	0.0035167		0.9467	-0.100296	0.1073291
TC[TiCN]*DoC[0.05]	0.0100227		0.8465	-0.092215	0.1122602
TC[TiCN]*DoC[0.075]	0.0126773		0.8070	-0.089828	0.1151827
TC[TiCN]*DoC[0.15]	-0.0227		0.6605	-0.124736	0.0793361
TC[DLC]*DoC[0.05]	0.0774116		0.1365	-0.024826	0.1796491
TC[DLC]*DoC[0.075]	-0.0186		0.7201	-0.121106	0.0839049
TC[DLC]*DoC[0.15]	-0.058811		0.2561	-0.160847	0.043225
TC[TiN and TiAlN]*DoC[0.05]	-0.080283		0.1227	-0.18252	0.0219547
TC[TiN and TiAlN]*DoC[0.075]	0.0022884		0.9648	-0.100217	0.1047938
TC[TiN and TiAlN]*DoC[0.15]	0.0779944		0.1328	-0.024042	0.1800306

Table E.7: Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Fr	3	2	1.2734975	10.0271	<.0001*	LostDFs
TC	3	3	2.6109013	13.7049	<.0001*	
DoC	2	1	0.3158138	4.9732	0.0275*	LostDFs
Fr*DoC	6	5	0.3815797	1.2018	0.3123	LostDFs
TC*DoC	6	6	0.2781252	0.7300	0.6263	

Figure E.4: Residual by Row Plot

Figure E.5: Residual Normal Quantile Plot

Figure E.6: Normal Plot

Response RMS

Figure E.7: Actual by Predicted Plot

Table E.8: Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	18	107.39336	5.96630	6.1151
Pure Error	106	103.42082	0.97567	Prob > F
Total Error	124	210.81419		<.0001*
				Max RSq
				0.7460

Figure E.8: Residual by Predicted Plot

Figure E.9: Studentized Residuals

Table E.9: Summary of Fit

RSquare	0.482268
RSquare Adj	0.402938
Root Mean Square Error	1.303884
Mean of Response	3.374174
Observations (or Sum Wgts)	144

Table E.10: Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	19	196.37334	10.3354	6.0793
Error	124	210.81419	1.7001	Prob > F
C. Total	143	407.18753		<.0001*

Table E.11: Parameter Estimates

Term	Scaled Estimate		Std Error	t Ratio	Prob> t
Intercept	3.8359014		0.262402	14.62	<.0001*
Fr[0.03]	-1.248235		0.294218	-4.24	<.0001*
Fr[0.15]	0.1907694		0.294218	0.65	0.5179
Fr[0.5]	1.5252247		0.758656	2.01	0.0466*
Fr[0.1]	-0.467759		0.302385	-1.55	0.1244
TC[Diamond]	0.5658407		0.195525	2.89	0.0045*
TC[TiCN]	-0.189415		0.189027	-1.00	0.3183
TC[DLC]	-0.421893		0.189027	-2.23	0.0274*
TC[TiN and TiAlN]	0.0454679		0.189027	0.24	0.8103
DoC[0.05]	-0.464476		0.428913	-1.08	0.2809
DoC[0.075]	0.3876903		0.156783	2.47	0.0148*
DoC[0.15]	0.0767862		0.452306	0.17	0.8655
Fr[0.03]*DoC[0.05]	0.124791		0.474646	0.26	0.7931
Fr[0.03]*DoC[0.075]	-0.570732		0.219531	-2.60	0.0105*
Fr[0.03]*DoC[0.15]	0.4459409		0.477696	0.93	0.3524
Fr[0.15]*DoC[0.05]	-0.612101		0.474646	-1.29	0.1996
Fr[0.15]*DoC[0.075]	0.8142452		0.219531	3.71	0.0003*
Fr[0.15]*DoC[0.15]	-0.202144		0.477696	-0.42	0.6729
Fr[0.5]*DoC[0.05]	0.3717057		1.272461	0.29	0.7707
Fr[0.5]*DoC[0.075]	0		0	0.00	1.0000
Fr[0.5]*DoC[0.15]	-0.371706		1.272461	-0.29	0.7707
Fr[0.1]*DoC[0.05]	0.115604		0.484126	0.24	0.8117
Fr[0.1]*DoC[0.075]	-0.243513		0.22605	-1.08	0.2835
Fr[0.1]*DoC[0.15]	0.1279093		0.476321	0.27	0.7887
TC[Diamond]*DoC[0.05]	-0.652696		0.276006	-2.36	0.0196*
TC[Diamond]*DoC[0.075]	1.333943		0.28205	4.73	<.0001*
TC[Diamond]*DoC[0.15]	-0.681247		0.271384	-2.51	0.0134*
TC[TiCN]*DoC[0.05]	0.2360339		0.267267	0.88	0.3789
TC[TiCN]*DoC[0.075]	-0.427643		0.267967	-1.60	0.1131
TC[TiCN]*DoC[0.15]	0.1916092		0.26674	0.72	0.4739
TC[DLC]*DoC[0.05]	0.21537		0.267267	0.81	0.4219
TC[DLC]*DoC[0.075]	-0.619574		0.267967	-2.31	0.0224*
TC[DLC]*DoC[0.15]	0.4042036		0.26674	1.52	0.1322
TC[TiN and TiAlN]*DoC[0.05]	0.2012922		0.267267	0.75	0.4528
TC[TiN and TiAlN]*DoC[0.075]	-0.286726		0.267967	-1.07	0.2867
TC[TiN and TiAlN]*DoC[0.15]	0.0854342		0.26674	0.32	0.7493

Table E.12: Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Fr	3	2	49.810581	14.6492	<.0001*	LostDFs
TC	3	3	18.170111	3.5625	0.0162*	
DoC	2	1	5.809504	3.4171	0.0669	LostDFs
Fr*DoC	6	5	25.833172	3.0390	0.0127*	LostDFs
TC*DoC	6	6	39.376198	3.8602	0.0014*	

Figure E.10: Residual by Row Plot

Figure E.11: Residual Normal Quantile Plot

Figure E.12: Normal Plot

Figure E.13: Prediction Profiler

Figure E.14: Prediction Profiler when Cost is included