Analysis of a machining process for glass fiber composites

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Abstract

The aim for this study is to observe and conduct experiments on a composite productions machining process in order to gather knowledge and data on the process. The information will be used to make recommendations for improving the process in terms of production capacity and product quality.

The initial part of the study was to conduct a literature review on composite machining and a market research on tool availability in order to set a foundation for the experimental work performed.

Experiments and measurements were done on various tool material, geometry and cutting data to test the viability and potentials of different cutting tools. Along with that, observations were made on the machining process as a whole to better understand it and how it could be improved.

From experiments and observations, it was apparent that the low machining stability causes accelerated tool wear and tool fracture, and limits quality and dimensional tolerances of machined parts. Multi-flute, polycrystalline diamond tools seemed to be the most viable for the application. They produced acceptable results and the cutting data could be increased for higher production rate. Other improvements are possible in terms of machining strategy, chip removal and fixture design. Those improvements could decrease cycle time and increase the overall production capacity of the process.

Keywords: Milling, Composites, FRP, PCD, Coated cemented carbide, Machine productivity, Process monitoring

Contents

Chapter 1

Introduction

This chapter introduces Corebon AB and the background of study. It also describes the problem, along with the purpose and limitations of the study.

1.1 Corebon AB

Corebon AB is a manufacturing company located in south of Sweden. In the recent years it has developed innovative technology to manufacture composite products with high frequency induction heating. This new technology can drastically reduce cycle time and energy usage compared to other production methods while improving the quality of the finished product. Corebon's work is divided in different fields including the development of the high frequency induction heating system, research and development of various composite projects and the development and setup of production processes for composite manufacturing using the aforementioned technology.

1.2 Problem description

Corebon is currently manufacturing highly specified radar antenna enclosure called *radome* (combination of the words radar and dome) as a glass fiber composite part. The radomes are manufactured with *resin transfer molding* (RTM) method where a certain amount of excess material is necessary between the mold's material flow channels and the finished product. This excess material is then machined off the product leaving a finished edge. It is important that the tolerance and quality of the finish product fulfills customer specifications and does not create additional work in post-machining or quality inspection. The quality of the finished edge depends on various parameters of the machining process including tool type, tool wear, cutting speed and feedrate of the machine. The production rate of the machine also depends of these parameters. In Corebon's current factory the RTM process is the bottleneck in production, and the machining process is able keep up while operating below maximum capacity. Corebon is currently working on setting up a new factory facility with increased production capacity for the RTM process. It is therefore necessary to analyze the current machining process and its capacity and how it can be increased through various improvements regarding choices of tools and cutting data during machining. It is also important to know if there is a necessity to purchase additional CNC (computer numerical control) machines or other ancillary equipment in order to avoid that the machining process step becomes a bottleneck.

1.3 Purpose

The purpose of this study is to accumulate knowledge and information about the productions machining process in order to find and make improvements to the process. This includes the selection of cutting tools and cutting data, tool wear and tool life, machining strategy and other factors that affect the machining process. It also includes analyzing the current production rate and capacity and how they might be increased. The outcome is aimed to be improved control of tool life, increased quality of finished part, increased production capacity and minimized additional work in post-machining and quality control.

1.4 Limitations

According to customer specifications, machining of the radomes requires two different edge geometries, a straight edge and a rounded or chamfered edge for the finished product. Only the straight edge machining will be tested during the experimental phase of this study. All tests were made in current production equipment and setup. Other methods of removing excess material from the workpieces will not be studied.

Other parts of the production such as the RTM process or post-machining process will not be studied although they can influence the machining process and the quality of the finished products.

Chapter 2

Method

The purpose of this study is to investigate how the production capacity of a machining process can be increased while maintaining acceptable product quality and cost. It is therefore necessary to gather usable data about the process that can then be analyzed to make assumptions about it. From this information it is possible to make recommendation for improvement to the process. The data gathering will be done in a combination of two methods. Firstly, quantitative data will be gathered with experiments on cutting tool and cutting data, in terms of measurements of tool wear, tool engagement time and cutting surface quality. Secondly qualitative data will be gathered in form of observation of the process and production. This data will be used to evaluate the process, find reasoning between the observation and the quantitative experiments and try to draw conclusions about the whole process.

The study itself is divided into three major phases.

The first phase is a prestudy in form of a literature review and market research. The literature review will be performed on the subject of composite machining and tool wear in machining composites. This is done to set up a foundation of previous work and experience gathered in the field of composite machining that is then possible to build upon during the later phases of the study. After the literature review a market research is conducted to find suppliers and manufacturers of viable tool solutions, both previously used suppliers and new manufacturers. Both commonly available catalogue tools and custom-made tools are considered.

In the second part of the study, when the scientific foundation has been laid on the subject and a number of possible candidate tools had been acquired, an experimental phase is conducted. Different tools and cutting data will be tested and measured and data gathered to analyze the process. The experimental studies combines machining tests with selected cutting data combinations with microscopical analysis of the tool wear. Since the end of life data for the actual machining application is not available the strategy is to prioritize the tools from the market research and run in ongoing production until the recommended flank wear or a measurable wear is reached. The repeatability and the generalizability is down prioritized in relation to test of multiple tool and cutting data combinations.

In the third phase, after the experimental phase, an analysis on the results from different cutting tools and cutting data will be performed in order determine tool life criteria and to map out the machining process and find possible improvements to it.

Chapter 3

Theory

3.1 Fiber reinforced plastic

For the last few decades the production and use of fiber reinforced plastic (FRP) in various applications has been increasing. In industries such as aerospace, automotive and defense the increased use of FRP is high due to material properties such as high strength-to-weight ratio, stiffness-to-weight ratio, corrosion resistance, thermal resistance and fatigue. FRP is a composite material that consists of reinforcement material such as carbon-, glass- or aramid fibers and matrix material such as metal- or polymer matrices. [1]

Glass fiber reinforced plastic (GFRP) has non-homogeneous structure so the machinability of the material differs from that of homogeneous material like steel or aluminium. [2] The reinforcement fibers are strong and brittle and have poor thermal conductivity while the polymer matrix is weak and ductile. GFRP is also anisotropic and abrasive so the problems arise with cutting it are different from that of metal cutting. Some of these problems include:

- Delamination due to local dynamic loading caused by different stiffness of fiber and matrix.
- Spalling, chipping, and delamination of the material on exit from cutting.
- Pulled out and crushed fibers causing fuzzing.
- Heat build-up during cutting of FRP composites. Low thermal conductivity compared to metals.
- Abrasive fibers in the composite rounding the tools cutting edge prematurely [3].

Delamination can be categorized in Type I, II and III delamination, seen in figure 3.1. Type I delamination is characterized as where surface ply fibers are broken from the machined edge and inwards towards the material, resulting in fibers being missing from the surface ply. Type II is where fibers are uncut along the machined edge and protrude from it. These delaminations can occur in fiber ply away from the surface ply. Type III delamination is loose fibers partially attached to the machined edge on top or bottom surface ply, causing a fuzzy appearance along the edge. Type II and type III can look similar as fibers protruding from the edge but have separate classification due to appearance [4].

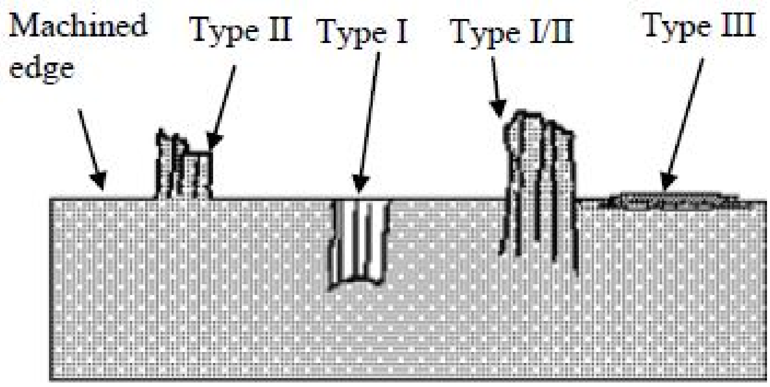

Figure 3.1: Different types of delamination [5]

3.1.1 Fiber orientation

Delamination of machined FRPs is dependent on the orientation of surface plies relative to the cutting path [4]. Different orientation of fibers will produce different type and amount of delamination. The fiber orientation also influences the chip formation during the process and the mechanisms of how the chips are severed from the workpiece material. For 0-degree fibers bundles of fibers are removed from the fiber matrix from buckling or delamination followed by bending (type I and II). 45- and 90-degree fibers are removed due to compression of the fibers (type III) along the cutting path. 135-degree fibers experience shear failure along the fiber matrix and fractures perpendicular to the fiber direction beneath the trimming plane, resulting in saw-tooth profile along the cutting path [6].

3.2 Milling

Milling is a cutting process that utilizes a rotating cutting tool with one or more cutting edges to remove material from a stationary workpiece in an intermittent process. The extent to which each edge is engaged and the occurrence of that depends on the tool geometry, positional accuracy and the state of each cutting edge during the process [7]. The most common milling operation in machining FRP are peripheral milling (edge milling) and end milling. The milling machine provides primary motion to the spindle where the cutting tool is held and feed motion can either be done to the machine table where the workpiece is held or movement of the spindle in relation with the workpiece held in place [6].

How the cutting tool approaches and moves in relation to the workpiece is categorized into conventional and climb milling. In conventional milling the direction of feed is opposite to the direction of rotation of the cutting tool while in climb milling the direction of feed is in the same direction as the rotation of the cutting tool as shown in figure 3.2.

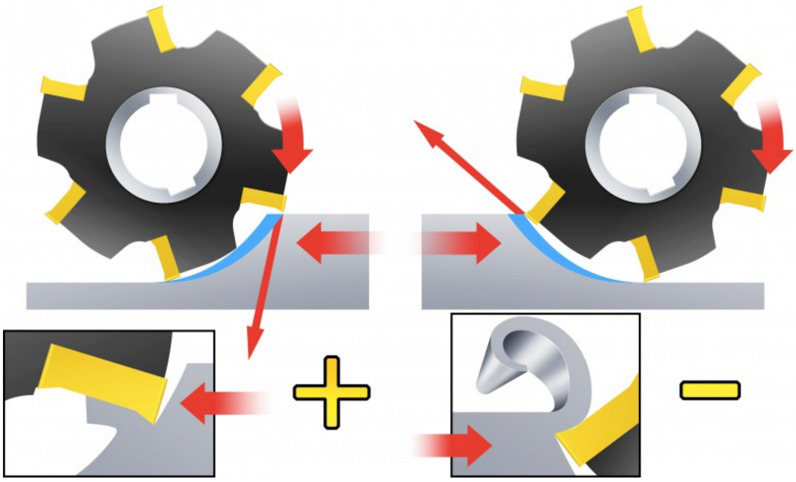

Figure 3.2: Climb and conventional milling and chip formation [8]

In figure 3.2 the chip is thickest in the feed direction and thinnest perpendicular to the feed direction. In conventional milling the cutting edge starts engagement at the thinnest part of the chip and moves into the thicker part with cutting forces following the same curve, lowest in the beginning and highest just before the edge leaves the workpiece. This causes the cutting forces to lift of the workpiece. In climb milling the opposite is true where the cutting edge starts engagement at the thickest part of the chip and moves into the thinnest part. The cutting forces are highest in the beginning of engagement and then decreases, pushing the workpiece down [6].

Milling FRP is generally done with low depth of cut and light material removal as parts are usually manufactured in near net shape and machining operations are often edge trimming for dimensional tolerances or for drilling assembly holes. The machinability of FRP differs from that of metal like described in section 3.1. Machining of FRP is characterized by uncontrolled intermittent fracture of the reinforcement fibers and the machinability is determined by the properties of the reinforcement fibers, matrix, fiber content and orientation. [6]

3.2.1 Cutting data

The cutting process can be described with a few parameters that influence the economic efficiency of the process and the quality of the finished product. Theses parameters are often called cutting data.

- Cutting speed v_c (m/min): Rotational speed of the tool in relation to the workpiece.
- Cutting feedrate v_f (mm/min): The speed which the tool advances along the cutting tool path.
- Axial depth of cut a_p (mm): The depth of tool engagement into the material.
- Radial depth of cut a_e (mm): The width of the tool engagement into the workpiece material.

The definitions of cutting speed and cutting feedrate are:

$$v_c = \frac{\pi \cdot D \cdot n}{1000} \tag{3.1}$$

$$v_f = f_z \cdot n \cdot z \tag{3.2}$$

with

- Feed per tooth f_z (mm/tooth): The distance the tool travels for each tooth of the tool.
- Spindle speed n (rpm): The rotational speed of the machine spindle.
- Diameter of cutting tool D (mm): The diameter of the rotating edges of the tool [9, 10].

The selection of cutting data depends on the workpiece material, cutting method, the tool geometry and material, quality requirements, economic requirements and cutting conditions [7].

3.3 Cutting tools

Cutting tool design has a strong impact on machining performance, productivity and economics of the process. It is important to consider tool geometries and tool material options for a given application, and especially the range of speeds and feeds for which each can be applied and their typical failure modes. Cutting tools can be divided in single point cutting tool with a single cutting edge commonly used for turning and boring, and multi-point tools which have multiple cutting edges used for drilling, reaming, boring and milling. The choice of cutting tool depends on the volume to be machined, geometry of the workpiece, workpiece material, tolerance, and the machine used [9].

3.3.1 Cutting tool material

Ideal tool material should have the following properties:

- High hardness at elevated temperatures to resist abrasive wear.
- High deformation resistance to prevent the edge from deforming or collapsing under the stresses produced by chip formation.
- High fracture toughness to resist edge chipping and breakage, especially in interrupted cutting.
- Chemical inertness with respect to the work material to resist diffusion and chemical wear.
- High thermal conductivity to reduce cutting temperatures near the tool edge.
- High fatigue resistance, especially for tools used in interrupted cutting.
- High thermal shock resistance to prevent tool breakage in interrupted cutting. [9]

This list is quite extensive and it is common for different tool materials to have high level of one property while lacking another. An example of that is high hardness tools are often lacking in toughness and vice versa. The most common cutting tool materials include high-speed steels, cemented carbide (WC), cermets, ceramics, polycrystalline cubic boron nitride (PCBN), polycrystalline diamond (PCD) and single-crystal natural diamond. These materials provide a wide range of combinations of properties [9]. In machining FRP material the most common tool materials are various coated cemented carbides and polycrystalline diamond tools.

Cemented carbide

Cemented carbide hardmetals are the most common tool material for turning, milling, threading and boring with both indexable inserts and solid round tools. The material is a composite material consisting of hard carbide particles sintered together with a high toughness binding material using powder metallurgy techniques. Hard particles can be of tungsten carbide (WC), titanium carbide (TiC), tatalnum carbide (TaC) and niobium carbide (NbC) and using cobolt (Co) as binding metal. Of the hard particles tungsten carbide is by far the most common [7]. Tungsten carbide can both be pure two-phase WC-Co carbide or combined together with different carbides TiC, TaC and NbC for achieving different hardness, fracture toughness and heat resistance [9].

Polycrystalline diamond

PCD tools are manufactured using a high temperature, high pressure process in which individual diamond particles are sintered together with an iron, nickel, and/or cobalt catalysts. Once manufactured the PCD is cut by electro discharge machining or laser etching into smaller pieces which can be brazed or welded onto WC inserts or endmills [9]. PCD is the hardest of all tool material with excellent wear resistance, sharp edges, high fracture strength and high thermal conductivity. This makes PCD well suited for machining of non-ferrous metals, composites, superalloys and non-metallic material. PCD is particularly well suited for abrasive materials compared to carbide and can have much longer tool life. Due to high solubility of carbon in iron, PCD is not suitable for ferrous material [9].

3.3.2 Coating

Coating is used to increase tool life and tool performance by increasing wear resistance, prevent chemical reactions between tool and workpiece material, reduce built-up edge formation, decrease friction, and prevent deformation due to excessive heat. This is often done with HSS, carbide and ceramic tools that are generally lacking the properties coating can provide. The performance of the coating depends on coating thickness, mechanical properties, chemical properties, adhesion with substrate material, wear resistance, thermal conductivity and application. [9].

The two most common coating methods are chemical vapor deposition (CVD) with typical thickness of 5-15 μm and physical vapor deposition (PVD) with typical thickness of 2-5 μm. The coating can be single or multilayer with the most common being titanium nitrate (TiN), titanium carbide (TiC) and aluminum oxide ($Al_2 0_3$). Multilayer coating combines different properties of single layer coatings [9]. Coating can have unwanted side effects to the tool as the coating increases the radius of the cutting edge, making it blunter which is unwanted when cutting FRP. TiC and TiN coating also have low thermal conductivity which is advantageous when cutting metal but in FRP machining heat must be dissipated through the tool [11]. Diamond is also used for tool coating to increase wear resistance and thermal conductivity. It is advantageous to use diamond coating for round solid WC tools as they can be shaped into more complex geometry for various effect compared to solid PCD tipped tools [9].

3.3.3 Geometry

Milling is conducted with multiple edge, round tools, either solid cutters or cutter bodies fitted with inserts. The geometry and nomenclature of cutting tools, even single point cutting tools are surprisingly complicated subjects [12]. It is beyond the scope of this paper to go in detail into the various planes and angles associated with machining and their effects on the process. A simplified, orthogonal view of the cutting process can be considered seen in figure 3.3.

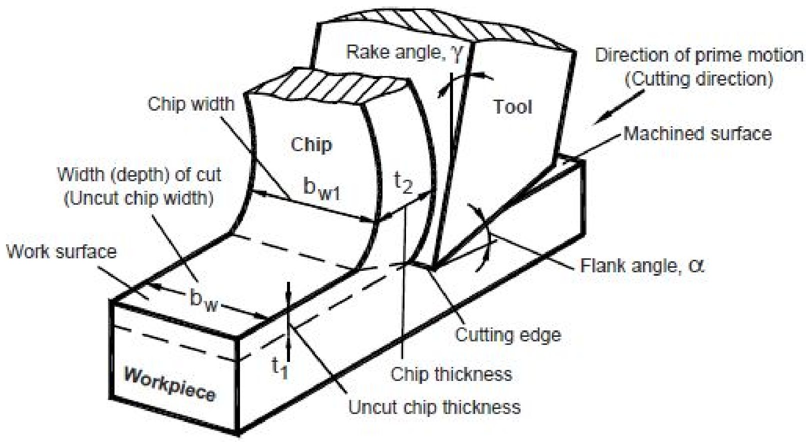

Figure 3.3: Terminology in orthogonal cutting [12]

In short, factors influencing the performance of a milling cutter include cutting edge geometry of cutting angles, cutter density and cutter construction [9]. Terminology for endmill geometry can be seen in figure 3.4.

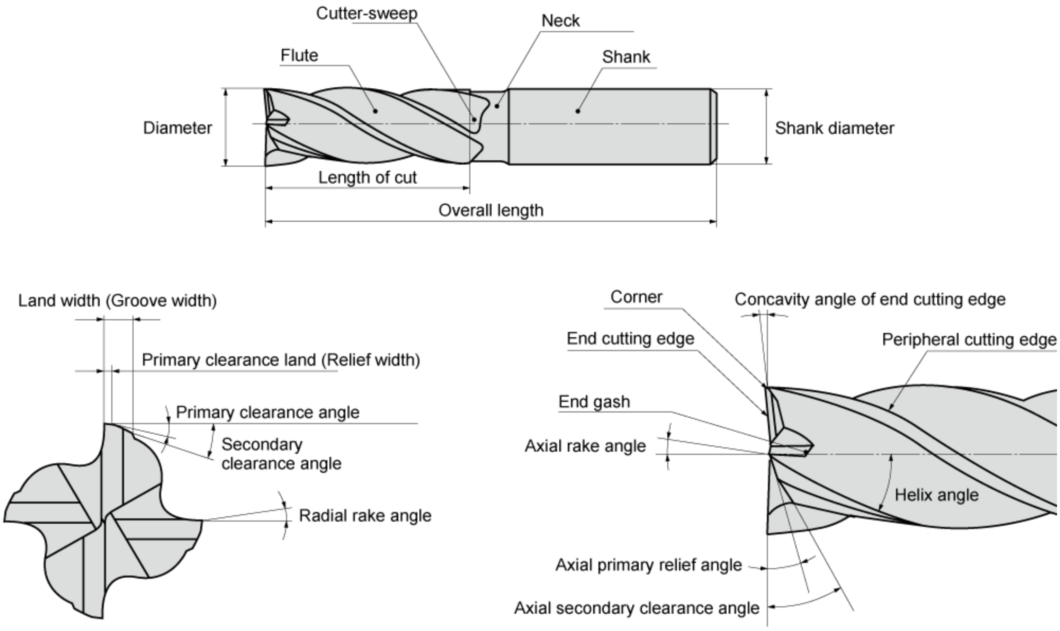

Figure 3.4: Terminology for endmill geometry [13]

3.3.4 Abrasive cutters

Abrasive wheels and cutters are used for edge trimming and cutting of FRP as they can provide less mechanical damage and better surface finish than traditional cutting tool geometries. Hard particles such as PCD or PCBN are brazed or bonded to the tool shank [6]. An example of this type of tool can be seen in figure 3.5 with a close up of the diamond particles in figure 3.6. The abrasive cutters are classified by their particle grit size and bonding method. Each hard particle acts as a cutting edge that each removes tiny chip (2 - 50 μm) so large amount of particles are necessary to provide significant material removal rate. Higher power is required for abrasive cutting compared to other machining operations as the specific cutting energy increases rapidly with decreasing chip size [6].

Figure 3.5: Abrasive cutter sample

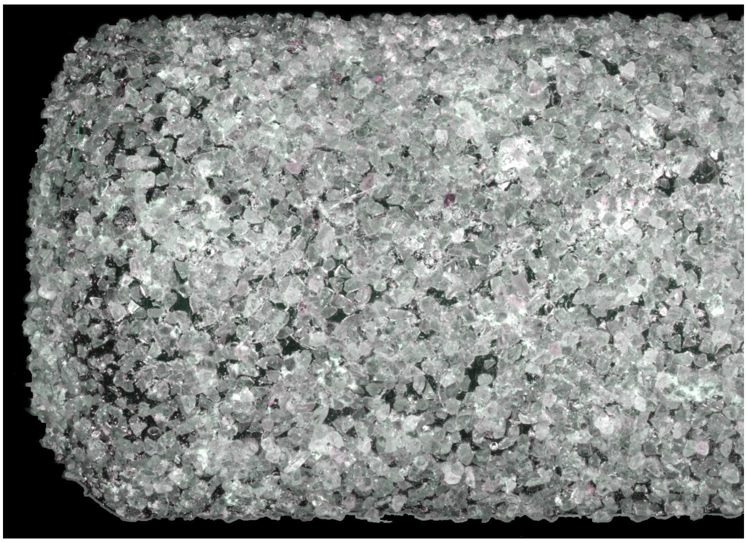

Figure 3.6: Close up of diamond particles. 5x magnification.

3.4 Tool wear

3.4.1 Tool wear in general

During the cutting process high pressure and temperature conditions are formed on the surface of the cutting tool that are in contact with workpiece and chip. Due to these extreme conditions all cutting tools experience wear of the edge and degradation of cutting performance. Tool wear can either occur prematurely or gradually over time. Premature wear or failure of the tool is often due to improper selection of cutting parameters, cutting tool material, and cutting tool geometry. Under normal circumstances and conditions, the tool wears out gradually over time until the wear reaches a point where the tool does not fulfill its intended functions of material removal and generating good quality surface and needs to be replaced [1].

Tool wear influences machining cost and quality of finished product. It is advantageous to have a tool wear slowly and predictably as that leads to reduce production cost and keep more constant dimension and tolerance of finished product. A tool with fast and unpredictable wear leads to more scrap and higher production cost [9].

The different types of tool wear are classified by the regions of the tool that they affect as seen in figure 3.7. The mechanisms that causes the wear is categorized in abrasive wear, diffusion wear, erosive wear, corrosive wear, and fracture. Abrasive wear is caused by hard particles in the workpiece material. Diffusion wear is when under high pressure and temperature, atoms of the cutting material diffuse over to the workpiece material and vice versa. Erosive wear is caused by abrasive particles in a fluid medium in the cutting process. Corrosive wear is mainly caused by oxidation of the tool under high cutting temperature. Fracture wear is caused by thermal or mechanical load of the cutting edge which causes micro cracks in brittle cutting material that lead to removal of particles or flaking on the tool surface. What influences these different types of wear is a combination of cutting temperature, cutting forces, workpiece and cutting tool material [1].

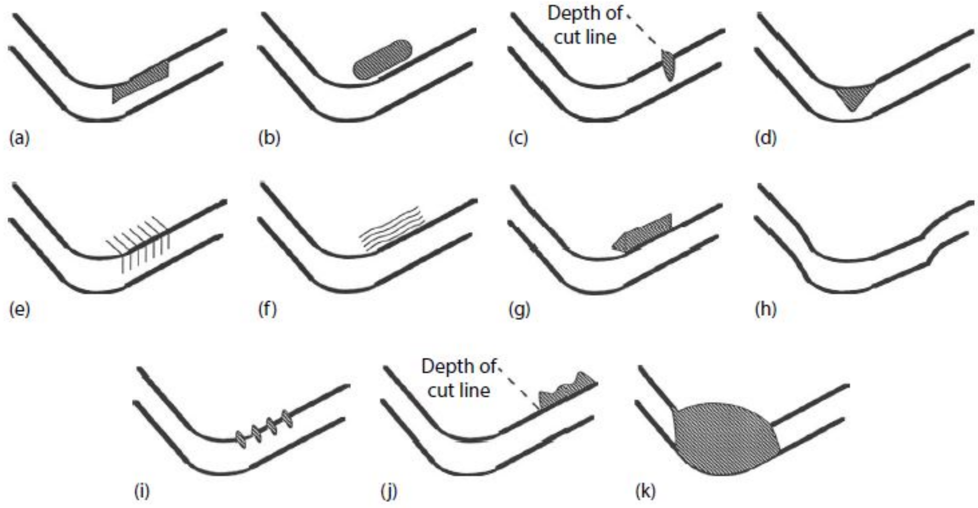

Figure 3.7: Types of wear on cutting tools: (a) flank wear; (b) crater wear; (c) notch wear; (d) nose radius wear; (e) comb (thermal) cracks; (f) parallel (mechanical) cracks; (g) built-up edge; (h) gross plastic deformation; (i) edge chipping or frittering; (j) chip hammering; (k) gross fracture. [9]

3.4.2 Tool wear in composite machining

In FRP the fiber reinforcement is usually continuous and a large part of the volume, thus making the material relatively brittle and producing non-continuous chip. The lack of continuous chip reduces the wear on the rake face of the tool. However, the tool surface slides along the newly machined fibers increasing the friction on the clearance face. This in turn causes two body abrasion between tool and workpiece, and hard particles and fiber fragments cause three-body abrasion between the workpiece and cutting tool surface, seen in figure 3.8. Both factors lead to flank wear being more prevalent when machining FRP [1].

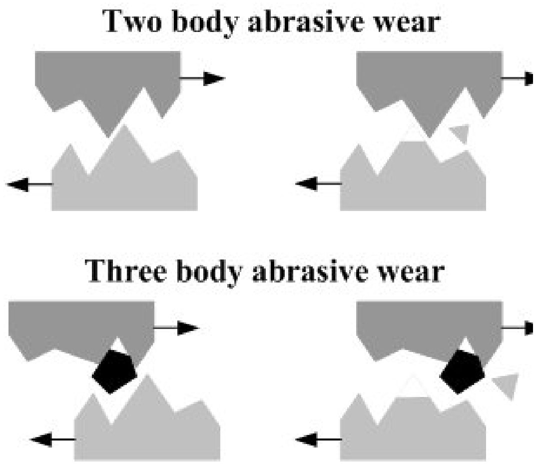

Figure 3.8: Two and three body abrasion wear [14]

For the application studied for this paper experience had shown that the quality of the cut section surface followed tool wear to some extent. The first number of machined workpieces show a clean, cut surface and then after some unknown time delamination starts showing on the edge. The delamination then increases as the tool wear increases.

3.4.3 Tool life criterion

For metal cutting exists tool life criteria recommended by ISO 8688-2:1989 for tool life testing in end milling, for high-speed tools (HSS), cemented carbides and ceramics [15]. Those criteria recommend limits for flank wear (VB_B) and crater wear (KT) listed below. Illustration of VB_B of KT can be seen in figure 3.9.

- Cemented carbides:
  1. VB_B = 0.3 mm
  2. $VB_{B,max}$ = 0.6 mm, if the flank is irregularly worn
  3. KT = 0.06 + 0.3 f where f is the feed
- HSS and ceramics:
  1. Catastrophic failure
  2. VB_B = 0.3 mm if the flank wear is regular
  3. $VB_{B,max}$ = 0.6 mm, if the flank wear is irregularly

This standard test strictly defines the tool and workpiece geometry, cutting conditions and machine tool characteristics. They can be used as a recommendation but not a strict rule for different application. The standard uses flank wear as that is the most desirable form of wear although other types of wear can be used when flank wear is not the critical failure mode. The ISO tests are mainly focused on steel and iron as workpiece material and HSS and cemented carbides as tool material. The test does not cover machining of material such as aluminium or composites or the use of polycrystalline tool material. The tests are not used for advanced tool materials cutting nonferrous work materials because prohibitive amount of material would have to be machined to produce the required level of flank wear [9]. There is not a standard tool life criteria for machining fiber reinforced plastics but VB_B = 0,2 mm has frequently been used. It is also possible to relate the quality of the machined surface with the wear of the tool. As the tool wear increases the surface quality of the workpiece decreases and the amount of delamination increases [6].

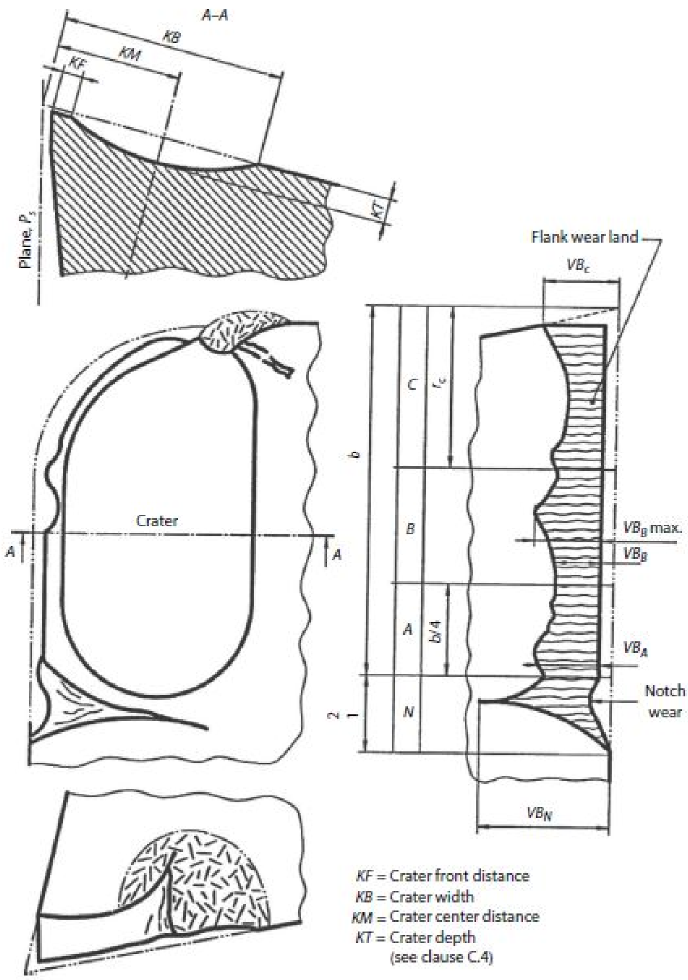

Figure 3.9: Types of tool wear [16]

Chapter 4

Experimental methods

4.1 Workpiece material

The workpiece is a rectangular composite panel made from glass fiber weave with 0- and 90-degrees fiber orientation and thermoset resin for matrix material. The weave pattern is inhomogeneous as seen in figure 4.1. The cut and layup of the weave is so that the fibers are in 45 and 135-degree orientation in relations to the milled edge.

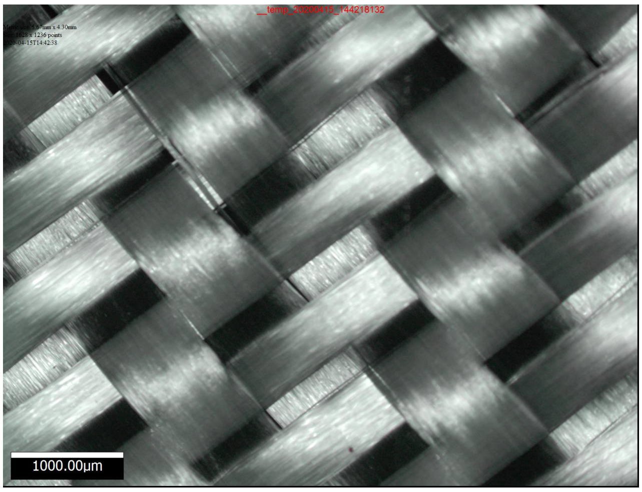

Figure 4.1: Glass fiber weave pattern

The workpieces seen in figure 4.2 were made with vacuum assisted RTM process. For each workpiece two dry glass fiber sheets were hand laid with foam core in between into a mold. The mold is then pressed together in a hydraulic press and heated up with high frequency induction heating panels on both sides of the mold.

When a set temperature is reached thermoset resin is injected into the mold and cured. According to production recipe the mold is then internally cooled with water, the workpieces removed out of it and are ready to be machined.

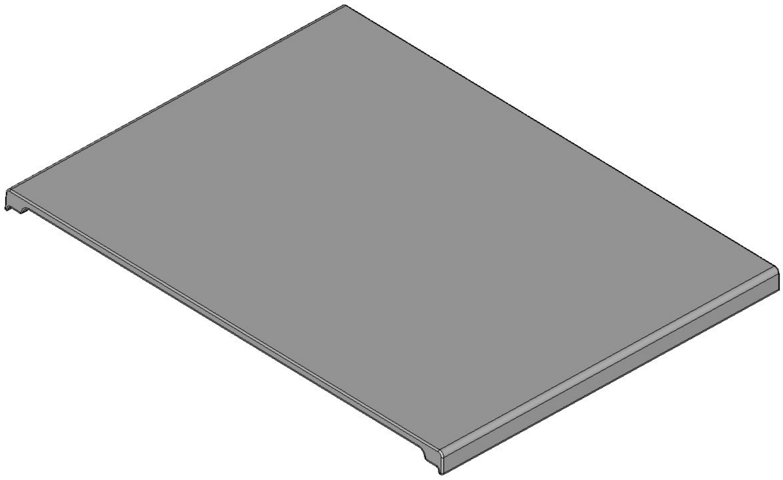

Figure 4.2: 3D model of casted radome workpiece

4.2 Test setup

4.2.1 Machine setup

The tests were conducted using a Datron M8Cube CNC milling machine with a PowerS Syncro 3.0 high frequency 3,0 kW spindle with a maximum speed of 40000 rpm. The tool holder system is Schunk Tribos HSK-E25. A 1000 x 700 mm aluminium vacuum table supplied by Datron is installed in the machine, that is operated through the machines display. On the vacuum table was installed a medium density fiberboard (MDF) fixture with machined cavities for holding workpieces in place during machining as seen in figure 4.3. The MDF is porous so vacuum is drawn through it from the vacuum table, thus holding down the workpiece. Epoxy was coated on parts of the fixture to seal it and improve the vacuum force, displayed in darker color in figure 4.3. Clamps were also installed on the fixture to clamp down the excess material removed during milling. This was done so the scrapped *collars* removed during milling do not damage the tool when they come loose from the workpiece. The tests were done in dry cutting conditions.

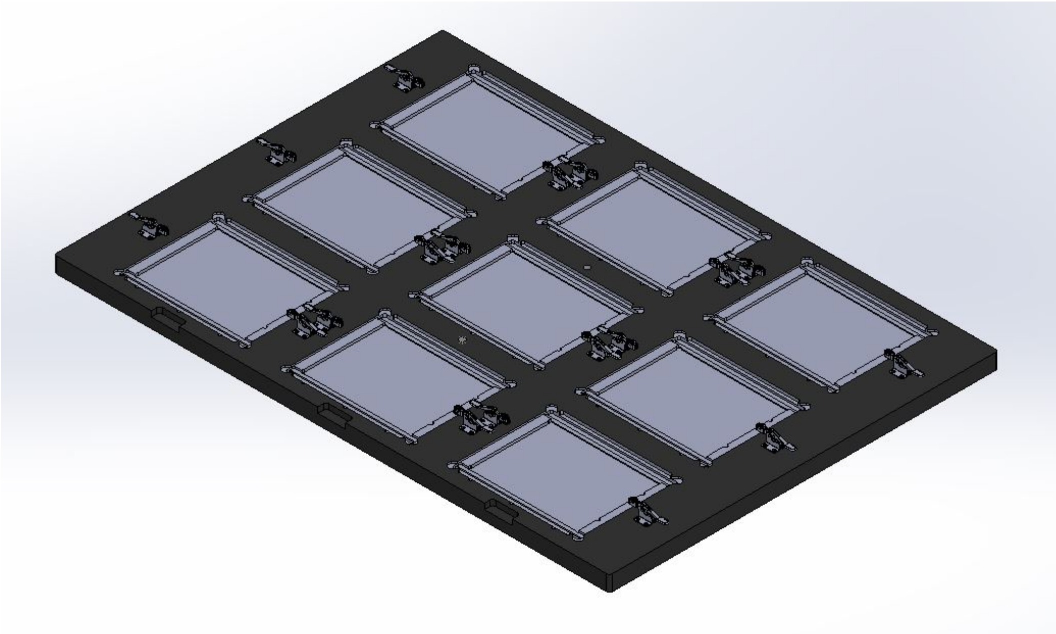

Figure 4.3: 3D model of the MDF fixture

In the beginning of this study it was considered to manufacture dedicated test samples of solely two glass fiber sheets that would fit the vacuum table and where a continuous path could be machined in the workpiece material. The idea was to have dedicated test samples were the process could be better monitored and controlled. Quick calculations were made on how much machining could be on a single sheet and was that compared to the total engagement distance for the current tool. It was estimated that around 22 m of engagement could be done on a single sheet, which equal less than two hour of production. Previous experience showed that a PCD tool could last multiple days. This test setup would therefore be unpractical as large number of sheets and large amount of run time would be needed to produce usable results. Therefore it was decided to use the live production for tests.

4.2.2 CAD and CAM programming

The MDF fixture needed to be designed and machined before testing could be started. 3D model of the fixture was created in the CAD software Solidworks and its design based on earlier fixtures used by the Corebon. Manual linkage clamps were added to the design to minimize scrap material flying off the workpiece and damaging the tool or obstructing the upcoming tool path. When the fixture design was finished a CAM (computer aided manufacturing) program was created using HSMWorks which is an add-on software for Solidworks. HSMWorks is used to specify operations, cutting tools, tool paths, cutting data and other process parameters required. When all necessary tool paths have been created a machine specific post-processor is used to create code that the targeted machine can run. Often that is G-code, a common language for CNC machine, specified for a particular machine. In this case the code is in the proprietary language SimPL, created by Datron to run on its machines. The MDF fixture was manufactured in the same Datron M8 Cube machine that was used for testing, the MDF was then coated with epoxy to restrict permeability and clamps installed.

To make process monitoring easier alterations were made on the post-processor for HSMWorks. The post-processor is a JavaScript script used to process different commands from HSMWorks. A feature was added to log data in the SimPL machine program during operations of the machine. That way each workload of the machine could be logged with program name, tool information, date and run time. This data could then be used to map each tools engagement time and workpiece quality and the production rate of the machine.

4.2.3 Engagement

In the resin transfer molding process the resin needs to evenly distribute into the mold cavity to infuse the fibers. To achieve this flow channels are required around the product for uniform impregnation of resin as seen in figure 4.2. This in turn leaves some amount of excess material around the final product that needs to be removed according to customer specifications. On the testing workpieces the excess material was less 1,0 mm thick and on each workpiece were two 210 mm long edges that require milling as seen in figure 4.4. For productivity, the milling strategy was to mill each workpiece side with a straight cut in one pass with slot milling without any additional finishing passes. The two other edges on the workpiece require round or chamfered finish and were not in focus for this thesis.

The experiments for this thesis were conducted during live production. Cutting tool for testing was inserted in the machine and allowed to run for a certain time. As seen in figure 4.3 each workload required an operator to insert 9 pieces into the fixture, clamp everything down, close the machine and start milling program specified for the tool being tested. Each workload was 3780 mm of engagement distance for the tool tested. For each new tool the first workpiece cut was removed as a test sample and then workpieces were removed from the production for measurements and quality assessment.

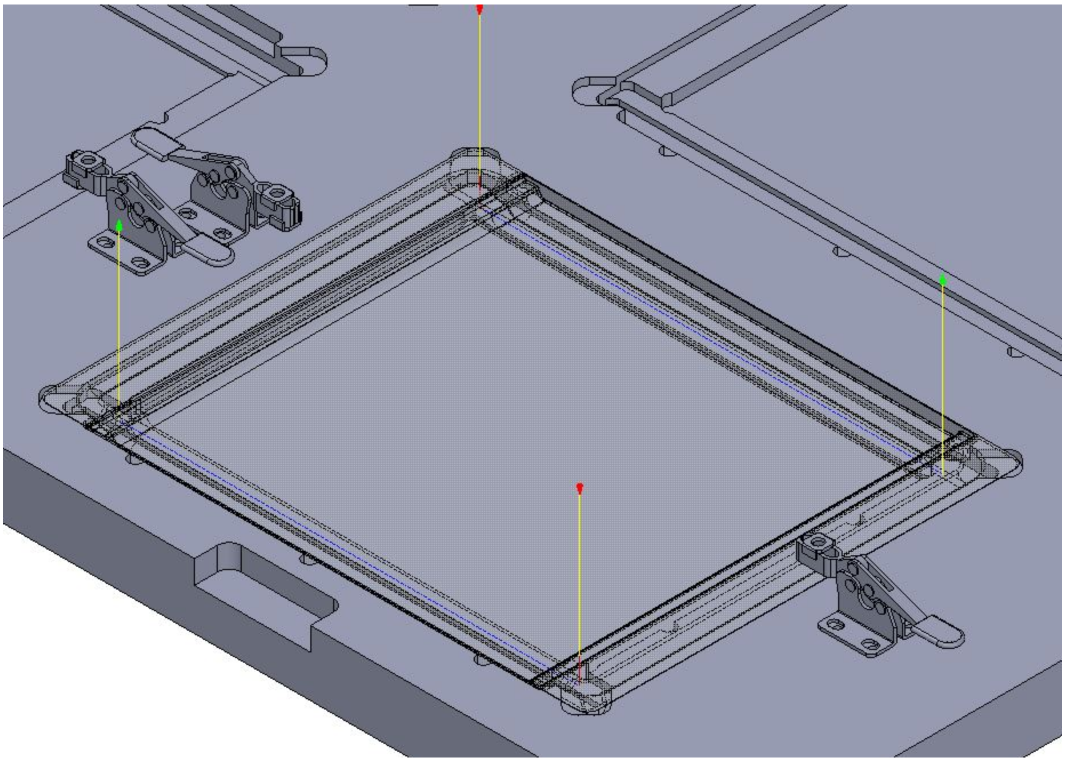

Figure 4.4: Tool paths for workpiece

4.3 Cutting tools

4.3.1 Cutting tool selection

For an experimental investigation of the machining process different commercially available cutting tools were considered for testing. In the current production process a two flute PCD endmill, 4 mm in diameter is used. Up to this point there have been no systematic trials or tests done for the wear and tool life of it. Tool changes are made mainly based on the quality of the cut surface on the workpieces.

Before choosing tools for testing in the cutting process multiple factors have to be considered:

1. Hard workpiece material requires a high hardness tool
2. The tool needs to plunge or ramp into the workpiece material and the operation is intermittent. That requires toughness in the tool material.
3. Heat needs to dissipate from the process. Thermal conductivity of workpiece

material is low so the heat needs to dissipate through the tool material.

4. The milling machine used. The power and spindle speed of the Datron machine is not a limiting factor but a maximum tool diameter of 8 mm was set. This was due to Corebon purchasing a slightly different model of the Datron M8 Cube with a spindle that has a maximum tool diameter of 8 mm.
5. Tool diameter influences cutting feedrate and cutting speed.
6. Tool holder available. Tool holders in the machine are Schunk Tribos-RM HSK-E25 which require tools to have shaft tolerance of h6 or higher. The tool holders are only available for metric diameter tools.
7. Tool cost is a consideration. A balance needs to be between tool life and tool cost.
8. Workpiece holding and the stability of the process.
9. Shallow requirements of cut depth. The edge that is cut has 1 mm clearance from the fixture that put restrictions on tool geometry.
10. Roughing and finishing passes. In machining most of the material is removed with roughing passes and then final surface is achieved with finishing passes. These operations can be combined in some circumstances. For this study only a single slot milling pass is used.

In the initial literature review various tools were considered for the machining process. The glass fiber material being cut is hard and abrasive so tool material with high hardness is required. PCD tools offer high hardness and high abrasive wear resistance compared to other tool material [1]. Initial focus was put on investigating the viability of PCD tools of larger diameter, increased number of flutes and different tool geometry. The viability of cemented carbide tools was studied as they provide higher toughness compared to PCD tools and offer more options for tool geometry. Different coating can increase the potentials of carbide tools while still retaining its toughness [1]. Ceramic materials have proved to be too brittle for machining of FRP and the low thermal conductivity of the ceramic material makes them unsuitable for FRP machining [11]. Finally, abrasive diamond cutter endmills were considered and investigated. The use of these types of tools is relatively new practice that has shown potential in terms of surface quality and less delamination for edge trimming [6, 17].

In the initial phase of the thesis project a market research was conducted for finding viable tools for the current machining process. The research was aimed at specialized tools intended for composite machining. Larger tool providers were first considered and their available catalog studied as these manufacturers have the benefit of good supply chain and stock availability. Smaller, more specialized providers were also studied as knowledge and expertise that the supplier can provide can be as valuable as the tools they sell. The market research was also aimed at finding valuable contacts withing the cutting tool industry that could provide this expertise.

Table 4.1: Testing tool samples and recommended cutting data

Tool description	Recommended cutting speed [m/min]	Recommended feed/tooth [mm/z
2 flute PCD end mill with 2-4 degree helix angle	150-450	0,03-0,12
5 flute PCD end mill with zero degree helix angle	300-500	0,05-0,067
10 flute diamond coated carbide end mill with zero degree helix angle	250-500	0,03-0,12
4 flute diamond coated carbide end mill with +10 degree helix angle	75-155	0,016-0,0392
6 flute diamond coated carbide end mill with -35 degree helix angle	150	0,024
Abrasive cutter with electroplated diamond grains of grit size D181	300-500	0,002-0,04

Figure 4.5: Testing tool samples

Abrasive cutter tools

When the initial test samples were received from manufacturer their shaft tolerance was h8. The test setups tool holders required shaft tolerance of at least h6 so a new batch had to be order to be compatible with the tool holders. Unfortunately the new batch samples were not of high quality as the shaft tolerance was not h6 and the diameter larger than 8 mm thus not usable for testing. No test results were produced from these tool samples but the manufacturers quality control was noted.

4.3.2 Cutting data

For each new cutting tool test cutting data was selected based on recommendations from the tool manufacturer or from previous studies with similar tools. As one of the focus of this thesis is to minimize cycle time of the process the selected cutting data was on the higher end of recommendations.

The current production process uses a 4 mm, two flute PCD endmill with cutting data shown in table 4.2. This data was used as a benchmark for feedrate and speed for tools in testing. For a new tool the same feedrate had to be maintained or increased for it to be worth considering. This was most apparent in testing of carbide tools compared to PCD tools. Because of lower hardness and wear resistance of carbide tools compared to PCD the recommended cutting data is lower. To be able to consider these tools for production the cutting speed and feed was exceeded beyond recommendations from manufacturer to match those of PCD tools.

Table 4.2: Currently used tool

Diameter [mm]	4
Flutes	2
Cutting speed [m/min]	251
Feed per tooth[mm]	0,06
Feedrate [mm/min]	2400
Helix angle [degrees]	0

Table 4.3: Cutting data for testing

Sample number	Tool	No. flutes	Cutting speed [m/min]	Feed per tooth [mm]	Price/tool [SEK]	Final cut dist. [m]
003	PCD	2	250	0,12	2284	143,6
004	PCD	2	300	0,10	2284	1134
005	PCD	5	350	0,045	4176	1353
006	PCD	5	300	0,06	4176	1304
009	DCCC 0 helix	10	200	0,04	2334	0,84
010	DCCC + helix	6	250	0,04	3660	45,36
011	DCCC	4	250	0,06	1470	49,14

In table 4.3 every tool has 8 mm diameter and was used with down milling operation. For tool samples 010 and 011 cutting speed and feed per tooth was above recommended values from manufacturer to have comparable material removal rate to PCD tools. See table 4.1 for recommended cutting data from manufacturers.

4.4 Tool wear measurements

Measurements of tool and workpiece samples were done in the facilities of Industrial Production at Lunds Tekniska Högskola with an Alicona InifinteFocus 3D microscope. Both 2D images and 3D datasets were taken of the tool edge and measurements made on both the clearance and flank face of the tool. Images were also taken off machined workpiece edges to inspect quality and delaminations. With the program Laboratory Measurement Module 5.1 integrated with the Alicona microscope it was possible to analyze the data set by making measurements on the profile of the tool edge image, and with that profile calculate flank wear and tool edge rounding of the tool at set locations on the edge.

The original tool life criteria were noted in section 3.4.3 but after initial tests this method of testing proved time consuming and inefficient due to the relatively low degree of wear. In order to test a certain number different tool the testing strategy had to be modified. It was changed so the tool edge was not measured as regularly but instead the tool was kept running in production and workpiece samples were taken on intervals and analysed. As the evolution of tool wear correlates to some extent with the evolution of workpiece quality the workpiece quality could be observed instead of tool wear [6].

For each cutting tool tested workpieces were saved as a sample in order to analyse them. The first workpiece cut with a new tool was saved as a reference to measure later sample against, and then additional samples were saved over the time the tool was being tested. The sample numbers and the engagement cutting distance is listed in table 4.4.

Table 4.4: Workpiece sampling

Tool sample nr	Date of sample	Sample nr	Cut distance [m]
003	16.3.2020	1	0,42
003	16.3.2020	28	11,76
003	19.3.2020	126	52,92
003	25.3.2020	342	143,64
004	16.3.2020	1	0,42
004	16.3.2020	28	11,76
004	19.3.2020	64	26,88
004	23.3.2020	144	60,48
004	25.3.2020	342	143,64
004	1.4.2020	792	332,64
004	2.4.2020	1404	589,68
004	3.4.2020	1584	665,28
004	4.4.2020	2007	842,94
004	5.4.2020	2448	1028,16
004	6.4.2020	2700	1134
005	9.4.2020	1	0,42
005	9.4.2020	234	98,28
005	14.4.2020	909	381,78
005	15.4.2020	1503	631,26
005	16.4.2020	2250	945
005	17.4.2020	2646	1111,32
005	20.4.2020	3042	1277,64
005	21.4.2020	3222	1353,24
006	6.4.2020	1	0,42
006	6.4.2020	252	105,84
006	8.4.2020	1341	563,22
006	9.4.2020	1629	684,18
006	21.4.2020	2115	888,3
006	22.4.2020	2862	1202,04
006	23.4.2020	3105	1304,1
010	20.4.2020	1	0,42
010	20.4.2020	63	26,46
010	20.4.2020	117	49,14
011	20.4.2020	1	0,42
011	20.4.2020	54	22,68
011	20.4.2020	108	45,36

Chapter 5

Results

Some problems arose in the measurement of tool edges. Due to the reflectivity of the PCD material it proved problematic to take complete images of the cutting edge with an optical microscope. With the Alicona microscope it was possible to take 3D data set images with a set depth, but increasing the depth drastically increased the measurement time. These issues were solved by making adjustments to the setup angle of the tool and with focus on capturing the tool edge to be measured and not the complete cutting faces. This gave usable 3D data sets for making measurements on tool wear but made the resulting images somewhat unclear out of context. In figure 5.1 a dummy PCD insert is shown and how the maximum depth of field creates a two-dimensional ridges covered in black (that is out of focus of the microscope).

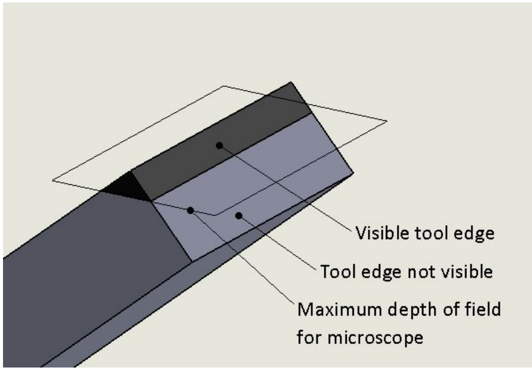

Figure 5.1: Points below the maximum depth of field plane appear as black. Cutting tool sample therefore appear as long, two-dimensional ridges covered with black, as in figures 5.2-5.8

5.1 Samples 003 and 004

The first tests were done on samples 003 and 004 that were two straight flute PCD end mills with 2-4 degree helix angle. Those tools had the same geometry as the current tool used in the process except for being larger in diameter. For the initial experimental test procedure the tool was used to cut certain number of workpieces and then removed from the process for measurements.

Table 5.1: Tool sample 003

Engagement [m]	Maximum wear [mm]
0	0
52,92	0,0359
98,28	0,0488
143,64	0,0497

Table 5.2: Tool sample 004

Engagement [m]	Maximum wear [mm]
0	0
56,70	0,0223
98,28	0,0818
143,64	0,0899

As seen in tables 5.1 and 5.2 the evolution of wear is quite low compared to previous tests reported in [11, 18]. This maximum wear did not occurred at the main cutting contact zone but instead higher up on the edge, examples noted in red in figures 5.3 and 5.4. One possible cause for this is that this is where the tool exits and enters the end sections of the workpiece that are thicker than the main contact edge. Another possible cause is scrap material hitting the edge when it is cut loose from the workpiece. At the main cutting contact zone smooth and even abrasion wear could be observed resulting in rounding of the cutting edge. This can be seen in figures 5.2 and 5.3 noted in green. The position where the flank wear is largest can be seen in red. Note the left most part of the edge in figure 5.3, the corner tip of the edge has been chipped off. This is likely from when the tool is plunged into the material at the start of the operation. This did not appear to affect the main cutting contact zone.

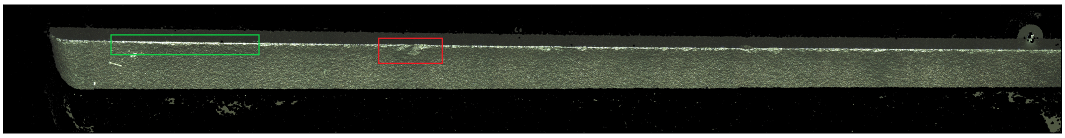

Figure 5.2: Tool sample 004 after 98,28 m of engagement.
20x magnification

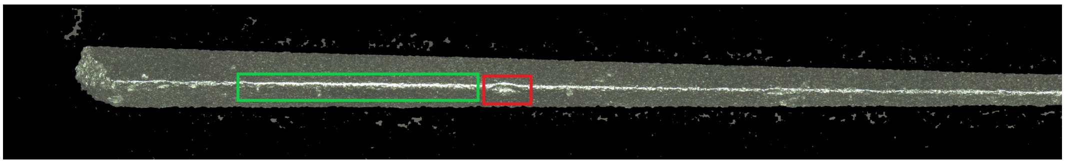

Figure 5.3: Tool sample 003 after 143,64 m of engagement.
20x magnification

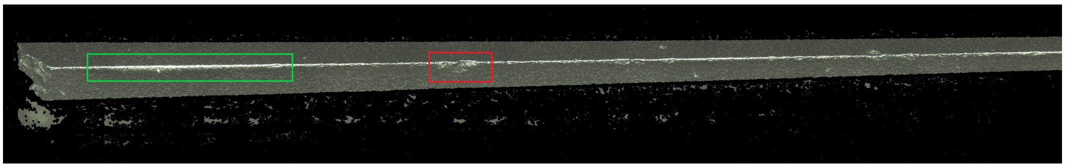

Figure 5.4: Tool sample 004 after 1134 m of engagement.
20x magnification

After 1134 m of engagement, amounting for 2700 workpieces the edge of tool 004 can be seen in figure 5.4. Rounding of the cutting edge at the main contact zone can be observed colored green as long with larger flank wear at point mentioned above, colored red. The edge corner tip has also been chipped off. Tool sample 3 fractured after 143,6 m of engagement when a workpiece that was not correctly fixed down came loose while being cut.

5.2 Samples 005 and 006

As tool samples 005 and 006 had 5 flutes compared to earlier tested 2 flute tools, the cutting speed and feedrate could be increase while keeping feed per tooth low.

From figure 5.5 rounding of the cutting edge can be seen at the main contact point colored green as well as chipping of the edge corner tip. This particular tool has chamfer at the corner tip of the edge as seen on the unused edge in figure 5.6, likely to avoid chipping of the corner.

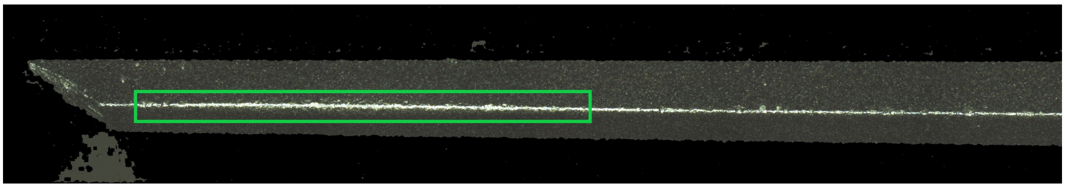

Figure 5.5: Tool sample 005 after 1353,24 m of engagement. 20x magnification

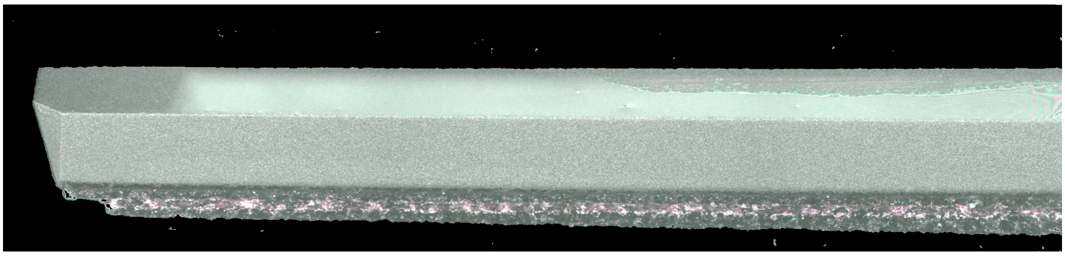

Figure 5.6: Tool sample 005 unused. 5x magnification

Tool sample 006 was run with lower cutting speed and higher feed per tooth than tool sample 005 as seen in table 4.3. After 1304 m of engagement, rounding of the cutting edge can be seen in figures 5.7 and 5.8 in the main cutting contact zone colored green and higher up on the edge for figure 5.5. On the flute seen in figure 5.7 large piece has fractured, colored in blue, close to the edge tip but not from the tip itself like seen on previous samples. This can also be seen to some extent in figure 5.8

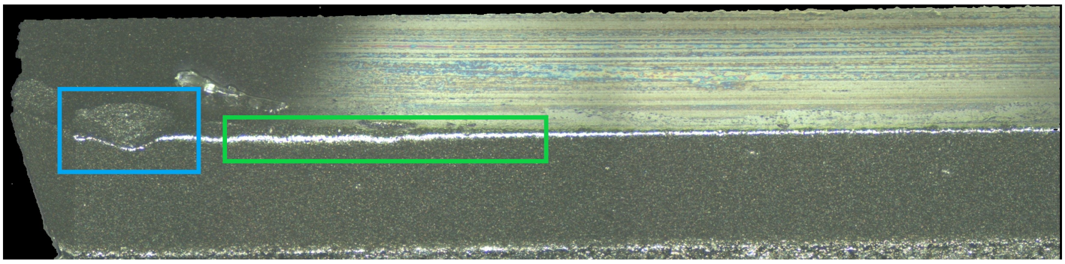

Figure 5.7: Tool sample 006 after 1304 m engagement. 10x magnification

Larger, concentrated flank wear higher on the cutting edge like seen on samples 003 and 004 were not present for 005 and 006.

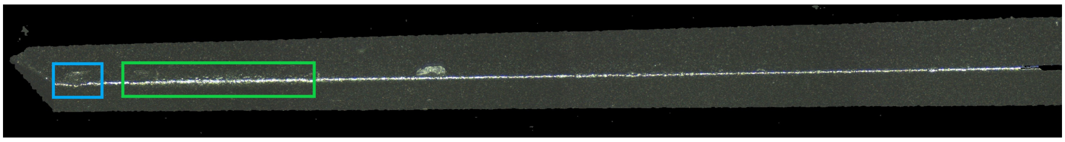

Figure 5.8: Tool sample 006 after 1304 m engagement. Another flute. 10x magnification

5.3 Samples 009, 010 and 011

Three different diamond coated carbide tools were tested from three different manufacturers. These test sample were mainly to test their viability in the production process as no previous testing had been done with these types of tool.

Tool sample 009 was ordered from the same supplier as samples 003 and 004 and from their tool catalog seemed to be promising for the application. When receiving the tool the center-cutting geometry of the tool seen in figure 5.9 became clear. The difference in flute lengths to give the tool its center-cutting function, noted in red, was larger than the available cutting depth that was limited due to the work-holding fixture. This made it so only four of the ten flutes could engage the edge sufficiently. After tests on two workpieces it was apparent that this tool and its geometry was not suitable for the testing application.

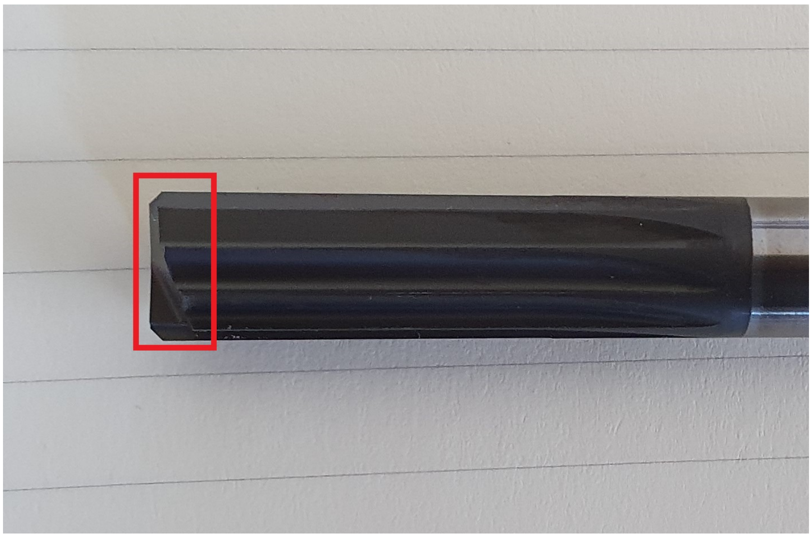

Figure 5.9: Tool sample 009

Sample 010 was a diamond coated carbide tool with negative helix angle of 25 degrees and geometry that produces down force during cutting, thus pushing the workpiece down into the fixture. The tool was used for 45,36 m of engagement time and rounding of the cutting edge could be observed. The image of the resulting tool edge was corrupted and not usable, and a new image could not be made due to problems with the measurement equipment.

Sample 011 was a diamond coated carbide tool with four flutes and positive helix angle. It was used for 49,14 m of engagement with feed and speed higher then recommended from supplier to be able to compare its productivity compared to PCD tools. The result was excessive removal of the coating, so the carbide substrate became visible like seen in figure 5.10. The positions were the coating has worn off are quite clear where the tool engages the main cutting zone noted in green in 5.10 and then the end part engagement higher up on the edge noted in red.

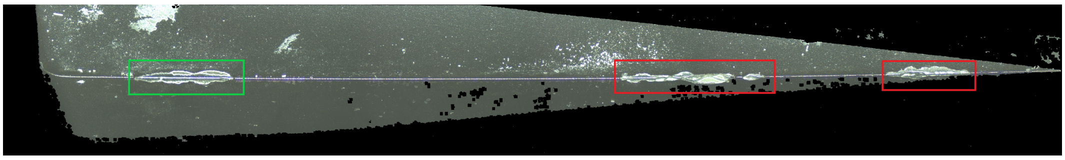

Figure 5.10: Tool sample 011 after 49,1 m engagement. 20x magnification

5.4 Workpiece quality

For each new tool the first cut workpiece was saved as an sample. In a macroscopic view of the edge the cut is clean of burrs and delaminations as seen in figure 5.12. In the magnified view figure 5.11 the cut surface can be seen with some unevenness along the edge, dependent on the fiber orientation. This is clearer in figure 5.13 were type I delimitation can be seen in the direction of the fiber weave.

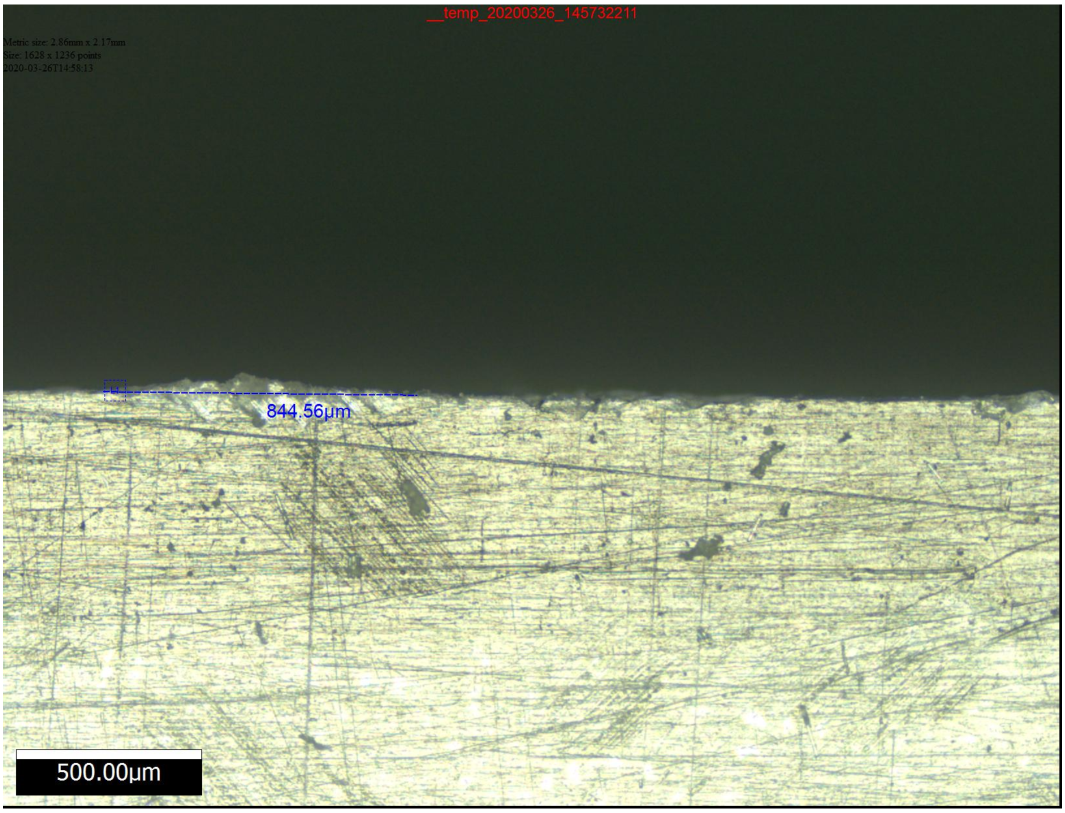

Figure 5.11: Edge quality of first cut workpiece

Figure 5.12: Macroscopic edge quality of first cut workpiece

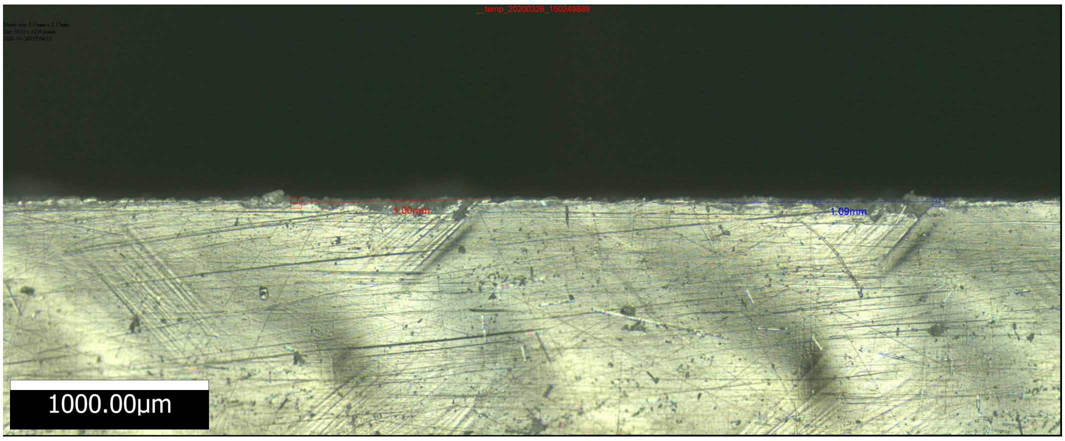

Figure 5.13: Edge quality of workpiece after 11,76 m

The quality of the machined workpieces was influenced by the orientation of the fibers as was mentioned in section 3.1.1. The 45-degree angle that the fiber weave was laid at caused fiber pull out in the 45- and 135-degree angles depending on which direction the thicker weave pattern had been laid as seen in figure 4.1. The fiber pullout can be seen in figure 5.14 were the tool is not able to cut through the fibers due to the orientation. Sawtooth like profile can be seen in figures 5.13 and 5.14 caused by the 135-degree orientation [6].

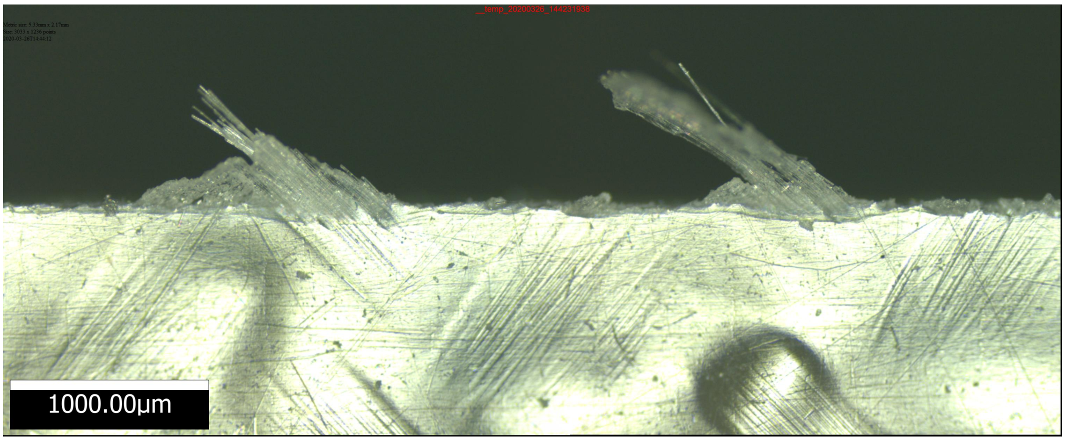

Figure 5.14: Fiber pullout in 45-degree angle after 52,92 m

It appeared not to be much consistency in evolution of delamination of the workpieces. Some pieces in a workload could show delamination like in figure 5.14 but not every piece of that workload. Later workload could then display less amount of delamination than earlier workloads with the same tool. An example of this can be seen in figures 5.15 and 5.16 were there is less amount of visible delamination in later cut workpiece. The location of delamination was also not uniform on the edge like seen in 5.17 and could vary between pieces. It was therefore difficult to monitor the delamination and quality of machined edges and to determine sensible progression of tool wear and degradation of edge quality.

Figure 5.15: Tool sample 004. Total engagement time 665,3 m

Figure 5.16: Tool sample 004. Total engagement time 1134 m

Figure 5.17: Tool sample 006. Total engagement time 684,2 m

Chapter 6

Discussion

During the experimental phase of this study extensive time was spent in the factory and production area of Corebon AB. To be able to perform experiments and tests on the process, knowledge and understanding are required. Part of the time was spent getting to know different aspects of the production process with focus on the machining operations. When a certain knowledge level and confidence had been established it was possible to start performing experiments required for the thesis work. During the experimental phase other aspects of the process were inspected and evaluated that were out of the main scope of the project. In this chapter results noted in earlier chapters will be discussed and also other non-focus aspects of the process that could be further analysed or improved upon.

6.1 Experimental results

6.1.1 Tool experiments

The results from the tool wear and cutting data experiments performed for this work showed that PCD tools were superior in regards to productivity and production capacity of the machine with the current fixture setup. They produced good or adequate surface quality for an extended period even with the selected cutting data exceeding recommended limits.

The variation and inconsistency in the evolution of delamination of workpieces was a cause of challenges. The amount and extent of delamination would fluctuate between individual pieces and between workloads. A workpiece in a workload would show some amount of delamination while other pieces would not and in the next workload this could be reversed. The reason for this is not clear at this point but the process instability and variance of the workpiece setup could be influencing these results.

From the experiments it was apparent that improving the stability and repeatability of the process would be needed to further improve machined edge quality. Due to the nature and orientation of the fiber-matrix some sanding will always be necessary which also puts an upper limit on the quality of the edge.

Carbide tools tested in the experimental phases wore out very quickly due to the selected cutting data. To be viable for this particular application, high production rate is required and therefore not worth considering tools that could not be run as fast or faster than current tool.

Part of the tool samples to be tested were not suitable for the application due to tool geometry or due to manufactured quality so they produced no real results apart from not being suitable.

The experimental results were lacking in comparable data or accurate measurements on the tool wear and surface quality due to non statistical result base. Better planning and testing procedure could have been done in order to improve data gathering that in turn could have produced clearer results in terms of tool wear, tool life and selection of cutting data. Instead the cutting process as a whole was analyzed which possibly produced more valuable results for Corebon than only the tool wear results.

6.1.2 Engagement at end section of workpiece

It was apparent from many of the tool samples that the most drastic wear or fracture occurred not in the main cutting zone of the edge but rather higher up on the edge were the tool engaged thicker end sections of the workpieces as seen in figure 6.1. One possible reason for this is the orientation of the fibers in the end section. In the main engagement zone, the tool is cutting in a normal to the plane of fiber laminates but in the end section the fibers are sloping up which causes the tool to cut the fibers near parallel with the fiber laminate. Another possible reason is that the workholding is less stable in the end section due to the geometry of the workpiece which causes more vibrations during cutting and exacerbating tool wear.

6.2 Chamfered sides

In the milling process a rectangular workpiece is cut with two different tools. This is from customer specifications that two sides have a straight edge and two sides have a rounded or chamfered edge. The focus of this thesis experimental chapter

Figure 6.1: End section of workpiece

was on the straight cut edges and testing various tools and process parameters for it. The chamfered edge was not in focus but inspections were made for that part of the process. The wear of the straight cutting PCD tools analysed influence the surface quality and fiber protrusion of the workpiece but the chamfer tool used for the other two edges influence the final part quality and tolerance to a much larger extent. Due to the requirements of large chamfer angle of 70 degrees, which is not a common geometry in standard tool catalogs a uncoated carbide tool is used for the operation. The tool wears much faster than the straight edge PCD tool and due to the geometry it has proved difficult to find a more suitable tool. For the chamfer tool good surface quality was seen in the first few workpieces. After a number of cut pieces material is not completely sheared from the edge but burrs are left along the cut edge. As the weave pattern is non-homogeneous these burrs are more prominent on one of the two edges and are created in the direction of the wider fibers as seen in figure 4.1. As more pieces are machined these burrs increase and become rougher and thicker and become problematic for the post-machining sanding. Due to the nature of machining FRPs and fiber orientation some amount post-machining sanding is often necessary [6]. As the workpiece requires some amount of sanding it can be acceptable to have burrs after machining, but further work needs to be done to determine to what extent.

Opportunity for further work is also to exchange the chamfer tool for one that has higher wear resistance and higher cutting data. Some market research was conducted during this project for a more viable tool but no clear results came out of that.

6.3 Milling strategy

For the machining process in general there is room for improvements. A balance between cost, productivity and quality is required and some minor modifications could be made to the process to increase productivity of the process. The gain in productivity versus time and effort need for each modification varies.

These improvements include minimizing time for unnecessary tool travel between workpieces and in retract direction. Changes could also be made to the different operations to minimize plunging/ramping into material by utilizing already machined slots or holes in the material. From experiments is was clear that plunging or ramping into the material was major cause for tool tip fracture and chipping.

One possible solution to avoid slow and damaging plunging or ramping operations is to utilize a fixture were the cutting operations can be continuous in a straight line engaging multiple workpieces without having to move up and down in the material. Challenges with that is possibly a more complex fixture design and by cutting the material continuously larger amount of excess scrap pieces will have to be removed after operation.

6.4 Chip disposal

The disposal of chip away from the cutting tool is minimal in the current machining process. Clogging of chip on the tool edge can present a problem in the process due to small tool diameter, small flute size and softening and adhering of the polymer matrix to cutting edge from high cutting temperature. This clogging can cause damage to cutting surface and poor surface finish [6, 19]. Options for chip disposal of the process is to use compressed air focused on the tool and vacuum cleaner available in the CNC machine. Compressed air is problematic due to fine dust particle dispersion and its possible effects on health of operators. Current workholding fixture prevents the use of vacuum cleaning from the tool but with a improved fixture design it could be possible to use a vacuum cleaner system for chip removal. Proper selection of cutting data can decrease the chip clogging as well as using larger diameter tool with more room for dispersing chip away from the flutes. As the operation are slot milling, larger diameter tool produces larger amount chips that need to be cleaned up so a balance is required. Disposing of chip during machining leads to less manual cleaning between workloads and thus possible increase in productivity from operators.

Chapter 7

Conclusion

7.1 Conclusion

To be able to maintain high production rate for the process a multi-flute PCD tool was the most viable option. Such tools can be run with high cutting speed and low feed per tooth, producing good surface quality while maintaining high feedrate. Tool wear was characterized by rounding of the cutting edge at the main contact zone and chipping of the tool edge due to vibrations or lack of stability in the process. PCD tools showed slow wear and produced results with low amount of delamination and burrs for an extended time, likely from low depth of cut in the application.

In the experiments emphasis was on increasing the cutting data for the straight edge operation. With tool samples 005 and 006 it was possible to increase the feedrate by 50% and thus decreasing the operation time by 24% with acceptable results. These experiments were a step in the right direction to a better tool selection and cutting data but not a completely optimized solution. Further work needs to done to find an optimal solution for the application.

The production capacity of the machine is not fully utilized as earlier steps in the production are the bottleneck. The current production capacity of the cutting process needs to be increased by 35% to be able to keep up with initial production phase of the new factory facility. Improvements in capacity are possible with change in milling strategy, cutting tools and chip removal.

7.2 Further work

There is a restriction to the quality of finished products due to low stability and low setup repeatability of the current workholding solution. Low workholding force causes premature damage to tools and influences final dimensions of workpieces. Low setup repeatability of the workholding has to be compensated by machining larger than final dimensions that is then removed in post-machining. The first step and possibly the largest impacting one in improving the process would be the design and manufacturing of an improved workholding fixture. This fixture should preferably be made from aluminium with high tolerances for increased positional stability. By using a machined vacuum pattern and sealing gasket the vacuum holding force could be improved to compensate for shape distortion from the RTM process and decrease vibration during workpiece machining. With a good fixture design the integrated vacuum cleaner in the Datron machine could be used to remove chips continuously from the tool. This could in turn increase tool life and decrease manual cleaning needed between workloads, thus decreasing the cycle time.

In terms of tool selection PCD tools have proved most suitable for the application. A suitable PCD tool for the rounded or chamfered edge specifications for the workpieces has up to this not been found. Some market research has been done but no viable solution has been found yet. Further work could be put into finding a better performing tool for this part of the application. Another possibility is making modifications to the RTM molds or product specifications to limit the need for a chamfer tool. Related to this is the viability of custom-made tool or tools for the application. There exist companies that specialize in customer specified tools so there is a possibility of a tool that could be cut a straight edge and a chamfered edge with different parts of the tool. That could decrease tool changing time and thus cycle time.

It was not possible to test an abrasive type cutting tool for the application because of manufacturer quality issues so their potential viability is still in question. Further effort could be put into finding a viable manufacturer for those types of tools and performing tests.

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