ABSTRACT

GISIP, JUDITH. Improvement of Wood-Based Machining Operations on a CNC Router through Extending Tool Life. (Under the direction of Dr. Richard L. Lemaster and Dr. Daniel E. Saloni.)

Improved machining processes provide economic benefits through increased productivity and product quality. The main goal of this study was to improve the CNC router performance through extending the life of the cutting tool when machining wood-based products. There were two main objectives: (1) to determine the relationship between tool wear, panel chipping, and tool spindle vibration; and (2) to demonstrate the use of a process monitoring and control technique for extending tool life, and reducing panel chipping when machining wood-based products. The relationship between tool wear, panel chipping, and tool spindle vibration was established through conducting an extensive background study. As for the demonstration of the application of a process monitoring and control system, a feedback control technique, where the spindle speed was increased based on the tool spindle vibration level, was compared with three other cutting scenarios: (1) a control test with a constant spindle speed of 18,000 rpm; (2) a test with a constant low spindle speed of 12,000 rpm; and (3) a step function cutting with the spindle speed increased at regular intervals. Each situation cut two 2 × 4 ft. panels of melamine-coated particleboard on a CNC router with a 10% cobalt grade tungsten carbide insert at 500 ipm of feed speed in a climb cutting direction. After each test, tool wear, and panel chipping of the melamine layer of the particleboard were measured. At a constantly low spindle speed of 12,000 rpm, tool life was increased, but the panel chipping was adversely affected due to a larger chip load. A constantly high spindle speed of 18,000 rpm produced lower panel chipping; however, it resulted in a higher rate of tool wear. Increasing the spindle speed at regular intervals showed a lower tool wear, and panel chipping; however, it provided no clue about when to systematically increase the spindle speed. The feedback control technique utilized the tool spindle vibration to regulate the spindle speed that could greatly extend the useful life of the cutting tool. A cost-benefit analysis was also done on the different spindle speed settings to determine their performance based on ease of use, cost of implementation, and the actual extent of tool life improvement obtained. The results of the cost-benefit analysis showed that
the step function tests produced the lowest cost per product while the highest was produced by cutting at 18,000 rpm. The 12,000 rpm had the second highest cost per product whereas the feedback control had a comparably low cost per product, and came in second for the lowest cost per product. In terms of tool life, the feedback control technique had a 33% increase when compared to the 18,000 rpm test.
Improvement of Wood-Based Machining Operations on a CNC Router through Extending Tool Life

by
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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Forest Biomaterials

Raleigh, North Carolina

2015

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DEDICATION

To my parents; for the love and sacrifice, and for giving me a chance at education.
BIOGRAPHY

Judith Gisip was born in Kota Kinabalu, Sabah, Malaysia on April 21, 1978. She spent most of her childhood in Keningau, Sabah, Malaysia. In 1996, she pursued a Diploma in Wood Industry at the branch campus of the Universiti Teknologi MARA (UiTM) in Jengka, Pahang, Malaysia. She successfully completed the degree in 1999 after which she continued a Bachelor of Science in Furniture Technology at the UiTM main campus in Shah Alam, Selangor, Malaysia. She graduated with a first class honor in 2002, and earned the Young Lecturer Scheme Scholarship from UiTM, to pursue graduate studies at Purdue University, West Lafayette, Indiana, U.S.A. in 2003. After earning a Master of Science in Wood Science and Technology in 2005, she returned to her home country, Malaysia, and served as a faculty member at the Faculty of Applied Sciences at UiTM in Shah Alam. In August 2009, she pursued a PhD at the Department of Forest Biomaterials at North Carolina State University in North Carolina, U.S.A., after successfully obtaining a partial funding from the UiTM’s Staff Scholarship, and the NC State’s Graduate Research Assistantship.
ACKNOWLEDGMENTS

All praise to Allah s.w.t. My deepest gratitude goes to the following people for which without them, a completion of my PhD journey would not have been possible.

First and foremost, Dr. Richard L. Lemaster as my advisor and co-chair of my doctoral advisory committee; for accepting me as his doctoral student, for being a great teacher, for patiently guiding me through the challenging path of a PhD, and for sharing his vast research experience and expertise. Dr. Daniel E. Saloni, co-chair of my doctoral advisory committee; for his contribution, passion, and advices, which are invaluable to my research. My doctoral advisory committee members: Dr. Sudipta Dasmohapatra, and Dr. Steven D. Jackson; for their crucial advices, and guidance in shaping up my research.

Fellow staffs and colleagues from the Forest Biomaterials department especially Dr. Tony LaPasha, Dr. Herman van Dyk, Guillermo Velarde, and Curtis Watkins; for their invaluable contributions in the completion of my research work; Mike Jett, for the training on the x-ray densitometer; and Dr. Fikrit Isik of the Forestry and Environmental Resources department for the guidance in the initial statistical analysis on the panel chipping method.

Universiti Teknologi MARA (UiTM), Selangor, Malaysia; the U.S. Department of Agriculture’s Wood Utilization Research Special Grant; and the North Carolina State University’s College of Natural Resources Hoffman Scholarship; for the significant funding and support. Friends that had contributed directly and indirectly in offering friendship, ideas, and emotional support throughout my stay in Raleigh, NC; and those throughout the U.S.A., and Malaysia; thanks for the wonderful friendships, foods, fun, and laughter.

My mother, Mulina; for her great vision, that an education is the key to success, and freedom in life; my father, Gisip; for the tremendous support and patience, and my siblings; Magdelen, Imelda, Celestina, Felicia, and Clarence, for the constant thoughts and hopes.

Last but not least, to my precious family: my husband, Asseri; for the love and sacrifice, for being there in good and bad times, and for always believing in the pursuit of my dreams; my hearts: Sofia, Serena, and Sarah; for lighting up my days, for being my greatest supporters, for giving me a reason to fight on, and for showing me the true meaning of love and happiness.
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LIST OF ABBREVIATIONS OR SYMBOLS

RMS – root mean square
FT – Fourier transform
FFT – fast Fourier transform
µm - micron
1. **INTRODUCTION**

The automation of the machining process has opened up new capabilities such as the ability to accurately manufacture complicated parts, as well as to produce products in large volumes. These capabilities were realized with the invention of computer numerical control (CNC) machines in the early 1970’s. The CNC technology has brought the machining process into a new level of high precision and flexibility.

In the wood industry, the machining process plays a crucial role in the conversion of wood into different shapes and dimensions. It involves the removal of unwanted materials in the form of small chips through the interaction of the tool and workpiece. The machining processes of wood include sawing, sanding, planing, turning, and routing to name a few. Each of the machining processes has to deal with several machining parameters, such as feed speed, spindle speed, and depth of cut, that determine the quality of the surface of the machined workpiece.

The properties of the material itself also affect the final surface quality. Insufficient control of these parameters and not taking the properties of the workpiece material into consideration will result in unacceptable parts that can be costly to production. Additionally, the corresponding cutting tools that are used in any wood machining operations are also equally important to consider. This is particularly true since the cutting tool has direct contact with the workpiece material during the machining. The condition of the cutting tool can contribute much to the quality of a machining process. Unexpected wear rates or tool failures can cause unacceptable product quality or unscheduled production downtime, both of which can adversely affect the cost of production.

1.1. **Objective**

The main goal of this study was to improve the CNC router performance through extending the life of the cutting tool when machining wood-based products. There were two main objectives: (1) to determine the relationship between tool wear, panel chipping, and tool spindle vibration; and (2) to demonstrate the use of a process monitoring and control technique for extending tool life, and reducing panel chipping when machining wood-based
products. The relationship between tool wear, panel chipping, and tool spindle vibration was established through conducting an extensive background work. As for the demonstration of the application of a process monitoring and control system, a feedback control technique, where the spindle speed was increased based on the tool spindle vibration level, was compared with three other cutting scenarios: (1) a control test with a constant spindle speed of 18,000 rpm; (2) a test with a constant low spindle speed of 12,000 rpm; and (3) a step function cutting with the spindle speed increased at regular intervals. A cost-benefit analysis was also done on the four types of cutting situations to determine their performance based on ease of use, cost of implementation, and the actual extent of tool life improvement obtained.

Prolonging tool life is vital since longer tool life results in increased productivity. Numerous direct methods have been investigated to increase tool life. These include new tool materials such as polycrystalline diamond (PCD), monocrystalline diamond, ceramics, as well as new formulations of tungsten carbide including tool coatings such as titanium nitride over traditional tungsten carbide tool materials. In addition, tool treatments such as cryogenic treatment has shown promise but produced mixed results depending on the type of blade materials being treated. One can opt to use the best blade such as PCD; however, it would depend on several factors such as the type of machining operations, raw materials, and cutting parameters in order to be determined as cost efficient. A tool condition monitoring (TCM) and control can be an efficient and a reliable way to optimize cutting operation.

One technique that has shown promise in studies where both wood-based panels (Gisip et al., 2007) and metal (Boswell and Chandratilleke, 2009) were machined is the use of compressed air-based cooling to extend tool life. The current research evaluated the technique of applying cold air to the edge of a cutting tool as an attempt to reduce the rate of tool wear. The effect of air pressure, air flow, and air temperature were also investigated.

Monitoring the condition of the cutting tool; or better known as TCM, can provide a tool changing strategy that may save manufacturing costs due to tool failure, unexpected downtime, and defective parts. Tool condition such as tool wear has been the focus of many studies. As stated by Sheikh-Ahmad (2009), tool wear alters the cutting tool geometry, which reduces the effectiveness of the tool to remove materials, and these result in poor
surface quality. Tool wear directly affects tool life in which it determines how much cutting can be done before the quality of the resulting cut becomes unacceptable. Tool life can be defined as a time period in which a tool can reliably perform cutting before it is discarded (Cheng, 2009).

Tool condition monitoring can be done through direct and indirect methods. Direct methods, as the name implies, deal with performing measurement of volumetric loss directly on the tool cutting edge. It is commonly done using an optical microscope to observe and measure the wear scar on the edge of the tool. This measurement may be done manually or with image analysis software. Indirect methods are related to monitoring tool condition during cutting, and may include the monitoring of torque, temperature, vibration, sound, acoustic emission or similar parameters. Some of these monitoring methods can be more expensive and highly invasive. Detailed discussion on TCM with references can be found in the literature review section.

Monitoring vibration signals has been one of the main indirect approaches to be successfully used in TCM systems. According to Heyns (2007), tool wear or tool breakage occurrence may affect the machine vibration response, which is detectable by a sensor, and the changes in the vibration response can be correlated to the wear condition of the tool. A study by Lemaster et al. (2000a) found that monitoring spindle vibration with an accelerometer can be used to monitor tool wear and product quality on a CNC router. The results showed that certain frequency bands of the vibration signals that were detected by the accelerometer were more sensitive to changes in the tool condition and the workpiece. It was also found that increasing the speed of the router spindle can reduce the degree of chipping of melamine-coated particleboard caused by a worn tool.

Another study (Lemaster et al., 2000b) was a continuation of the work as explained in the previous paragraph. Vibration signals were once again monitored using an accelerometer, and a control system was developed to optimize the machining operation on a CNC router. The control system was used to increase the speed of the router spindle based on the sensor data that was related to the progression of tool wear, and workpiece quality. The spindle speed parameter was chosen as the control parameter because slowing the feed
speed to delay the wear process is undesirable by many manufacturers as it will cause a decrease in production. It should be noted that the study by Lemaster et al. (2000b) was conducted on one particular type of router, spindle, and grade of carbide. Thus, there is a clear need for additional studies to determine the effect, if any, of varying grades of carbide, and spindle design.

As one of the main areas in this research, the indirect monitoring of the tool condition presented a challenge in analyzing vibration signals when machining with different spindle speeds. In vibration analysis studies, Fast Fourier Transform (FFT) analysis is commonly used to analyze vibration signals. It deals with the transformation of the vibration signals from the time domain into the frequency domain. The FFT power spectrum is able to identify and quantify the frequency components of the vibration signals. However, the FFT analysis cannot detect mechanical characteristics with changes in spindle speed. A technique called order analysis can identify and isolate the vibration signals, and further analyze the variations in the sensor signal with changes in the spindle speed. A section was written detailing if order analysis is better than traditional frequency analysis for the monitoring and control of tool wear. This study performed the order analysis using LabVIEW™ (Laboratory Virtual Instrument Engineering Workbench); a graphical programming language software, which can be used for applications such as data acquisition, instrument control, pre/post processing of acquired data, and industrial automation.

This dissertation contains four important chapters: (1) Literature Review, which provides the fundamental knowledge on every aspect in the research such as the properties and machining process of wood, process monitoring and control, signal processing and filtering, and vibration monitoring; (2) Methodology and Preliminary Work, which covers the procedures in conducting several preliminary tests. Results from the preliminary tests are grouped into two major stages. The first stage was establishing a relationship of the effect of tool grade, feed speed and spindle speed on tool wear, the degree of chipping of melamine-coated particleboard, and spindle vibration. The relationship provides crucial information for the feedback control technique. A control system that can regulate the spindle speed is needed to optimize tool life and product quality. The second stage was
analyzing the vibration signals from the machining processes; (3) Additional Studies, which contains several additional experiments that bring the research to completion. These include the effect of tool cooling application, measuring panel chipping area with image analysis, process control test, cost-benefit analysis, and repeated tests for the effect of feed speed and table position; and (4) Conclusion and Future Work, which concludes the dissertation with the study’s findings as well as some suggested future work. The future work provides an avenue for other researchers to give valuable contributions in the area of process monitoring and control in the wood-based machining processes.
2. LITERATURE REVIEW

2.1. Introduction

In this chapter, several topics that are directly related to the research are presented in four main sections. The first section covers the properties, and machining processes of wood and wood-based composites. This information provides a fundamental understanding on the anatomical and physical properties of wood, and the different properties of wood-based composites. It also discusses the types of materials that are commonly used to produce cutting tools, the theory and mechanisms of tool wear, and finally the two types of cutting processes, i.e. orthogonal and peripheral cutting. Finally, this section will also include a brief discussion on the CNC technology related to wood and wood-based machining operations.

Process monitoring and process control topics are covered in the second section in which both terms are defined and discussed. For process monitoring, the difference between tool condition monitoring (TCM) and machine condition monitoring (MCM) are presented. TCM is further discussed in terms of its two methods of measurement, i.e. direct and indirect. Previous studies on tool wear monitoring are also presented to provide an overview of what has been done in the past, and to demonstrate why the current study is needed.

One of the main portions of the current study was dealing with the acquisition and processing of vibration signals that were generated by the CNC router machine. Thus, the third section of this chapter is dedicated to a topic in signal processing. It covers the data acquisition process, signal processing for analog and digital signals, and the domains involved in digital signal processing such as the time, frequency, and joint time-frequency domains. Signal filtering is also discussed including analog and digital filters, as well as time versus frequency domain filters.

The fourth and final section discusses the vibration monitoring topic. This includes the equipment and techniques that are required in conducting vibration monitoring such as the sensors, and signal conditioning. Different types of sensors are presented such as displacement, velocity, and acceleration. Applications of vibration signals in TCM are also presented for an overview of its past and current status.
2.2. Properties and Machining Process of Wood and Wood-Based Composites

2.2.1. Introduction

Machining of wood differs from metal cutting mainly due to the inherent properties of the material being cut. Unlike metal, the non-homogeneity of wood can be of great concern in the machining process. Knowledge of the material properties and its composition are important for producing good machining quality. Due to some disadvantages of solid wood, such as dimensional stability-related properties namely shrinkage and swelling, as well as striving to better utilize this natural resource, has led to the development of wood-based composites including plywood, oriented strand board (OSB), particleboard, fiberboard, and cement-bonded board. These wood-based composite products present different challenges in the machining process since they contain chemicals such as urea-formaldehyde and phenol-formaldehyde that are used as resins and wax as one form of additives. The current study focused on the routing, also known as milling, operation performed on melamine-coated particleboard. A milling operation is a type of peripheral machining process in which a surface is generated through the rotation of a cutting tool that moves relative to the material being cut.

2.2.2. Properties of Wood and Wood-Based Composites

Wood is a unique, non-homogeneous material. Trees that produce wood can be classified into two categories namely hardwoods and softwoods (it is worth noting that the names of the categories are not indicative of the actual hardness of the resulting wood). In the plant kingdom, hardwoods and softwoods are included in the spermatophytes divisions, which mean they produce seeds. However, both categories are in different subdivisions where hardwoods are in the subdivision of angiosperms, producing seeds in fruit, and softwoods in the subdivisions of gymnosperms, producing naked seeds (Bowyer et al., 2007).

Softwood trees are referred to as conifers (mainly bear scaly cones) with needlelike leaves, which are normally evergreen. There are also conifers that shed their leaves such as dawn redwood (Metasequoia glyptostroboides), tamarack (Larix laricina), and bald cypress
(Taxodium distichum) (Equiza et al., 2005). In the Northern Hemisphere, the genera included in the softwood group are Pinus (pine), Picea (spruce), Larix (larch), Abies (fir), Tsuga (hemlock), Sequoia (redwood), Taxus (yew), Taxodium (cypress), Pseudotsuga (Douglas-fir), and the commonly known cedars such as Junipers, Thuja, Chamaecyparis, and Calocedrus (Bowyer et al., 2007).

Hardwoods are angiosperms that produce broad leaves. They can either be deciduous in which the leaves change color before they drop during autumn season in temperate zones, or evergreens that do not lose their leaves. Their seeds are produced within fruiting bodies such as acorns and pods. Angiosperms are divided into two classes: monocots and dicots, and the hardwood-producing species are under the dicots class. Common commercial species include Quercus (oak), Fraxinus (ash), Acer (maple), Betula (birch), Fagus (beech), Prunus (cherry), Juglans (walnut), and Populus (cottonwood, aspen).

The anatomical details on hardwood and softwood are covered in details in several references (Panshin and DeZeeuw, 1970; Core et al., 1979; Bowyer et al., 2007). Both groups are anatomically different on their external appearances as well as their internal morphology. In hardwoods, different types of cells are present such as vessel, fibers, parenchyma, tracheids, and rays, whereas in softwoods, tracheids are the main wood cells followed by rays, longitudinal parenchyma, and resin canals. The shapes and sizes of these cells are what make each of the three major wood surfaces namely the transverse, radial, and tangential have distinctive looks. In Figure 2.2.1, the location of the three surfaces in a tree trunk is shown while the microscopic views of the surfaces are presented in Figure 2.2.2.
Figure 2.2.1 Anatomy of a tree trunk showing the location of the three main wood surfaces namely transverse, radial, and tangential (Encyclopedia Britannica, Inc.).
The vessel cells in hardwoods are an important anatomy feature that needs to be further discussed. The vessel cells and fibers affect the appearance, and hardness uniformity of wood due to their size, number, and distribution. The vessels or pores (i.e. exposed vessels on the transverse surface of wood) are what make hardwoods known as porous woods. Based on the size and distribution of the vessels, hardwoods can be termed as: (1) ring-porous where the distribution of pores is concentrated in the earlywood such as in oak and ash; (2) diffuse-porous where pores are evenly distributed such as in maple and birch; and (3) semi-ring porous or semi-diffuse porous where the presence of large pores in the earlywood gradually becomes smaller in the latewood such as in black walnut (Hoadley, 2000). Figures 2.2.3, 2.2.4, and 2.2.5 illustrate the vessels arrangements.
Figure 2.2.3 Ring porous wood. Cross section of black oak (*Quercus velutina* Lam.) (5×) (Panshin and DeZeeuw, 1970).

Figure 2.2.4 Diffuse porous wood. Cross section of bigleaf maple (*Acer macrophyllum* Pursh.) (5×) (Panshin and DeZeeuw, 1970).
Wood physical properties such as moisture content, density and specific gravity, mechanical properties such as bending and compression, and chemical properties such as the amount of chemical constituents may affect the machining process and the surface quality of machined wood. It is also important to note that the nature of a living tree affects wood quality. These include the site conditions, soil type, soil moisture, direction of the sun, and the shade from other trees, which can make the wood from nearby trees have different densities, and hence, different machining characteristics.

The occurrence of reaction wood, which is a natural tendency of a tree to maintain upright, can cause eccentric growth in the tree on a slope or striving to reach the sunlight blocked by other larger trees. Reaction wood has different characteristics than that of normal wood. Reaction wood that is found in hardwoods is called tension wood, and when found in softwoods is called compression wood. Tension wood in hardwood can cause fuzzy surfaces during machining whereas compression wood can cause abnormal shrinking and swelling of the wood.

Wood-based composites are a means of effectively utilizing wood. Wood composites are engineered wood products that are used extensively for a variety of applications.
are mainly composed of wood elements that are bonded together by an adhesive. A wide range of wood-based composites are available, and are classified according to its particle size, density, and process type such as dry or wet. Different types of wood elements are used such as dimension lumber, veneers, fibers, particles, flakes or strands, and scrims. Several types of adhesives are available specifically for the manufacture of wood composites. The adhesives can be urea-based, phenolic-based, isocyanates-based, as well as made from renewable resources such as soybean and lignin (Walker, 2006). Maloney (1993) presented the family of wood composites materials, which include panel products (e.g. plywood, fiberboard, particleboard, and oriented strand board), lumber and timber products (e.g. laminated veneer lumber, parallel strand lumber, and oriented strand lumber), molded products (e.g. automobile panels), and inorganic-bonded products (e.g. shakes and shingles).

Although the innovative creation of this class of material has addressed the issues of dimensional stability and small diameter raw material of solid wood, one of the main constituents, the adhesive resin, has been found to be corrosive and abrasive on cutting tools during the machining process. Information on tool materials and tool wear mechanisms is given below to provide a fundamental understanding on cutting tools.

### 2.2.3. Tool Materials

Selecting the right tool materials is important for producing cutting tools that can cut efficiently as well as can withstand harsh cutting conditions. Three critical characteristics of cutting tool materials that must be considered are **hardness**, **toughness**, and **wear resistance**. Hardness can be defined as material’s resistance to surface indentation, cutting, abrasion, or scratching. Toughness can be described as the resistance to fracture when a material is being stressed or in other words, the amount of energy per volume that a material is able to absorb before it ruptures. Wear resistance refers to the ability of tool material to cut satisfactorily before being replaced. The term **strength** is also generally used to describe a material, which refers to the material’s capacity to resist loads (Gere and Goodno, 2009). Ideally, cutting tool materials should be harder than the workpiece it is cutting, have high
temperature stability, impact resistant, able to resist wear and thermal shock, and chemically inert to the work material.

There are three main groups of cutting tool materials: high speed steel (HSS), cemented carbides, and ceramics/superhard materials such as ceramics and polycrystalline diamonds (Sheikh-Ahmad, 2009). These groups are classified according to their hardness, toughness, and strength as illustrated in Figure 2.2.6. In the figure, PCD stands for polycrystalline diamond, and PCBN is an abbreviation for polycrystalline cubic boron nitride. They are also common cutting tool materials besides cermet (a ceramic-metallic tool made from titanium nitride, TiN). Further discussion on these cutting tool materials are given in the following paragraphs.

Figure 2.2.6 Toughness and hardness relationship for HSS, cemented carbides, and ceramics/superhard cutting tool materials (Sheikh-Ahmad, 2009).
High speed steel is a type of alloyed steel (note: steel is a mixture of iron and 0.05% to 1.7% carbon), which commonly consists of 18% tungsten, 4% chromium, and 1% vanadium or molybdenum. It is able to withstand a temperature up to 1100°F. High speed steel can be graded in three main categories: tungsten, molybdenum, and molybdenum-cobalt based grades. Often time HSS is coated with harder materials such as titanium nitride (TiN) or titanium aluminum nitride (TiAlN), in order to provide hardness and corrosion resistance (Münz, 1986). Although tool coating has been successfully implemented in the metal industry, it has experienced limited success in the wood industry due to the wood industry’s requirement for tooling with smaller sharpness angles. A smaller sharpness angle (or wedge angle) is needed for machining of wood as it generally generates a better surface quality; however, lower angles cause higher wear (Endler et al., 1999).

Cemented carbides come in the form of hard carbide particles (usually tungsten carbide) that are cemented together with a metallic binder (usually cobalt). Figure 2.2.7 shows a scanning electron microscope image of tungsten carbide powder. Cemented tungsten carbide tools are harder but more brittle than HSS, and are able to withstand temperature higher than 1400°F. These tools can cut much faster than HSS. The amount of tungsten and cobalt binder determines the cutting tool characteristics. Carbide tools with a high content of tungsten have higher wear resistance, but lower tool strength and toughness, while a higher percentage of cobalt binder lowers the wear resistance, but increases the tool strength and toughness. Different carbide grades for a wide range of applications are available due to the different properties from combinations of tungsten carbide grain size and cobalt percentage as illustrated in Figure 2.2.8. From the graph, it can be seen that for most woodworking applications, the grain size approximately falls between 0.5 to 2.5 µm, and the cobalt percentage is between 2.5 – 12 %. Some carbide tooling has also replaced the cobalt binder with ingredients such as chromium in order to increase its resistance against corrosion.
Ceramic alloys cutting tools are fused together without a binder. They are harder, more heat-resistant, and more brittle than carbide tools. Ceramic alloys can be either
alumina-based or silicon nitride-based. Cermet tools, where the name is derived from the two words ceramic and metallic (Smith, 2008), are made from titanium carbide. Both ceramic and cermet tools are very brittle although very tough. Ceramic and cermet tools can be used in extreme applications such as in sawmilling (Carbide Processors Inc.).

Polycrystalline and monocrystalline diamond tools are man-made diamonds. Diamond is the hardest known material and is able to resist chemical and thermal effects. Despite these advantages, diamond tools are very brittle as well as expensive.

Polycrystalline cubic boron nitride tools are made from CBN crystals and binder such as TiN. They are usually meant for cutting super alloy, hardened steels, and hard cast iron (Sheikh-Ahmad, 2009).

Cutting tools are subjected to wear during machining and the amount or rate of wear is different depending on the materials they are made from, as well as the type of workpiece they are cutting. The next section describes the theoretical aspect of tool wear and the wear mechanisms that can occur during machining of wood and wood-based composites.

2.2.4. Tool Wear: Theory, Mechanisms, and Past Studies

As a general definition, tool wear can be defined as the permanent deformation of the tool cutting edge that leads to unwanted changes in its geometry (Sheikh-Ahmad, 2009). What makes tool wear of primary concern is that since the initial geometry of the cutting tool is altered, the cutting tool becomes less effective in removing material and in producing good surface quality. Not only that, tool wear causes other adverse effects such as reducing the strength of the tool edge, increase in tool forces and power consumption, higher temperature at the tool and material interface, poor surface quality, loss of part dimensional accuracy, and loss of productivity (Sheikh-Ahmad, 2009). Tool dullness is a subjective term that means the tool is no longer producing an acceptable product or is using too much energy.

Cutting tools with severe wear may eventually break, and can cause machine stoppage. Unexpected stoppage of a machining process can have serious economic impacts on the production process. By controlling tool wear, specifically reducing it, tool life is increased. In terms of the machining process, tool life is mainly affected by cutting speed as
it influences the cutting temperatures the most, followed by feed speed, depth of cut, and geometry of cutting tool (Sheikh-Ahmad, 2009). In addition, workpiece material also affects tool life. As an example, wood residues that are used in particleboard manufacture contain silica, which is known to cause excessive tool wear (Lehmann and Geimer, 1974).

The occurrence of tool wear is a complex phenomenon and is due to several wear mechanisms. In wood and wood-based materials, common wear mechanisms are abrasive wear, corrosion, oxidation, erosion, and electro-chemical wear. Abrasive wear deals with the indentation of cutting tools due to the presence of hard particles in the workpiece that is being cut; corrosion is associated with chemical attack on the cutting tool surface; oxidation is triggered by high temperatures; and erosion relates to loose abrasive particles (Sheikh-Ahmad, 2009). Electro-chemical wear is usually related to cutting wet wood (Mohan and Klamecki, 1981), and the presence of wood extractives found in heartwood (Kirbach and Chow, 1976).

Past studies have largely covered the different aspects that deal with wear mechanisms, and the application of treatments to extend tool life. As far as the wear mechanisms, it can easily be grouped as mechanical- and chemical-related wear. The following paragraphs discuss the studies that were done on the mechanisms and treatments on tool wear when machining wood or wood-based materials.

Scholl and Clayton (1987) observed the wear behavior of unplated and chromium-plated steel saw chain cutters. They concluded that abrasive wear to be the dominant cause of tool wear when cutting Douglas-fir and hemlock.

Several studies suggested other mechanisms, which are mainly related to the removal of the cobalt binder and the tungsten carbide grains as described in the next two paragraphs.

Sheikh-Ahmad and Bailey (1999) suggested that chemical reaction is responsible in the preferential removal of the cobalt binder that holds the tungsten carbide grains together, and the grains are mechanically removed (i.e. erosion) due to the lack of bond between them. Similar conclusion was made by Bailey et al. (1983) in which they conducted a tool wear study on cemented tungsten carbide tools to examine its wear mechanisms during machining of green oak. It was observed that wear occurs through a process of continuous tool nose
rounding. When cutting oak with high moisture content, the dominant mechanism of wear involves the preferential removal of the cobalt binder through chemical reaction with tannins, a type of oak extractive, followed by the loss of tungsten carbide grains through mechanical action due to the insufficient strength of binder to resist shear forces generated by the motion of the chip and cutting tool.

In terms of chemical-related wear, Kirbach and Chow (1976) found that chemical wear of carbide-tipped saws and knives that cut green western red cedar occurred due to the presence of heartwood extractives that were believed to attack the cobalt matrix. Mohan and Klamecki (1981) found that cutting wet wood resulted in electro-chemical action due to the nature of the cutting tools and the water in the wood. Studies on the electrical effects in wood and wood-based panels machining were also conducted (Stewart et al., 1994; and Klamecki, 1979).

High-temperature corrosion/oxidation was found to be a predominant wear mechanism when machining MDF with tungsten carbide tools at high temperature (Reid et al., 1991; Stewart et al. 1986).

The application of different treatments on tool was done to reduce the effect of wear on tool life such as cryogenic treatment (Stewart, 2004; Gisip et al., 2009), and the use of refrigerated air during machining (Gisip et al., 2007). It was suggested that the application of cryogenic treatment and refrigerated air improve the resistance of the cobalt binder against oxidation or corrosion, and by retaining more of the cobalt binder, it ultimately enhances tool life. Less tool wear can also be achieved by reducing the heat in the cutting zone with the cold air.

Corrosion was also found to significantly accelerate tool wear on cutters that cut green wood due to the presence of acetic acid and polyphenols (McKenzie and McCombe, 1968).

Reviews on tool wear studies were also done to disseminate comprehensive information on the subject. Klamecki (1979) presented a lengthy review on tool wear as related to three main areas: tool material, work material, and tool-work interactions during
the machining of wood and wood-based materials. Ko et al. (1999) provided a review that focused on the actual wear mechanisms involved in a machining process.

The next section discusses the two major types of cutting, i.e. orthogonal and peripheral cutting. Discussion on how chip formation affects surface quality and the amount of tool wear are also included.

2.2.5. Orthogonal Cutting and Peripheral Milling

A thorough discussion on the fundamental machining operation is pertinent in order to understand how materials properties affect the outcome of any machining processes. Machining processes for wood are commonly classified into two basic processes namely orthogonal cutting, and peripheral milling as depicted in Figure 2.2.9. The former involves a continuous machining condition where the cutting edge is perpendicular to the direction of the relative motion of the tool and the workpiece. Its surface plane is parallel to the original material surface. Examples of operations are veneer peeling and lathe turning. Peripheral milling is a rotary cutting process with a cutterhead carrying knives around its periphery where it involves the intermittent engagement of the cutting knives with the workpiece (Koch, 1964). Planing and routing are examples of peripheral cutting.

Figures 2.2.10 and 2.2.11 illustrate examples of the two cutting operations; i.e. veneer peeling, and planing, respectively. Since the study is dealing with the milling process on a CNC router, peripheral milling of wood is discussed in detail in the following paragraph.
Figure 2.2.9 Classification of the machining process of wood: (a) orthogonal cutting, and (b) peripheral milling.

Figure 2.2.10 Peeling of red maple veneer (Koch, 1985, photo courtesy of Woodson).
Peripheral milling can be easily depicted as the planing operation. It produces single chips during the intermittent engagement between the material being cut, and cutter knives that are fixed around the periphery of a rotating cutterhead (Koch, 1964). Due to the contact between the cutter knives and workpiece during the machining process, and the trochoidal path (Figure 2.2.12) taken by each knife tip, a series of individual knife traces is produced (Koch, 1964).

Figure 2.2.11 Planing of Douglas-fir (Koch, 1964).

Figure 2.2.12 Path of knife related to workpiece is a curtate trochoid (Koch, 1985).
Peripheral milling can run in two different conditions based on the workpiece-feed direction in relation to the direction of cutterhead rotation. These two milling conditions are conventional cutting also known as up-milling, and climb cutting also known as down-milling as illustrated in Figure 2.2.13. In conventional cutting, the cutterhead rotation is against the movement of the feed of the workpiece, whereas in climb cutting, the rotation of the cutterhead is in the same direction with the workpiece movement.

![Diagram of Up-Milling and Down-Milling](image)

Figure 2.2.13 Conventional cutting (left); climb cutting (right) (Koch, 1985).

Conventional cutting is a common operation in wood machining. It does not wear the cutting tool as quickly as the climb cutting, it requires less cutting power, and the workpiece material can be hand fed. Nevertheless, climb cut is superior in terms of producing a good surface finish compared to conventional cut when cutting solid wood. Besides the difference in the rotation of the cutter as related to the workpiece movement, another significant difference is in terms of chip formation. In conventional cutting, the chip thickness increases (i.e. minimum to maximum thickness) as the cutting progresses, and in the case of climb cutting, it is the opposite. In solid wood, this type of chip formation in climb cutting results in a better surface finish while in melamine-coated particleboard, as was used in this study, results in greater chipping. This will be discussed in more detail in the preliminary research section of this thesis.
Figure 2.2.14 introduces the terminology of the peripheral milling. Related nomenclature is listed following the figure.

Nomenclature:

- $\alpha$: Rake angle (in degrees)
- $\beta$: Sharpness angle (in degrees)
- $\gamma$: Clearance angle (in degrees)
- $d$: Depth of cut (in inches)
- $D$: Cutting-circle diameter (in inches)
- $F$: Feed speed of workpiece (in feet per minute)
The nature of the cutter rotation and workpiece relation in the conventional and climb cutting operations, characterize the resulting machining quality. In terms of chip formation, the chip types in peripheral milling were reportedly similar to the ones produced in orthogonal cutting parallel to the grain as classified by Franz (Koch, 1964). However, the geometry of the chip is completely different. This is due to the fact that in peripheral milling, the rake angle, and clearance angle change proportionately as the cutter knife-edge emerges from the workpiece. Based on this, chip thickness is constantly changing from the first contact of the knife-edge to the workpiece until its emergence from the workpiece (Koch, 1964).

The formation of a chip is important since it can determine the surface quality of the machining process. All three types of chips namely Type I, Type II, and Type III can be produced consecutively in a single knife trace (Koch, 1964). The formation, causes, and effects of the three types of chips are illustrated in Table 2.2.1.

Surface quality can be categorized as a function of machining geometry, chip type, and several other factors. In terms of geometry, a satisfactory surface can be produced through an optimal combination of feed per knife, the wave height, and the radius of knife-path curvature. The optimal combination can be determined through altering the cutting-circle diameter, cutterhead revolution per minute (rpm), feed speed, depth of cut, and number of jointed knives in the cutterhead (Koch, 1964). In terms of chip type, a Type II chip generates the best surface quality as a Type I chip produces chipped grain, and a Type III can cause fuzzy grain. Chip marks caused by shavings and fiber bundles falling onto the surface of the workpiece can also affect the surface quality as they can indent into the machined surface (Koch, 1964).
Table 2.2.1 Types of chips and its causes and effects (Franz, 1958).

<table>
<thead>
<tr>
<th>Type of Chip</th>
<th>Description</th>
</tr>
</thead>
</table>
| **Type I**   | **Formation:** Wood splits ahead of tool edge until failure in bending  
               **Causes:**  
               - Large chip thickness  
               - Workpiece having low resistance to cleavage due to high strength in bending & stiffness  
               **Results in:**  
               - Chipped grain (when cutting against the grain)  
               - Lower power consumption  
               - Low tool wear (small chip contact)  
               - Low friction between wood chip and tool face |
| **Type II**  | **Formation:** Wood failure occurs along a line extending from tool edge to workpiece surface  
               **Causes:**  
               - Workpiece is prone to diagonal shear failures  
               - Small chip thickness  
               **Results in:**  
               - Good surface quality  
               - Intermediate power consumption  
               - Rapid tool wear due to constant attrition |
| **Type III** | **Formation:** Compression and shearing failures in wood ahead of tool edge  
               **Causes:**  
               - Small or negative rake angles  
               - High coefficient of friction between wood chip and tool face  
               - Dull cutting tools  
               **Results in:**  
               - Fuzzy grain  
               - High power consumption  
               - Rapid tool wear |
As discussed in Koch (1964), factors such as workpiece, cutterhead, and feed, affect the surface quality and cutting power. These factors are listed in Table 2.2.2.

Table 2.2.2 Factors affecting surface quality and cutting power.

<table>
<thead>
<tr>
<th>Workpiece factors:</th>
<th>Cutterhead factors:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Species</td>
<td>• Cutting velocity</td>
</tr>
<tr>
<td>• Moisture content</td>
<td>• Cutting-circle diameter</td>
</tr>
<tr>
<td>• Specific gravity</td>
<td>• Number of jointed knives cutting</td>
</tr>
<tr>
<td></td>
<td>• Rake angle</td>
</tr>
<tr>
<td></td>
<td>• Clearance angle</td>
</tr>
<tr>
<td>Feed factors:</td>
<td>• Sharpness of cutting edge</td>
</tr>
<tr>
<td>• Feed speed</td>
<td>• Width of joint</td>
</tr>
<tr>
<td>• Depth of cut</td>
<td>• Knife extension beyond face of gib</td>
</tr>
<tr>
<td>• Direction of cutterhead rotation with relation to direction of feed</td>
<td>• Shape of gib face</td>
</tr>
<tr>
<td></td>
<td>• Angle between rotational axis of cutterhead and direction of feed</td>
</tr>
</tbody>
</table>

Poor surface quality contains surface defects that are produced based on the type of chip. As stated earlier, chipped grain produced by a Type I chip can be associated with the mechanical properties of wood such as low tensile strength perpendicular-to-the-grain, high compression strength parallel-to-grain, and high static bending strength (Stewart, 1980).

Raised grain and fuzzy grain produced with a Type III chip are most commonly related to very low or negative rake angles and dull cutting tools. These generate excessive high cutting forces and a surface with wood fibers that are not completely severed (Stewart, 1980). The variations of wood, especially in terms of its mechanical properties with species and moisture content, present additional problems in the machining of wood (McKenzie, 1960).

2.2.6. Computer Numerical Control (CNC) Technology in Wood-Based Machining

The history of CNC dates back to the late 1940s and early 1950s when numerical control (NC) was developed by John T. Parsons and Massachusetts Institute of Technology
It was a collaborative effort to manufacture complex parts, which are unattainable by human operators. A NC program contains coded instructions that direct a machine regarding which paths and operations it is to perform. The instructions or machine programs were originally fed to the NC machines via a punched paper.

The development of microprocessor technology in the 1970s and 1980s contributed to the advancement of NC technology where NC machines were controlled by computers. This was when the term CNC was created. Three common features of CNC machines are (1) a machine program that contains instructions, (2) a controller, which reads the program and directs the machine, and (3) a machine tool that performs the actual cutting (Albert, 2008).

Examples of processes utilizing the CNC technology are milling, turning, and routing. Routing is a common operation in wood-based machining, which results in an extensive use of CNC routers. There are different types of CNC routers based on the number of axes such as 3-, 4-, and 5-axis machines. Each axis represents a motion either linear or rotational. The Cartesian coordinate system is used for the 3-axis CNC router where the machine moves linearly along x, y, and z axes. Additional rotational movements are found in the 4-, 5- and 6-axis CNC routers. Figures 2.2.15 and 2.2.16 show the 3-axis and 5-axis CNC routers, respectively. The 5-axis can accommodate cutting large three dimensional parts whereas 3-axis machine is specifically designed to cut flat parts (Albert, 2008).

![3-axis CNC router](image)

Figure 2.2.15 3-axis CNC router (DMS Inc.).
Machining on the CNC routers is done through the movements of the axes. Positioning of the axes is one of the critical aspects in order to manufacture accurate products. Accurate positioning of the axes is achieved through a feedback control system. In a feedback control system, a sensor is used to detect the actual velocity and position of the axes, and the current position is sent to a control circuit of the CNC machine (Suh et al., 2008).

The location of the sensor or detector is the basis of the four types of a control system; i.e. semi-closed loop, closed loop, hybrid loop, and open loop. The semi-closed loop has a position detector attached to the shaft of a servo motor. A servo motor is used to move the table or spindle of a CNC machine. In the closed-loop control system, the position detector is attached to the machine table or spindle, which results in a more accurate position detection. The hybrid loop combines both the semi-closed and closed loops. Open loop means no feedback, thus no detector and feedback circuit are required (Suh et al., 2008).

A discussion on CNC technology is vital since it is very much involved in today’s manufacturing industries such as wood, metal, textile, plastics and etc. In the wood industry, CNC machines particularly CNC wood routers have gained much importance and popularity due to their benefits such as improved automation, high precision, and flexibility. A highly automated machine can reduce human errors since a human operator is no longer needed to
produce complicated work that requires a high skill level. Accuracy and consistency are obtainable with high precision CNC machines where identical work pieces are machined using the same programs. In terms of flexibility, they offer the ease of performing different cutting operations for producing different products. Machine setup time can be greatly reduced as machine programs can be easily loaded into the computer.

Wood-based machining operations with CNC wood routers can have significantly increased spindle speeds. The spindle speeds in today’s CNC wood routers can range from 3,600 to 30,000 revolution per minute (rpm). Feed speed can typically reach up to 1,500 inches per minute (ipm) or faster and rapid rates are up to 4,000 ipm (Purnell, 2012). Cutting with a high spindle speed means cutting tools can become worn more rapidly as well as reductions in spindle life. Feed and/or spindle speed can be controlled in order to optimize the cutting on the CNC wood routers.

As varying the feed speed is considered by the industry as a reduction in productivity, this research chose to control the spindle speed of the CNC router. For this research, the spindle speed was altered during cutting through a process monitoring and control scheme in order to optimize the tool and spindle life while still producing acceptable product quality. The next section further discusses about process monitoring and control.

2.3. Process Monitoring and Process Control

2.3.1. Introduction

Process monitoring and control are two distinct processes that can be used to optimize a machining operation. In process monitoring, a measurable machining condition (e.g. vibration of tool spindle) is monitored in order to determine the status of the machining process. Control of the machine parameters such as feed speed, and spindle speed, can then be altered by the operator. In process control, the machining parameters are altered by the machine itself. In process control, as long as the value of the sensor input representing the machining condition does not exceed a specified threshold, no corrective actions (e.g. increasing the spindle speed) are taken. In the following sections, process monitoring and its methodologies are further discussed. A description on process control is also presented.
2.3.2. Process Monitoring: Tool Condition Monitoring (TCM) and Machine Condition Monitoring (MCM)

As described in the previous section, process monitoring deals with monitoring the tool and machining condition using sensors attached to the machining operation. For example, spindle vibration, spindle temperature, and power consumption can be used to monitor the tool condition. A significant increase in the values of these responses should trigger a concern, and it also provides a clue on a developing adverse condition (e.g. progressive dulling of cutting tool) within the machining process.

Two of the commonly used applications of process monitoring are tool condition monitoring (TCM) and machine condition monitoring (MCM). In TCM, the status or condition of the cutting tool is monitored throughout a machining process. As stated earlier, several monitoring techniques can be used to achieve this.

On the other hand, MCM provides information on the condition or health of the entire machine. The information can be used to detect early warning signs of a possible failure in the future. The MCM is done by placing sensors on the machine components that are subject to wear such as the gearbox, generators, and bearings in order to continuously monitoring their status. Any discrepancy signals between the ideal and actual conditions of the machine will indicate a need for a preventive service operation before damage occurs.

2.3.3. Tool Condition Monitoring (TCM): Direct and Indirect Methods

The technologies in signal processing and analysis have allowed for various applications such as TCM. A vast amount of research has been conducted in the area of TCM. This is due to the fact that tool wear can negatively affect the product quality, and tool failure can lead to an unscheduled machine down-time, which can be costly to a production.

A TCM system generally consists of: sensors, signal conditioners/amplifiers, and a monitor (Jemielniak, 1999). The sensors are the heart of any TCM system as they determine the quality of the data that is later analyzed in order to make appropriate adjustments in a machining process. Due to its importance, certain requirements have to be met for a successful use in process monitoring.
Byrne et al. (1995) stated the following requirements: measurement as close to the machining point as possible; no reduction in the static and dynamic stiffness of the machine tool; no restriction of working space and cutting parameters; wear- and maintenance-free, easily changed, low costs; resistant to dirt, chips and mechanical, electromagnetic and thermal influences; function independent of tool or workpiece; adequate metrological characteristics; and reliable signal transmission, e. g. from rotating to fixed machine components. Based on these requirements, there are limitations on the type of sensors that can be used.

The utilization of TCM on the various types of machining operations has been extensively studied and reported in the literature. A vast majority of the TCM literatures can be found in the metal cutting field, which focuses on several machining operations such as milling (Chen and Chen, 1999; Shao et al., 2004; and Szwajka and Górski, 2006), turning (Cuppini et al., 1990; Lim, 1995; and Kopač, and Šali, 2001), drilling (El-Wardany et al., 1996), and broaching (Axinte and Gindy, 2003). Some of the parameters that were measured for monitoring of the cutting tool were vibration, cutting power, sound, cutting forces, acoustic emission (AE), and hydraulic pressure.

There are two methods for conducting TCM: direct and indirect. Indirect methods have gained much acceptance compared to direct methods due to their cost-effective approach, and reliability (Heyns, 2007). Detailed discussions on the two methods as well as related studies for each method are presented in the following paragraphs.

a) Direct Methods

In direct methods, tool wear is directly measured on the tool cutting edge. Optical instrument and vision sensor are usually used to perform the measurement. In this method the wear scar is observed and quantified in some manner. The method provides an accurate representation of the amount of tool wear, however, it can be a time consuming process.

Several approaches can be found in the literature in quantifying the condition of worn tools. A weight-loss approach was applied to weigh the difference in tool weight before and after the experiment to determine tool wear (Englesson, 1964). This could be unreliable
based on the assumption that tools can be chipped or broken during the experiment. Work-piece material deposition can also occur on the tool, resulting in inaccurate measurement of the amount of weight loss.

**Edge recession** is another approach where linear measurements are taken on the clearance and rake faces of the tool, and the bisector of the knife angle. As the tool can wear unevenly along the cutting edge due to density variation of the materials being cut, many measurements are required to determine the amount of reduction of the tool cutting edge (Stewart, 1988).

Sheikh-Ahmad and McKenzie (1997) discussed several parameters namely **nose width, rake recession**, and **clearance loss** as wear measurements for quantifying tool dulling. Their results supported the hypothesis that the wear profile of the tool cross section assumes a characteristic shape and a fixed geometrical relationship exists between the different wear parameters. Therefore, the choice of which parameters to use is dependent on the simplicity and accessibility of measurement.

Gisip et al. (2009) quantified tool wear by subtracting the remaining clearance face from the original clearance face. Tool wear was then expressed as a percentage of the original clearance face area. With this type of approach, the original clearance face of the tool cutting edge might be different from one tool to another. This is due to grinding during the tool making process. The percentage of tool wear should be based on the original clearance face of each respective tool in which the real measurement was taken.

Kurada and Bradley (1997) discussed the application of machine **vision sensors** for TCM. Vision sensors provide a direct measurement of tool wear on the tool cutting edge. It characterizes tool wear through detecting the difference between the wear land and the unworn surface. It further described the three major components of a vision-based TCM system, i.e., illumination from a light source, video camera, and image digitization.

**b) Indirect Methods**

Indirect methods deal with measuring parameters that can be correlated with the tool condition. The parameters can be in the form of signals (e.g. force, power, acoustic
emission, tool temperature, and vibration) that are detected by sensors; and surface roughness.

Tool wear can be indirectly determined through measurement of the **cutting forces** of the tool with a dynamometer (Stewart, 1985; Sheikh-Ahmad and Bailey, 1999), and also monitoring of **power consumption** with power analysis equipment (Smith, 1996; and Englesson, 1964). These methods are used to indicate the presence of tool wear rather than quantifying it. Further studies have shown that other indirect approaches have made considerable progress for the past few decades.

**Vibration** monitoring for instance can successfully determine the wear state of tools. It is based on the premise that tool wear progression and breakage may affect the vibration response of the machine tool system, which can be observed using a vibration sensor (Heyns, 2007). While many researchers could not identify the source of the vibrations, they could establish a relationship between tool wear, and changes in the vibration signal (Lemaster et al., 2000a).

**Acoustic emission** (AE) was found to be sensitive to changes in the formation of the chip during the cutting process and thus, could be used to monitor a cutting process (Lemaster et al., 1985). The study observed that the AE output and the amount of the cutting of wood had a linear relationship particularly at the early stages of the tool dulling process. An asymptotic relationship was observed as the cutting tool became severely worn in which the AE levels had a significant drop.

Tool **temperature** was found to have a significant impact on the wear of cemented tungsten carbide tools when cutting particleboard and solid wood (Ratnasingam et al., 2010). Further, Ratnasingam et al. (2010) also found that there was a direct relationship between cutting forces and tool temperature. This suggested that as the tool edge wear area increased, both cutting forces and tool temperature were also increased.

**Surface roughness** can also be used to monitor tool wear based on the fact that tool wear affects the quality of the machined surface. Zeng et al. (2009) utilized areal surface characterization to monitor tool wear in peripheral milling. They used a set of areal surface roughness parameters to characterize the surfaces of machined workpieces in order to
evaluate the tool wear state. Measurements of both tool wear amount, and the machined surface were conducted after machining was done using a surface profiler (i.e. a device that is used to measure surface shape, texture, and contour in two and three dimensions).

In order to ensure reliable data are obtained, multi-sensor system or intelligent sensor can be applied. One of the things that can be done is sensor fusion, which as stated by Byrne et al. (1995), is the capability to combine outputs from different sensors in order to make a more robust decision. Bhar et al. (1997) combined an indirect method (i.e. capturing vibration signals with a piezoelectric accelerometer), and a direct method (i.e. a vision sensory system) to form a multisensory tool monitoring system for turning operations. They suggested that the combination presented a more accurate tool monitoring system. They found that a multisensory technique was proved to be reliable as the vision system was able to detect false signals received from the vibration sensor. Wang et al. (2007) combined sensors’ outputs from a direct sensor (vision) and an indirect sensor (force), which they called an intelligent integrated TCM. This sensor fusion was used for online TCM in a milling process. The vision sensor was used to verify tool breakage identified from the cutting force values. Based on the results, the sensor fusion scheme was found to be a feasible and an effective solution for online TCM.

2.3.4. Process Control: Proportional Integral Derivative (PID) Controller and Fuzzy Logic Controller (FLC)

Process control allows process parameters such as spindle speed, and feed speed to be automatically adjusted in order to optimize cutting process. Optimizing the cutting operation will result in increased productivity such as producing quality products in an extended period of time due to longer tool life. In the present study, the spindle speed was automatically adjusted based on a set value derived from the tool spindle vibration. Although other types of controllers were considered, a simple P controller was used as it showed enough improvement. The other techniques were PID controller, and fuzzy logic controller. Detailed discussion on these techniques is presented in the following paragraphs. Comparisons including strength and weaknesses are also discussed at the end of the section.
a) **Proportional Integral Derivative (PID) Controller**

Proportional integral derivative is the most commonly used control loop feedback controller due to its simple structure and simply understandable (Wu et al., 2002). It is popularly used in industrial processes (Kazemian, 2005), and also in chemical process industries (Yang et al., 2011). There are three basic elements in a PID controller, the words that form the name itself: proportional (P), integral (I), and derivative (D). The PID controller is an algorithm where the three elements perform different tasks in order to control the process. In summary, the PID control applies an algorithm, which considers the current location of the actual process from the desired one, and how far as well as how fast the actual process needs to go in order to reach the desired state (Masi, 1997). The following paragraphs provide detailed discussion of PID controllers.

As described by Airikka (2003), a PID controller works based on feedback in which the controller receives a measured process variable, and compares it with a setpoint. The difference between the process variable and setpoint is termed as the control error. Based on the control error value, the PID controllers perform a calculation that determines a correction that is fed to a control device, which then makes the necessary change on the process variable until it reaches the setpoint.

The PID controller is designed by determining the proportional gain, integral gain, and derivative gain. It can be used as a single controller such as a P controller, which is specifically for a proportional (P) control actions, an I controller for integral (I) control actions, and a D controller for only derivative (D) control actions. It can also be used as a combination of single controllers such as a PI controller or PD controller (Suh et al., 2008).

A block diagram of PID control is shown in Figure 2.3.1. The difference between the process output feedback, y, and the reference input or setpoint, r, produces the error, e. The PID controller produces the control output, u, which acts as the input of the process.
Equations 2.3.1 and 2.3.2 show the transfer function of a standard PID controller written in the “parallel form”, or the “ideal form” as found in Ang et al. (2005). The $T_I$ and $T_D$ can be further defined as shown in Equations 2.3.3 and 2.3.4 (Suh et al., 2008).

\[
G(s) = K_P + K_I \frac{1}{s} + K_D s
\]  \hspace{1cm} \text{Equation 2.3.1}

\[
G(s) = K_P \left(1 + \frac{1}{T_I s} + T_D s\right)
\]  \hspace{1cm} \text{Equation 2.3.2}

Where:
- $K_P$ = proportional gain
- $K_I$ = integral gain
- $K_D$ = derivative gain
- $T_I$ = integral time constant
- $T_D$ = derivative time constant

\[
T_I = \frac{K_P}{K_I} \hspace{1cm} \text{Equation 2.3.3}
\]

\[
T_D = \frac{K_D}{K_P} \hspace{1cm} \text{Equation 2.3.4}
\]

It is important to note that parameters from the standard PID controller are what are found in commercial PID controllers, and not the theoretical PID algorithm (i.e. proportional gain, P; integral gain, I; and derivative gain, D), however, both algorithms produce the same end results (VanDoren, 2009). Figures 2.3.2 and 2.3.3 illustrate the theoretical and standard PID controllers. It can be observed that the terms in both algorithms operate in parallel.
The terms from the theoretical PID algorithm can be related to the standard PID algorithm as presented in Equations 2.3.5 to 2.3.7 (VanDoren, 2009). The next paragraph discusses each of the controller elements (i.e. the P, I, and D) in details.
\begin{align*}
P &= K_p & \text{Equation 2.3.5} \\
I &= \frac{K_p}{T_I} & \text{Equation 2.3.6} \\
D &= \frac{K_p}{T_D} & \text{Equation 2.3.7}
\end{align*}

Each element of the PID controller has its own control actions. In the \textbf{proportional control}, or P control, the control error is compensated thru multiplying it by the proportional gain, known as \textbf{constant P} (Suh et al., 2008). The P control quickly reacts to a non-zero control error. It has a dominant effect whenever the control error is large, and goes away as the error reaches zero (Airikka, 2008). As the objective of PID control is to obtain a new setpoint as fast as possible (Masi, 1997), larger proportional gain is needed as it decreases the time spent to reach the setpoint.

A large gain means a large control effort is done to eliminate the errors between the process variable and setpoint. Although this reduces the error, this also reduces the control effort, hence, the process variable settles close to the setpoint. As the control effort becomes too small, a large gain can no longer generate control effort that is large enough to completely eliminate the error between the process variable and the setpoint (VanDoren, 2007). In order to deal with the situation, an integral action is needed, which can be provided by an integral control as described in the next paragraph.

The \textbf{integral control} (i.e. I control) integrates the control error over a period of time, and multiplies it with a \textbf{constant I} or the integral gain (Suh et al., 2008). The integral control reduces the control error until it becomes zero. The integral action is also known as automatic reset where the control effort is automatically increased proportional to the total of past errors (VanDoren, 2007).

In the \textbf{derivative control} or D control, the derivative gain, \textbf{constant D} is multiplied with the first calculated derivative (i.e. the slope of error). Faster response can be achieved with larger derivative gain, although it also resulted in increased variability (Suh et al., 2008). The derivative control responds to a rate of change in the process variable (Airikka, 2008). The derivative action dampens the control effort. As the P control tries to reach the setpoint, the I control will push the system, which may exceed the setpoint. The D control counteracts
these control efforts, and settles the process variable at the setpoint with minimum overshoot (Welander, 2010).

Designing the combination of the P, I, and D constants is what is called as the process of **tuning**. Specifically, the values of the tuning parameters of $K_P$, $K_I$, and $K_D$ are determined in order for the controller to eliminate an error. The main objective is to quickly reach the setpoint with little overshoot (Masi, 1997). Tuning is the hardest part in setting up a process-control feedback loop; however, automatic tuning has simplified the use of the PID control (Masi, 1997), which will be further discussed at the end of this section. Adequate gains must be set in order to avoid getting a system response, which is slow, contains oscillations, and less accurate. Some of the types of PID gain tuning methods are **Ziegler-Nichols**, and **relay** gain tuning.

The Ziegler-Nichols is a popular method that provides optimum settings for the tuning parameters. It determines the initial estimates of the parameters using a reaction-curve method (shown in Figure 2.3.4) before setting the controller’s gain according to the formula shown in Table 2.3.1 (Ziegler and Nichols, 1942).

Figure 2.3.4 Reaction curve of the Ziegler-Nichols method (Ziegler and Nichols, 1942).
Where:

$L = \text{lag or delay time}$

$R = \text{reaction rate (i.e. maximum rate that occurs at the point of inflection in the reaction curve)}$

**Table 2.3.1 Formula for the optimum settings of } K_P, K_I, \text{ and } K_D \text{ (Ziegler and Nichols, 1942).}**

<table>
<thead>
<tr>
<th>Controller</th>
<th>$K_P$</th>
<th>$K_I$</th>
<th>$K_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$\frac{1}{R_1L}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PI</td>
<td>$\frac{0.9}{R_1L}$</td>
<td>$\frac{0.3}{L}$</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>$\frac{1.2}{R_1L}$</td>
<td>$\frac{0.5}{L}$</td>
<td>$0.5L$</td>
</tr>
</tbody>
</table>

Note: $R_1 = \text{unit reaction rate}$

There is also **automatic tuning** that has been developed to automatically tune the gains (Suh et al., 2008).

The next section describes another type of controller; i.e. fuzzy logic controller (FLC), which has gained much acceptance in a wide range of applications.

**b) Fuzzy Logic Controller (FLC)**

Fuzzy logic controller (FLC) is based on **fuzzy logic**, which is a logical system that closely applies human thinking and natural language (Lee, 1990). It is based on fuzzy set theory, which was introduced in 1965 by Lotfi A. Zadeh of University of California at Berkeley (Cirstea et al., 2002).

Fuzzy set can be defined as a set of ordered pairs as shown below (Zimmerman, 2001; Chen and Pham, 2001):

$$\tilde{A} = \{(x, \mu\tilde{A}(x)) \mid x \in X\}$$
Where:

- $X$ = universe set
- $\tilde{A}$ = fuzzy set (a subset to the universe set $X$)
- $x$ = a member or an element in the universe set
- $\mu_{\tilde{A}}(x)$ = membership function or grade of membership associated with the fuzzy set
- $x \in X$ = $x$ is a member of $X$

In Figure 2.21, a fuzzy set can be differentiated from a classical set in terms of its boundary. In classical set theory, a universe of discourse or universe set, $U$, can be defined as a collection of objects with similar characteristics. Thus, elements with different characteristics are considered non-member elements, and this relationship is clearly defined with a definitive boundary of the classical set (Cirstea et al., 2002).

In Figure 2.3.5a, point $a$ is a member while points $b$ and $c$ are not members. Zadeh described a fuzzy set as a class that has unsharp boundaries in which membership is a matter of degree (Dumitras and Moschytz, 2007). This is illustrated in Figure 2.3.5b where point $a$ is a member, and point $c$ is not a member. Point $b$ is located on the boundary, thus, the extent of point $b$ belongs to the set can be determined by its membership function (Cirstea et al., 2002).

![Figure 2.3.5](image)

Figure 2.3.5 (a) Classical set boundary; and (b) fuzzy set boundary (Cirstea et al., 2002).
In a membership or characteristic function, each object is assigned a grade of membership with value that ranges from zero to one (Zadeh, 1965). All information in a fuzzy set is described by its membership function (Ross, 2009). Figure 2.3.6 describes the features of a membership function. The core represents a region that has a full membership in a fuzzy set; the support is a region characterized by non-zero membership; and the boundaries are a region in which elements have partial membership, i.e. having non-zero and not complete membership (Ross, 2009).

There are various types of membership functions with different shapes. It can be triangular, bell, or trapezoidal and these shapes are shown in Figure 2.3.7, with shapes in Figures 2.3.7a, 2.3.7c, and 2.3.7d are most commonly used (Cirstea et al., 2002).

![Figure 2.3.6 Membership function’s features of a fuzzy set (Ross, 2009).](image)
The objective of FLC is to control complex processes through human experience (Zimmermann, 2001). It uses an algorithm that converts a linguistic control strategy according to expert knowledge into an automatic strategy. It effectively captures the approximate of the real world (Lee, 1990). In FLC system, linguistic variables are used to describe the inputs and outputs, for example, ‘AGE’ is a linguistic variable that may have fuzzy sets (or linguistic values) ‘YOUNG’ and ‘OLD’ (Cirstea et al., 2002).

Figure 2.3.8 represents a general configuration or structure of a FLC. The three principal components are: (1) fuzzification unit; (2) inference engine built on the fuzzy logic control rule base; and (3) defuzzification unit (Chen and Pham, 2001).
**Fuzzification Unit**

The purpose of a fuzzification unit is to ensure the compatibility of the controller input with the fuzzy control rule base (Chen and Pham, 2001), which is located in the core of the FLC as shown in Figure 2.24. The crisp values of the control inputs are converted into fuzzy values that will enable them to be processed with the fuzzy set representation in the rule base (Cirstea et al., 2002).

**Rule Base**

The rule base serves as the control strategy of the FLC system. It is a set of linguistic description rules based on expert knowledge or heuristics, and expressed as a set of IF–THEN rules as follows (Lee, 1990):

IF (a set of conditions are satisfied) THEN (a set of consequences can be inferred)

The IF–THEN rules consist of antecedents and consequents, which are associated with the fuzzy inference concept; i.e. linguistic terms, thus, they are also known as fuzzy conditional statements (Lee, 1990). An example of a rule using linguistic variables is presented below (Cirstea et al., 2002):
IF error \((e)\) is Positive Big \((PB)\) THEN output \((u)\) is Negative Big \((NB)\)

In the above example, error \((e)\) and output \((u)\) are known as the linguistic variables; whereas Positive Big \((PB)\) and Negative Big \((NB)\) are known as the linguistic values. This is an example of rules that are interpreted using Mamdani’s implication technique, which is a type of fuzzy operation. It is also the most popular technique used in control applications (Cirstea et al., 2002). The fuzzy system can be multi-input-multi-output (MIMO) when the antecedents and consequents contain several linguistic variables. It can also be referred to as multi-input-single-output (MISO) for a fuzzy system with a multiple input and a single conclusion (Lee, 1990).

**Defuzzification Unit**

Defuzzification deals with converting the fuzzy values to crisp values. Defuzzification procedure is needed as most applications require non-fuzzy control actions. There are several methods for defuzzifying fuzzy outputs, and some of them are listed and illustrated in Table 2.3.2 below. The centroid method is the most prevalent one, and the weighted average method is the most frequently used as it is more computationally efficient. However, it is restricted to symmetrical output membership functions (Ross, 2009). Each method has its own advantages and disadvantages. Choosing a method over the other will be depending on the type of data that are available.
Table 2.3.2 Methods of defuzzification (Ross, 2009) (Note: $z^*$ is the defuzzified value).

<table>
<thead>
<tr>
<th>Method</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max membership principle (or height method)</td>
<td><img src="image1" alt="Max membership principle" /></td>
</tr>
<tr>
<td>Centroid method (also called center of area or center of gravity)</td>
<td><img src="image2" alt="Centroid method" /></td>
</tr>
<tr>
<td>Weighted average method</td>
<td><img src="image3" alt="Weighted average method" /></td>
</tr>
<tr>
<td>Mean max membership (or middle-of-maxima)</td>
<td><img src="image4" alt="Mean max membership" /></td>
</tr>
</tbody>
</table>
Table 2.3.2 Continued.

<table>
<thead>
<tr>
<th>Center of sums</th>
<th><img src="image" alt="Graph" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of largest area</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>First (or last) of maxima</td>
<td><img src="image" alt="Graph" /></td>
</tr>
</tbody>
</table>

c) **Comparisons between Proportional Integral Derivative and Fuzzy Logic Controllers**

This section discusses the applications as well as the advantages and disadvantages of PID and FL controllers. Both control schemes were being considered in the current study. The objective to apply a control scheme is simply to aid in the optimization of the cutting
process on a CNC router. A control scheme will allow the cutting of different materials, and enable the technique to work on other tool spindle designs.

With a control scheme, an operator can simply make adjustments based on analyzed sensor data, and change machining parameters such as rotational speed of the cutting tool to prolong its usable life. Since it is impractical to set a standard of cutting for different materials, a control scheme can act as a tool that can efficiently optimize the cutting operations.

The PID controllers are widely used with more than 90% of control loops implementing PID algorithms (Ang et al., 2005; Åström and Hägglund, 2001). The PID controllers are applied in process control, motor drives, automotive, flight control, and instrumentation to name a few (Åström and Hägglund, 2001). Conventional PID controllers require a lot of experience and conducting of experiments as it cannot be easily tuned (Eker and Torun, 2006). Automatic tuning had been created, and it has simplified the tuning process (Åström and Hägglund, 2001). A frequently suggested alternative for the PID control is FLC. The FLC is suitable for processes that are difficult to analyze by conventional techniques, as well as when the information is qualitative, inexact, or uncertain (Lee, 1990).

There had been some misconceptions about FL as discussed by Entemann (2002) such as FL is inconsistent, produces results that no human can accept, is too complex for practical use, and etc. However, FLC has been implemented extensively particularly in consumer products that are developed by the Japanese. As an example, a shower head that controlled water temperature was developed in 1987; and other examples of consumer products are dishwashers, washing machines, air conditioners, microwave ovens, cameras, camcorders, televisions, copiers, and automobiles (Perry, 1995).

Eker and Torun (2006) demonstrated that FLC can be used for controlling the speed of electrical drive systems where the FLC was able to achieve satisfactory speed control. They concluded the strengths of the FLC include fast response, less overshoot, and less settling time.
As both PID and FLC controllers have their own sets of strength and weaknesses, it is important to consider several factors in order to assess their suitability. Åström and Hägglund (2001) listed these factors such as performance, tuning, ease of use, and maintenance.

The next section discusses a subject on signal processing, which will provide a basic understanding on how signals are acquired, converted, processed, and analyzed. The analyzed data is a critical component in the monitoring, and control process for making decisions that ultimately can optimize the machining operation.

2.4. Signal Processing

2.4.1. Introduction

Knowledge in signal processing is crucial in order to gain a better understanding in the tool condition monitoring (TCM) field, particularly in the vibration monitoring process. Thus, this section explores the fundamental aspects of signal processing in six parts.

The first part is the data acquisition process, which introduces the process of acquiring data or signals as well as the components of a data acquisition system. The second part is analog signal processing that provides some basic descriptions of analog signals. The third part, which is on digital signal processing, covers the sampling process of analog signals, and the conversion of analog to digital signals.

The fourth and fifth parts are types of domains (i.e. time, frequency and joint time-frequency), and signal filtering (i.e. analog, digital, time versus frequency domain), respectively. The final part discusses order analysis, which is a signal processing technique for analyzing noise and vibration signals in rotating machines and shafts. A section devoted to order analysis is needed as it provides an in-depth information on the technique as its application will be a novel attempt, particularly in wood machining operations.

2.4.2. Data Acquisition

A signal can be defined as a measure of a physical quantity, which is detectable or measurable in which its magnitude varies with time (Pallás-Areny and Webster, 1999). It
can also vary with distance, temperature, rotational angle, etc. A signal is produced in the form of a continuous analog signal from a source such as machine vibration that can be detected using a vibration sensor (e.g. accelerometer). An analog signal, or a continuous-time waveform signal can be a mixed of impulse, sine wave, square wave, noise, etc. Sensors (or transducers) convert physical phenomena such as vibration, temperature, or pressure into electrical quantities such as voltage or current, which are continuous analog signals.

Signals can be classified as **analog** and **digital**. Figure 2.4.1 illustrates the difference between an analog signal, and a digital signal. An analog signal has a continuous characteristic, and it is converted into digital signal through a process called analog-to-digital conversion (ADC). A digital signal consists of binary digits of ones and zeros. The ADC process is elaborated in details in later section. As in the case of digital signals that are simulated in a computer, the signals are not converted from analog signals, since a computer only works with digital data. Further explanations of the nature of both analog and digital signals are covered in their respective part.

![Figure 2.4.1 Illustration of the difference between analog and digital signals. The amplitude of $x[n]$ has infinite precision, whereas $x_d[n]$ has finite precision $\Delta$ amplitude (Manolakis and Ingle, 2011).](image-url)
The acquisition of data is one of the main stages in the TCM process. The data acquisition (DAQ) process deals with sampling analog signals and converting the signals into digital form that can be manipulated by a computer.

A DAQ system consists of: (1) sensors; (2) signal conditioning; (3) DAQ hardware, (4) computer, and (5) software. Sensors measure a physical quantity (e.g. vibration and temperature), and convert it into an electrical signal (e.g. voltage and current). Signal conditioning “manipulates” the signals from the sensors in some form such as amplification or analog filtering of signals, into appropriate forms before being digitally converted. The DAQ hardware includes an analog-to-digital (A/D) converter, which digitizes the analog signals from the sensors to be processed on a computer. A computer is used for collecting data or measurements, visualizing the collected data, performing analysis, and storing the data. Software is the interface between the computer and the DAQ hardware, and enables the analysis and presentation of data. Programming languages such as BASIC, C++, FORTRAN and, Java are used to develop the programs. Graphical programming languages such as Visual Basic®, MATLAB® and, LabVIEW™ can also be used for building the software for the DAQ systems.

Knowledge on the types of signals is imperative prior to discussing the signals conversion process. The next part discusses the first type of signals, which is an analog signal.

2.4.3. Analog Signal Processing

As mentioned in the previous section, signals can be characterized as either analog or digital. Signals from the real world come in analog form. For ease of clarification, consider an analog signal, which is denoted as \( x(t) \). The analog signal has a continuous independent variable (usually time), and its amplitude (i.e. dependent variable) can take any value of a continuous range. This is why an analog signal can also be referred to as a continuous-time signal.

Additionally, analog signals can be either direct current (DC) or alternating current (AC). By definition, DC is a current that flows steadily in one direction, while AC is a
current that flows back and forth in a conductor (Herman, 2007). The DC and AC can be distinguished based on the type of its sources. The DC has a fixed polarity with two terminals, much like a battery that has positive and negative terminals. Polarity is absent in AC sources (Herman, 2007). Figure 2.4.2 shows a comparison between the DC and AC signals.

![Comparison between DC and AC signals](image)

Direct current

Alternating current

Figure 2.4.2 Comparison between DC and AC signals.

Direct current is applied to batteries, all electronic devices, and industrial application such as adjustable speed drives (Herman, 2007). The AC is the most commonly used form of electricity delivery system. It is generated and offered commercially by public utilities to both average consumer, and industrial applications (Herman, 2007).

The AC signals can be periodic or transient, and periodic signals can be further characterized as either narrowband or broadband based on their frequency range (Pallás-Areny and Webster, 1999). Analog signals can be processed to meet certain needs as in the conversion of signals from analog to digital, and voltage to current and vice versa. Other processes that are involved when processing analog signals include minimizing interference, and reducing noise in the signals through the utilization of analog filters.
As the current research was mainly dealing with analyzing, and representing data using a computer, the next part discusses the nature of digital signals, and the process of converting analog signals to digital.

2.4.4. Digital Signal Processing

Signals that are acquired directly from a machine are considered raw signals. Important information is embedded in these raw signals, thus, they need to be processed, and manipulated in order to remove unwanted signal components (i.e. noise) that might be present. Following is a detailed discussion on how analog signals are converted into digital signals.

**a) Conversion Process of Analog to Digital Signals**

An analog signal must be converted to digital format in order for it to be processed by a computer through a process called analog-to-digital conversion (ADC). A continuous-time analog signal \( f(t) \) is sampled at **regular time intervals**: \( nT \) \( (n = 0, \pm 1, \pm 2, \ldots) \), which eventually produces a **discrete-time signal** or also known as **analog sampled-data signal** as illustrated in Figure 2.4.3 (Baher, 2001). The signal may be represented with as a sequence of numbers (Baher, 2001):

\[
\{ f(nT) \} \equiv \{ f(0), f(\pm T), f(\pm 2T), \ldots \}
\]

The next step is quantizing the discrete-time signal where the **amplitude** is converted into a discrete value. Each \( f(nT) \) is assigned with a quantization level value to form a new quantized sequence \( \{ f_q(nT) \} \) as illustrated in Figure 2.4.4. The final step is encoding where each member in the quantized sequence is represented by a code, which is usually a **binary** code (Baher, 2001) (Figure 2.4.5).
Figure 2.4.3 Discrete-time (or analog sampled-data) signal (Baher, 2001).

Figure 2.4.4 Quantization levels of the sampled signal (Baher, 2001).

Figure 2.4.5 Digitized analog signal (Baher, 2001).
An analog-to-digital (A/D) converter is a device that is used to sample the signal, then quantize and code it, which finally produces a digital signal. Resolution is a very important aspect of the A/D converter, thus the A/D converter is specified by its **amplitude resolution** in terms of how many **bit** (i.e. binary digits of ones and zeros) such as 8-bit, 12-bit, 16-bit, and etc. due to the fact that computer processing only functions with binary numbers (i.e. 0, 1). The higher the resolution means a smaller change of voltage can be detected. An illustration (adapted from Pallás-Areny and Webster, 1999) of the ADC process is presented in Figure 2.30. In the figure, an output code is assigned to each amplitude value or **quantization interval** $q$ (i.e. least significant bit or LSB). The quantization interval can be expressed as below:

$$q = \frac{V_{ir}}{2^n}$$

where $V_{ir}$ is the full scale voltage range that can be coded by the A/D converter, $2^n$ is the total number of the output codes, and $n$ is the resolution of the A/D converter in bits (i.e. binary digits). Thus, the quantization interval for a 3-bit A/D converter in Figure 2.4.6 for an input range from 0 V to 10 V is $q = \frac{10 \text{ V}}{2^3} = 1.25 \text{ V}$.

![Figure 2.4.6 Conversion of a sine wave into digital form using a three-bit A/D converter](image)

(Pallás-Areny and Webster, 1999).
The quantization interval $q$ is also known as the **least significant bit (LSB)**, which is the minimum increment of voltage that an A/D converter can convert. The LSB value can be varied depending on the operating input voltage range of the A/D converter. Therefore, when it is required to detect smaller changes in voltage, an A/D converter with higher resolution is needed. As an example, for an input range of 10V, a 12-bit gives 4096 levels or intervals, resulting in an LSB, $q = 10 \text{ V}/2^{12} = 0.0024 \text{ V}$. Meanwhile, a 16-bit resolution gives 65536 levels, and an LSB, $q = 10 \text{ V}/2^{16} = 0.00015 \text{ V}$. Thus, a 16-bit A/D converter is able to detect smaller increments of the input signal.

b) **Sampling Theorem**

In order to sufficiently reconstruct the original analog signals, one must implement the **sampling theorem**, which states that the **Nyquist sampling rate** $f_s$ should exceed twice the **highest signal frequency** $f_{\text{max}}$. Another way to define it is that the highest frequency should be less than half the sampling rate, termed the **Nyquist frequency** as denoted below:

$$f_{\text{max}} = f_s/2$$

If the sampling rate is less than the Nyquist rate, a phenomenon called **aliasing** will occur. These two phenomena (i.e. sampling at Nyquist rate, and inadequate sampling, which causes aliasing) are discussed in the next topic. In order to sufficiently reconstruct an analog signal, the sampling rate and the number of samples to be taken from the entire signal must be adequate. **Sampling rate** refers to the number of samples per unit time (usually second) taken from a continuous analog signal to form a discrete signal. It can be expressed in **Hertz** (cycles per second, abbreviated as Hz) or **samples per second** (Sa/s).

Additionally, the $f_s$ is also defined as an inverse second, i.e. $1/T_s$, 1/s or s\(^{-1}\). Thus, the inverse of $f_s$ is $T_s$, or known as the **sampling period** or **sampling interval**, which is the time between samples. As stated earlier, the sampling rate should be at least twice the highest frequency component. As an example, if the highest frequency from an analog signal that a sensor can detect is 20,000 Hz, the sampling rate or sampling frequency should be at least
40,000 Hz (20,000 Hz × 2). However, a higher number is usually adopted in order to adequately sampling the signal especially for a rapidly varying signal (Orfanidis, 1996). Therefore, from the previous example, 200,000 Hz is a better sampling rate for a sufficient reconstruction of the original analog signal. The **number of samples** refers to the total samples obtained from an analog signal. Table 2.4.1 shows typical sampling rates for common DSP applications.

<table>
<thead>
<tr>
<th>application</th>
<th>( f_{\text{max}} )</th>
<th>( f_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>geophysical</td>
<td>500 Hz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>biomedical</td>
<td>1 kHz</td>
<td>2 kHz</td>
</tr>
<tr>
<td>mechanical</td>
<td>2 kHz</td>
<td>4 kHz</td>
</tr>
<tr>
<td>speech</td>
<td>4 kHz</td>
<td>8 kHz</td>
</tr>
<tr>
<td>audio</td>
<td>20 kHz</td>
<td>40 kHz</td>
</tr>
<tr>
<td>video</td>
<td>4 MHz</td>
<td>8 MHz</td>
</tr>
</tbody>
</table>

c) **Aliasing**

**Aliasing** is a term referring to a signal with high-frequency components having low frequencies due to inadequate sampling rate (Bergland, 1969). It misrepresents the true form of the original analog signal. The following figures illustrate the aliasing phenomenon in greater detail. A LabVIEW™ program (program name: *Sampling Theorem.vi*) is used to provide the illustrations. Figure 2.4.7 shows a 5 Hz sine wave (green line) digitized by a 7 samples per second ADC. The calculated ratio of sampling frequency per signal frequency is 1.4. The signal is inadequately sampled resulting in an aliased signal (yellow line) due to **undersampling**. The aliased signal can also be seen in the power spectrum graph (i.e. a **frequency representation** of the time-varying analog signal).
In Figure 2.4.8, the same 5 Hz signal is sampled at about twice the signal frequency, i.e. 11 Hz. This has resulted in an adequately sampled signal; however, the reconstructed signal is still not exact and complete as compared to the true form of the original signal. When using sampling rate of 10 times of the 5 Hz signal, the sampling process takes 50 samples per second resulting in a reconstruction of the original signal (Figure 2.4.9).
It should be noted that, the minimum sampling rate (i.e. at least twice the highest frequency) should meet a requirement as illustrated in Figure 2.4.10. As illustrated, a sinusoid with a frequency $f$ has been sampled at three different rates, which refer to taking 8, 4, and 2 samples per cycle. It can be concluded that the minimum acceptable number of samples per cycle for a successful reconstruction of a sine wave is two, provided that the sampling is at the peaks and not at the zero crossings. The number of samples per cycle can be determined using the calculation below:

$$f_s = \frac{\text{samples/sec}}{\text{cycles/sec}} = \frac{\text{samples}}{\text{cycle}}$$

Figure 2.4.10 Sampling of sinusoidal signals at sampling rates $f_s = 8f, 4f, 2f$ (Orfanidis, 1996).
These digital signals are expressed and analyzed in domains such as the time and frequency domains. Other domains include joint time-frequency domain, spatial domain, and wavelet domain. For the purpose of this study, three types of domains: time, frequency, and joint-time frequency are presented in the following section.

2.4.5. Domains in Digital Signal Processing: Time, Frequency, and Joint Time-Frequency Domains

Signals can be analyzed, and represented in several domains. In this section, three types of domains namely time, frequency, and joint-time frequency are discussed.

a) Time Domain

The time domain representation provides the value of the signal for all times (Stein, 2000). In the time domain, one can observe how a signal changes in amplitude over time (Winder, 2002). Figure 2.4.11 shows an example of a signal in which its amplitude is plotted against time. The amplitude, which is on the vertical axis, can represent the voltage, current, acceleration, displacement, or force. A signal that is viewed in the time domain is called a time waveform signal.

![Figure 2.4.11 Analog signal in time domain (Winder, 2002).](image)
The time domain is commonly used for signal processing in various work related to machines. In a study by Tarng (1993) that developed a sensor system to detect tool breakage in NC milling, time domain was used to monitor the changes in the cutting-force signal pattern. A vibration analysis study by Orhan et al. (2007) on tool wear evaluation used time domain to illustrate raw vibration signals as viewed in a waveform graph. A certain pattern can be seen in the waveform graph.

b) Frequency Domain

In the frequency domain representation, the harmonic content (i.e. multiple of the fundamental frequency) of the signal at every frequency is shown in a form of spectrum (Stein, 2000). The signal is viewed where the horizontal axis (x-axis) is expressed in frequency instead of time, and the vertical axis (y-axis) is the amplitude. A signal that is viewed in the frequency domain is called a spectrum. A time waveform signal is a composite or sum of signals at varying frequencies. It might be of interest to see the individual component of the signal with its respective frequency. Thus, presenting the signal in the frequency domain gives the frequency component of the individual signal.

An algorithm is used to transform the discrete signal in the time domain into its discrete frequency domain representation. A common algorithm to perform the task is the fast Fourier transform (FFT), which will be discussed later in this section. Figure 2.4.12 shows the frequency domain representation (using FFT) of the time waveform signal shown in Figure 2.4.11, which can be seen as having a single peak representing a single frequency in the time signal.
A better overall view of what a time waveform signal is composed of can be found in Figure 2.4.13. The illustration shows the original time waveform signal as a sum of several frequency components. The fundamental frequency (i.e. the lowest frequency or the first harmonic) is denoted as $f_0$, the second harmonic at frequency $2f_0$, and the third harmonic is at frequency $3f_0$. 
In order to obtain more information of a signal, a waveform graph in the time domain is usually converted to frequency domain by FFT, and it is called a spectrum graph. Orhan et al. (2007) conducted a vibration analysis, which used the frequency domain to detect tool wear changes throughout a cutting process. This was done through observing the amplitudes at certain frequencies, where an increase in vibration amplitude reflects an increase in tool wear.

The next part presents a discussion on algorithms that are used to transform a time domain signal to its frequency domain representation.

c) **Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT)**

**Fourier analysis** was discovered by Jean Baptiste Joseph Fourier (1768-1830), and Fourier series and Fourier integral are mathematical tools for Fourier analysis. The Fourier series was first introduced in 1822 to demonstrate the application of a mathematical series of sine and cosine terms in analyzing heat conduction in solid bodies (Ramirez, 1985).

Fourier analysis consists of mathematical techniques that are used to decompose signals into sinusoids in which time-domain waveforms are transformed to frequency domain (Ramirez, 1985). **Fourier transform** is a general term, which consists of four categories that are characterized based on the four basic signal types: continuous, discrete, periodic, and aperiodic (Smith, 2003). In relation to signals, these terms carry the following meanings: continuous means a signal that is in a form as a whole, and uninterrupted; discrete means separated; periodic is occurring at regular intervals, in which the same pattern of variation occurring repeatedly (Winder, 2002); and aperiodic means non-periodic or irregular.

The four possible signal types combinations of the Fourier transform are namely (1) Fourier transform with signals that are continuous and aperiodic, (2) Fourier series with signals that are continuous and periodic, (3) discrete time Fourier transform with signals that are discrete and aperiodic, and (4) discrete Fourier transform or DFT with signals that are discrete and periodic. Since DFT is specifically used with digitized signals, it is the only
type of Fourier transforms that find application in digital signal processing (Smith, 2003). Table 2.4.2 illustrates the four types of the Fourier transforms.

Table 2.4.2 Fourier transforms (Smith, 2003).

<table>
<thead>
<tr>
<th>Type of Transform</th>
<th>Example Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourier Transform</td>
<td></td>
</tr>
<tr>
<td>signals that are continuous and aperiodic</td>
<td></td>
</tr>
<tr>
<td>Fourier Series</td>
<td></td>
</tr>
<tr>
<td>signals that are continuous and periodic</td>
<td></td>
</tr>
<tr>
<td>Discrete Time Fourier Transform</td>
<td></td>
</tr>
<tr>
<td>signals that are discrete and aperiodic</td>
<td></td>
</tr>
<tr>
<td>Discrete Fourier Transform</td>
<td></td>
</tr>
<tr>
<td>signals that are discrete and periodic</td>
<td></td>
</tr>
</tbody>
</table>

The DFT takes a discrete signal in the time domain and transform it into its discrete frequency domain representation. The DFT is extensively applied in vast fields such as spectral analysis, instrumentation, telecommunication, and etc. The transformation can be calculated in three ways namely simultaneous equations, correlation and the fast Fourier transform (FFT). The FFT is the most common method to calculate DFT due to its efficiency and significantly reduced computation time. Thus, in this dissertation, the discussion will be limited to the FFT.

The invention of digital computers has made it possible for FFT to be put into practical use. The FFT was first introduced in a paper written by Cooley and Tukey (1965). They demonstrated how the algorithm differs from previous algorithm when dealing with Fourier series particularly the evaluation of the DFT. The massive reduction in computation
time is achieved by calculating the DFT coefficients iteratively (Cochran et al., 1967). It uses $N \log_2 N$ as a way to reduce the number of computations. The cosine and sine functions have periodic properties that can be manipulated in order to eliminate redundancies (Guo et al., 1998).

In FFT, the first step involves the decomposition of $N$ point time domain signal into $N$ time domain signals, which consist of a single point in each signal. Next, $N$ frequency spectra for the time domain signals are calculated, and finally, the $N$ spectra are synthesized into a single frequency spectrum (Smith, 2003). The structure of the time domain decomposition in FFT is demonstrated in Figure 2.4.14.

When squaring the FFT’s magnitude, it produces what is known as the **power spectrum**, which can be used to characterize the energy distribution of a signal in the frequency domain (Qian and Chen, 1996). An example is shown in Figure 2.4.15. The figure shows a power (or frequency) spectrum of a vibration signal. Several peaks can be observed in which the frequency component with the highest amplitude is located within the 5,500 Hz to 6,500 Hz frequency band.
Signals can change their frequency content over time. As this change cannot be identified in the time waveform signal, and the DFT or FFT, a different domain is needed. The domain is a combination of the time and frequency domains called joint time-frequency.

d) **Joint Time-Frequency Domain**

In the joint time-frequency domain, a technique known as **joint time-frequency analysis (JTFA)** is used. It is a different approach to frequency analysis in which a signal is analyzed in both time and frequency domains simultaneously. It can closely track a changing spectrum over time. Thus, the main objective of JTFA is to identify how each frequency component changes over time.

**Short-time Fourier transform (STFT)** is used to perform JTFA through observing its spectrogram. The STFT spectrogram represents the energy distribution of a signal in the
joint time-frequency domain (Qian and Chen, 1996). As regular Fourier transforms do not have a time-varying nature of a signal, STFT solved this deficiency (Qian and Chen, 1996). The STFT has a window function, which is applied to a signal in segments. The size or width of the window must be short enough where it determines the temporal resolution of the time-frequency analysis (Nuruzzaman et al., 2006). Figure 2.4.16 illustrates how STFT is calculated. The STFT has a window function denoted as $\gamma(t)$. The function is multiplied with signal $s(t)$, and the Fourier transform is produced from the product of the multiplication. The short time duration property of the window function signifies the signal’s local frequency properties. The calculation process is repeated by moving the window function across the signal in order to see the evolution of the frequency contents of the signal over time (Qian and Chen, 1996).

![Short-time Fourier transform process](image)

Figure 2.4.16 Short-time Fourier transform process (Qian and Chen, 1996).

Figure 2.4.17 illustrates the advantage of JTFA over traditional time domain, and frequency domain analysis where two signals having frequency components of 30 Hz, and 80 Hz are represented in the three domains. As shown in the time domain, the first signal (on the left column) has its frequencies occur at a different time while the signal on the right
column has its frequencies occurs simultaneously. The frequency representations of these two cases are similar as depicted in the middle portion of the figures (i.e. power spectrum graphs). Meanwhile, using JTFA (bottom figures), the spectrograms of the STFT clearly show two lines referring to the frequency components in each signal.

Figure 2.4.17 Two signals (left and right), which composed of two frequency components (at 30 Hz and 80 Hz) are represented by its time domain, frequency domain, and joint time-frequency domain (top, middle, bottom, respectively) (graphs were generated with LabVIEW™ program).

The STFT has several shortcomings such as its window length, and also it is computationally expensive (Rao, 1996). The window length or size affects the time resolution and frequency resolution of STFT. A short window produces higher time resolution with poor frequency resolution. On the other hand, a long window generates high frequency resolution with low time resolution.
As mentioned earlier, signals that are acquired from sensors are raw signals in time domain, which contain noise and unwanted frequencies that have yet to be removed and analyzed. They need to be manipulated in order to extract important information. One of the most important processes is filtering, which deals with eliminating unwanted signal components. The next portion of this section discusses the filtering process as well as windowing function that need to be conducted on a signal.

2.4.6. Signal Filtering: Analog, Digital, and Time Domain versus Frequency Domain Filters

Filtering is a vital process in signal processing. Smith (2003) listed two general purposes of filtering: (1) separation of combined signals, and (2) restoration of distorted signals. Signal separation is a process of removing frequencies that are considered as noise or interference from an incoming signal or to isolate a particular frequency of interest. Important information in the signal of interest can be easily detected, and analyzed through a successful application of filtering. In addition, signal restoration can be accomplished on a distorted signal, as an example, restoring a low quality audio recording that is produced with poor equipment by filtering to improve the sound (Smith, 2003).

Filters can be classified in several ways such as either analog or digital, linear or non-linear, passive or active, and etc. These classifications can be overlapped (e.g. passive or active analog filter, linear or non-linear digital filter). The primary discussion on filtering in this dissertation is on analog filters, digital filters, and filters in the time and frequency domains. A general discussion on filtering is presented first to aid in the understanding of the filtering concepts.

Figure 2.4.18 shows an ideal lowpass filter, which is commonly described as a “brick wall” (note: lowpass filter is defined later in the following paragraphs). As illustrated, the ideal shape has a steep change in its frequency response in which all signals below the cut-off frequency (also known as cut-off point and corner frequency) are allowed to pass through, while those above it are completely blocked (i.e. no gain in signal).
Different types of filters are used in signal processing. In the frequency domain, when different signal frequencies pass through a filtering system, their **frequency response** or **gain curve** can be graphically presented as shown in Figure 2.4.19. As illustrated, the gain curve is composed of several frequency bands: **passband** is a range of signal frequencies that are allowed to pass through a filter; **stopband** contains a range of signal frequencies that are blocked or attenuated (i.e. reduction in the signal’s amplitude); and **transition band** (or transition region) that links the passband and the stopband where it rolls off or reduced the gain of a signal. Another important term called **cut-off frequency** $f_c$, which is a frequency that sets the limit of the filter range.
Figure 2.4.20 shows the shape of the gain curve in a practical setting where instead of getting a flat gain, the passband exhibit some **ripple** or fluctuations (measured in dB), and the stopband contains some **droop**. Filters can be designed appropriately in order to reduce the amount of fluctuations in the gain response. There is always some form of tradeoff such as performance, speed, accuracy, and ripple. As an example, digital filters can produce a flat passband as opposed to analog filters, which depend on the accuracy of its resistors and capacitors to adjust the flatness in the passband. However, the downside is, digital filters are slow (Smith, 2003). Additionally, filters that have a steeper roll-off will have more ripples in the passband region.

![Diagram showing fluctuations in the filter gain response](image)

**Figure 2.4.20 Fluctuations in the filter gain response (Déziel, 2001).**

As described in the DFT and FFT section, a signal power spectrum exhibits the power or energy distribution of a signal across different frequency bands. Frequency bands that contain a high power or amplitude signify its importance. When a signal passes through a filter, there is a 3 dB (i.e. half-power point or 50% power level) reduction in the signal amplitude as illustrated in Figure 2.4.21. The relationship between the signal’s gain, power, and amplitude is important. Different filter types can be used to obtain a specific gain curve whereby the shape of the gain curve determines the amplitude of the signal. Since the power is proportional to the square of its amplitude, the amplitude of a 50% power level can be calculated as \( \sqrt{0.5} = 0.707 \) (i.e. –3 dB).
A filter can be classified based on its gain shapes as can be found in Figure 2.4.22. **Lowpass filters** (Figure 2.4.22a) allow low frequencies below the cut-off frequency limit $\omega_c$ to pass through the filter, and blocked the upper frequencies that are beyond the stipulated limit. **Highpass filters** (Figure 2.4.22b) block all frequencies below the cut-off point. **Bandpass filters** (Figure 2.4.22c) set a range for the frequency bands to pass through, which is between the low frequency limit $\omega_{c1}$ and high frequency limit $\omega_{c2}$. **Bandstop filters** (Figure 2.4.22d) only allow the frequency components outside the range of $\omega_{c1}$ to $\omega_{c2}$ to pass through.
Signals can be filtered using analog or digital filters. Both filter types can also be used in combination in the DAQ process whereby an analog filter performs as an anti-aliasing filter (i.e. a low-pass filter that removes unwanted signals from the ADC input at a specified cut-off frequency), and a digital filter is used to filter the signal that is coming out from the A/D converter. The paragraphs that follow describe these two types of filters in details. In this particular research, digital filter was used as the data can be stored prior to filtering, and the original signal can be restored for further analysis.

**a) Analog Filters**

Prior to the invention of digital filters, signals were first processed with analog filters in order to separate meaningful frequencies from unwanted ones. Analog filters utilize electronic components such as resistors, capacitors, transistors, and diodes. Thus, the
accuracy of the analog filters relies on the performance of these components. The components may fluctuate overtime, and this could cause errors in the analog filters. The analog filters are usually required for anti-aliasing in data acquisition systems.

Common analog filters are Chebyshev, Butterworth, and Bessel, which were named after the individuals who developed them. As shown in Figure 2.4.23, each of the filters has its own characteristic that distinguishes itself from the other filter types. It can be observed that these filters can be characterized by their passband, stopband, and transition band response. Both Bessel and Butterworth filters show a smooth passband as well as the stopband while Chebyshev filter has ripples on its passband. The number of poles shown in the figure is also known as the order of the filter. It affects the bandwidth of the transition band in which more poles will produce smaller transition bandwidth (Baker, 1999).

Other variants of passband and stopband combination are those with ripples on the stopband (e.g. inverse Chebyshev), and those having ripples on both the passband and stopband such as in the Cauer (or elliptic) filter.
Due to its high accuracy, and easy to design, the current study applied a digital filter to perform filtering on the acquired signal. Raw signals were saved, and run through the digital filter in order to analyze specific frequencies. The next part discusses digital filters in greater detail.

b) Digital Filters

Digital filters are one of the most important components in digital signal processing. The area of digital filtering was introduced as a result of earlier work in sampled-data control systems (Jackson, 2004). Earlier implementation of digital filters was not widespread due to their complexity, and the cost involved (Jackson et al., 1968). However, the invention and rapid development of integrated circuits as well as increase speed and power of affordable
computers have provided the possibilities of producing digital filters that are low in cost, small in size, and reliable.

A digital filter performs mathematical operations on a discrete-time signal resulting from the ADC process. The implementation of digital filters is conducted in two stages (Young, 2001): (1) **determination of the filter specifications** (e.g. cut-off frequency, roll-off rate, stopband attenuation), which produces a set of filter coefficients (i.e. list of numbers that contain key information to build a filter); (2) **performing the actual filtering** using the calculated filter coefficients. Designing digital filters involve mathematical calculations that can be automatically performed by a computer. Programming software such as LabVIEW™ is able to calculate the coefficients, and then provide the values directly to the filter to be implemented.

Two basic types of digital filters are: (1) **finite impulse response (FIR) filters** and (2) **infinite impulse response (IIR) filters**. These classifications are based on each filter’s impulse response. An impulse response can be described as the reaction (or response) of a system after receiving an input such as signal pulses. The impulse response of a FIR filter has a finite duration of non-zero input values whereas the IIR filter’s impulse response has an infinite duration (Litwin, 2000).

The FIR filters have a **linear phase** and a constant **group delay** (i.e. the time for a signal to pass through a filter). These characteristics are important to ensure that the signal is not distorted. Table 2.4.3 presents a summary of the main differences between FIR and IIR digital filters in that contradictory to the IIR filters, the FIR filters are easy to design, and more stable. However, they are computationally intensive. Its linear phase response characteristic is one of the main reasons for it to be applied in the filtering process. Linear phase means that a filter’s phase response has a linear function of frequency.
Table 2.4.3 Main differences between FIR and IIR digital filters (Young, 2001).

<table>
<thead>
<tr>
<th>Finite Impulse Response Filters</th>
<th>Infinite Impulse Response Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relatively easy to design</td>
<td>Relatively difficult to design</td>
</tr>
<tr>
<td>Stable</td>
<td>Unstable if not properly designed</td>
</tr>
<tr>
<td>Large number of filter coefficients</td>
<td>Small number of coefficients</td>
</tr>
<tr>
<td>Linear phase response</td>
<td>Non-linear phase response</td>
</tr>
</tbody>
</table>

The Fourier transform method (or windowing or windowed-sinc method) is a common method to design FIR filters. The Fourier transform method truncates the impulse response of the digital filter in the time domain. The term truncation is also known as **windowing**. Figure 2.4.24 illustrates the effect of windowing when applied to a waveform signal. Samples from the input time are multiplied by a window function in order to bring the signal to zero at the edges of the applied window, and prevent a **spectral leakage**. The occurrence of discontinuities at the data window endpoints cause a spectral leakage in the frequency domain as depicted in Figure 2.4.25. It is due to the fact that periodic signals are required for the application of the FFT algorithm. A signal that is produced from non-integer samples causes discontinuities in the FFT periodic signal, where the energy from a signal frequency bin enters or ‘leaks’ into the adjacent frequency bins (Aeroflex, Inc., 2005).
Figure 2.4.24 Application of a window function to a signal (Kester, 2003).

Figure 2.4.25 Non-integral number of cycles in the data window causing spectral leakage in the frequency domain (Kester, 2003).
Figure 2.4.26 shows how the windowed-sinc method is applied (note: the word sinc in the windowed-sinc phrase refers to the use of the sinc function in the method). A frequency response of an ideal lowpass filter is shown in Figure 2.4.26a, and its corresponding impulse response is shown in Figure 2.4.26b. The FIR filter truncates the signal, which causes discontinuities at the endpoints of the impulse response (Figure 2.4.26c). The discontinuities cause poor side lobe performance (or tails as can be found in Figure 2.50c). A window function is applied to the truncate impulse response, and brings the endpoints to zero (Figure 2.4.26d). The corresponding impulse response after the window function is shown in Figure 2.4.26e, and the final frequency response is shown in Figure 2.4.26f.

Several common window types include rectangular, triangular (Bartlett), Hanning, Hamming, Blackman-Harris, and Kaiser-Bessel. These windows have different
characteristics, and are selected based on different applications. Figure 2.4.27 illustrates three common window types, i.e., rectangular (no window), Hamming, and Blackman. It can be seen that the differences between the windows lie on the sizes of the main lobe, and tail (or sidelobe).

![Diagram of window types](image)

**Figure 2.4.27** Frequency response of some common window types: (a) rectangular, (b) Hamming, and Blackman (Kester, 2003).

The filter responses can be represented in the time and frequency domain. This is further discussed in the next topic.
c) **Time versus Frequency Domains Filters**

As signal can be represented in the two domains namely time and frequency, filters also can be used in both domains. In the time domain, digital filters can be used to perform smoothing (i.e. low-pass filtering), that reduces random noise. In the frequency domain, the filters are used to separate one band of frequencies from another through extracting information from sinusoids components such as the amplitude, frequency, and phase (Smith, 2003). Each domain has their own set of parameters that are important when considering the filter designs.

In the time domain, three important parameters are **transition speed** (or risetime), **overshoot**, and **phase linearity** (Smith, 2003). The risetime is related to the **step response** (note: step response is produced through the integration of the impulse response) that shows how well the filter performance is. When an input is a step, the output is called step response.

Important parameters that are used to evaluate filters’ performance in the frequency domain are **roll-off sharpness**, **passband ripple**, and **stopband attenuation** (Smith, 2003). Figures 2.4.28 and 2.4.29 illustrate how the parameters are used to evaluate and measure filters’ performance in the time domain, and frequency domain, respectively.
Figure 2.4.28 Parameters used in the time domain for filter’s performance evaluation: (a and b) transition speed, (c and d) overshoot, and (e and f) phase linearity (Smith, 2003).
Figure 2.4.29 Parameters used in the frequency domain for filter's performance evaluation: (a and b) roll-off sharpness, (c and d) passband ripple, and (e and f) stopband attenuation (Smith, 2003).

The next topic discusses a method of analyzing vibration signals called order analysis.
2.4.7. **Order Analysis**

The present study deals with the monitoring of the tool condition on a CNC router. The tool shaft rotation produces vibration that can be detected by acquiring its signal. The vibration signals can then be analyzed in order to determine the tool condition.

In vibration analysis study, FFT analysis is commonly used to transform vibration signals from the time domain to the frequency domain. However, the FFT analysis cannot detect mechanical characteristics with changes in spindle speed. Order analysis is a technique for analyzing noise and vibration signals produced by rotating or reciprocating machinery. It obtains the instantaneous speed of a machine’s rotating shaft from a tachometer signal.

The vibration from the rotational speed of the tool shaft can be represented in the frequency domain. The harmonics nature of the frequency domain can also be related to the rotational speed, which can be referred to as orders. Thus, the first order is the harmonic at the same frequency of the rotational speed; the second order is the harmonic at twice the frequency of the rotational speed and so on (National instruments, 2003).

The spindle speed is correlated to a machine’s vibration signal in order to generate information about the order components of the machine. Order components can be found in an order power spectrum where each order component represents a part of a machine. As an example, the first order can correspond to the frequency at which a tool is rotating. A second order can be bearings. An order power spectrum enables one to identify and characterize significant orders. The orders are significant due to its high amplitudes.

An illustration is presented in Figure 2.4.30 on how FFT analysis is done on vibration signals of a PC fan. As shown in the figure, the PC fan is composed of four coils and seven blades. Each component of the PC fan has its own vibration signal pattern, thus, the vibration signal of the PC fan is the superposition or combination of the vibration, generated by the shaft, coils, and blades. The rotation of the shaft is similar to the rotational speed of the PC fan, which is at 3,300 rpm; therefore, their vibration signals are at the same frequency of 55 Hz (i.e. 3,300 rpm ÷ 60 Hz). The rotation of coils and blades are four and seven times of the rotational speed, respectively, which means the vibration signals is at frequencies of

85
four (220 Hz) and seven times (385 Hz) the rotational speed. The repetition of the rotational speed is what also known as **harmonics**. At constant speed, the vibration signals of the PC fan have peaks at the rotational speed, as well as at the fourth, and seventh harmonics of the rotational speed of the PC fan.

![Diagram of vibration signals](image)

**Figure 2.4.30 Fast Fourier Analysis of vibration signals from a PC fan (National Instruments, 2003).**

In Figure 2.4.31, a vibration signal of a machine running at 3,000 rpm is shown in the first graph. Its rotational speed is presented in the form of the tachometer signal shown in the second graph. A similar pattern in the signal can be observed in the frequency domain and order domain as depicted in the respective third and fourth graph. The third graph shows a frequency spectrum of the vibration signal whereas the fourth graph presents the vibration signal of the machine components in their respective orders.
Figure 2.4.31 Frequency and order spectra of a shaft rotating at 3000 rpm (Source: National Instruments, 2003).

The FFT process resulted in a frequency spectrum and an example of a frequency map as shown in Figure 2.4.32. The figure represents an FFT spectrum map of an automobile engine run-up test (i.e. acceleration test) running from 665 to 3,995 rpm. On the X-axis is the frequency, the Y-axis is the count, and the z-axis is the amplitude in RMS.
Figure 2.4.32 FFT spectrum map of an automobile run-up test (Hewlett-Packard, 1996).

Meanwhile, Figure 2.4.33 shows the same measurement of the engine run-up test presented in the form of order spectrum map with X-axis as the order of rotation. It can be observed that it is difficult to relate the peaks in the frequency spectrum map to shaft speed (Figure 2.4.32) whereas in the order spectrum map, each peak line indicates the relationship between vibration and the position of the shaft. It can be seen that the peak at the 12\textsuperscript{th} order and 3,815 rpm has the highest amplitude, which indicates that a component occurs 12 times for each revolution of the engine revolution.
A specific order can be further analyzed while excluding others in a step called order tracking as shown in Figure 2.4.34. In the figure, the 12th order is extracted from the order map in Figure 2.4.32 in order to determine the relationship between the order vibration and the speed of the engine. It is also to measure its contribution to the overall machine performance whereby a higher amplitude of a specific peak would indicate a developing problem exists.
The terms order tracking and order analysis are usually used interchangeably. While order analysis means performing analysis on already acquired signals, order tracking is constantly updating as the data continue to be acquired. Order tracking can be done using several methods such as computed order tracking (COT), Vold-Kalman filter order tracking, and Gabor order tracking.

The COT applies a re-sampling procedure (Wang and Heyns, 2011). Fyfe and Munck (1997) compared between conventional and computed order tracking methods. The order tracking technique deals with sampling the vibration signal at constant increments of shaft angle. In the conventional technique, special analog hardware is used to sample at a rate that is proportional to the shaft speed. As for the computed method, it first samples at a constant rate (or uniform period) before resampling the data using software at constant angular increments. Significant improvement in terms of spectral accuracy was achieved with the computed method.

The Vold-Kalman filter and Gabor are also known as waveform reconstruction order tracking techniques. They are able to extract the time history including its amplitude and phase of an order from the original data (Wang, 2008). Zhao (2008) used the Gabor approach in applying the order tracking technique, and found that the method was more
powerful as well as can be applied without having rotational speed information. The Gabor expansion-based order tracking approach is more intuitive and computationally faster compared to the Vold-Kalman filter (Qian, 2003). The Vold-Kalman filter enables simultaneous tracking orders in systems that have multiple independent shafts (Herlufsen et al., 1999).

A topic in vibration monitoring is presented next to provide an understanding on its fundamental, and application. It will give a better appreciation on the overall objective of the current study especially on the use of sensors and signal processing techniques.

2.5. Vibration Monitoring

2.5.1. Introduction

Vibration monitoring has been an important area for many industrial applications. As productivity is of a primary concern, monitoring machine vibrations provides a way to reduce operating cost due to machine failure, and to determine the condition of machines for early problem detection.

2.5.2. Vibration Monitoring Equipment: Displacement, Velocity, and Acceleration Sensors; and Signal Conditioner

The main components in a vibration monitoring system are the sensors and the signal conditioner. The vibration sensors are used for detecting displacement, velocity, and acceleration motions. These three categories motion-based sensors or transducers are discussed here. Some of the most common types of vibration sensors are piezoelectric, capacitive, strain gage, and magnetic induction, to name a few. Selection on the types of sensors should be based on their accuracy (i.e. percentage of allowable error over the full measurement range), frequency range (measured in Hz), measuring range (either in G for acceleration, in/sec for linear velocity, or inches for displacement), ambient conditions (e.g. temperature and maximum shock and vibration), and sensitivity range. Detailed description of each component is presented in the following paragraphs.
a) **Displacement Sensors**

Displacement sensors are used to measure the distance an object moves. They are best suited for measuring low frequency as well as low amplitude displacements. Signals with high frequency and high amplitude motion can be detected using piezoelectric accelerometers. Displacement sensors have a natural frequency of less than 80 Hz (Johnson, 2003). There are two broad types of displacement sensors: (1) **contact types** (e.g. linear variable differential transformers (LVDT), strain gauges, etc.), which utilize a dial gage, differential transformer, etc., and (2) **non-contact types** (e.g. capacitive), which utilize a magnetic field, laser beam, ultra-sonic wave, etc.

b) **Velocity Sensors**

Linear velocity sensors involve measuring the linear velocity of an object. They are suitable for low to medium frequency measurements. Traditional velocity sensors apply an electromagnetic system in order to produce the velocity signal. The basic principle is that a voltage signal representing the vibration is produced when a coil of wire is moved through a magnetic field. Similar to displacement, velocity is best measured at low frequencies. However, the mounting and calibration of the sensors present some difficulties that make it rarely used in measuring vibration (Morris, 2001).

c) **Acceleration Sensors**

Accelerometers are examples of acceleration sensors in which the most commonly used in the field of vibration monitoring are those that utilize a piezoelectric sensing element. Turner et al. (1994) stated that despite the various shapes and sizes, accelerometers operate based on Newton’s second law, $F = ma$. According to the law, a mass, $m$, imparts a force, $F$, as a response to acceleration, $a$, generating a voltage that is proportional to the magnitude of the stress. This type is widely used due to its small size and robustness. Unlike displacement and velocity sensors, acceleration sensors have a wide dynamic frequency ranges (Rao, 1996). For example, a low-frequency industrial accelerometer can have a frequency range
from 0.2 – 6,000 Hz (PCB Group, Inc., 2007), whereas a low-frequency displacement sensor’s frequency range can be from 1.5 – 300 Hz (IMI Sensors).

d) Signal Conditioner

The purpose of signal conditioning is to aid in conducting more accurate and reliable sensor measurements. A signal conditioner can serve one of the several functions of signal conditioning described here: (1) amplification, in which amplifiers are used to increase the voltage level in order to improve measurement resolution and sensitivity; (2) attenuation is used to decrease the amplitude of the signal in order to bring the conditioned signal within the ADC range (National Instruments, 2010); (3) isolation passes the signal from its source to the measurement device without a direct physical connection by using techniques such as transformer, or optical in order to prevent improper grounding that causes measurement problems (National Instruments, 2010; Park and Mackay, 2003); (4) filtering remove unwanted noise and to prevent aliasing; and (5) excitation is important for transducers that require external voltage or current excitation (National Instruments, 2010).

2.5.3. Application of Vibration Signals in Tool Condition Monitoring (TCM)

It is known that machine rotational speed is a source of vibration signals. In a CNC router, the part that rotates is the cutting tool that is attached to the spindle. Thus, the vibration signals from the cutting tool can be related to the tool condition specifically as tool wear progresses during machining.

Mehta et al. (1983) studied the effect of the interaction between tool wear and vibrations of carbide tool bits on a vertical milling machine. It was found that the increase in vibration frequency led to higher tool wear rate, and the cutter blade vibration was found to be the most crucial as it was characterized by high frequency and large amplitudes.

Past studies had used vibration signals for TCM (Alonso and Salgado, 2008; Dimla, 2002; Lemaster et al., 2000b; Mehta et al., 1983). A vibration accelerometer was preferred over other methods due to its robustness; i.e. wide range of operation conditions (Lemaster et al., 2000a).
Mehta et al. (1983) demonstrated that the vibration behavior of the machine tool-cutting tool-workpiece (MCW) can be characterized by a certain number of frequencies with each corresponding to a specific element of the MCW system.

Gupta (1997) suggested that vibration monitoring is a very effective tool for diagnosing mechanical defects. Lemaster et al. (2000a and 2000b) found that tool wear can be monitored through monitoring the spindle vibration when cutting particleboard on a CNC router. Signals that were detected by an accelerometer showed that the frequency band from 1,000 to 7,000 Hz was the best frequency range to monitor the tool condition, and also product quality. The second part of the study further established a correlation between tool wear and surface quality (Lemaster et al., 2000b).

The current study is a continuation of the work by Lemaster et al. (2000b). A novel contribution of the study is the application of order analysis method in the process monitoring and control of the machining process on the CNC router. Previous works in wood-based machining have not applied the technique, and the current study is the first known attempt.

The next chapter (Methodology and Preliminary Work) discusses several preliminary experiments that were done to establish the relationship of the vibration signals of a CNC router with tool wear on tungsten carbide inserts, and chipping of melamine-coated particleboard. Establishing the relationship is crucial since machining parameters such as feed speed, and spindle speed as well as tungsten carbide insert grades determine the quality of the machining process. Preliminary results are also presented.
3. METHODOLOGY AND PRELIMINARY WORK

3.1. Introduction

This chapter provides detailed descriptions on the methods and procedures that were applied in the research. The Experimental Work section discusses the equipment and materials that were used. The section also covers the processes of acquiring the vibration signal of a CNC router tool spindle, measuring the chipping of melamine-coated particleboard and also measuring the tool wear on tungsten carbide insert tool.

Some preliminary work had been conducted and the results are included in this chapter. A brief description of the preliminary work and its importance are summarized below:

- **Sensitivity and Accuracy of Tachometer**
  The objective was to determine the sensitivity of the tachometer and the reading accuracy. The tachometer was used to provide a rotational speed of the CNC router tool spindle. A tachometer that is sensitive and accurate is important to ensure a reliable data is being produced.

- **Tool Spindle Vibration during Idling for Different Cutterhead Diameters, Number of Cutting Flutes and Spindle Speeds**
  The tool spindle vibration during idling was collected for two cutterheads with different diameters. Idling data for different number of cutting flute and spindle speed was also investigated. The objective was to observe the vibration patterns of these factors that can later be used for comparing with the data from a cutting operation.

- **Vibration Signal Analysis: Frequency Band Selection and Extraction Processes**
  The process of selecting a frequency band that could accurately represent the relationship between the vibration signal and chipping was described in section 3.5. Three frequency bands were initially selected based on their high energy content in the power spectrum. The RMS, ratios, and centroid frequency values were extracted from all three
frequency bands in order to make a comparison and decision on which method to be used to monitor the tool spindle vibration.

- **Some Key Results from Preliminary Tests:**
  - **Effect of Tool Wear on Chipping**
    This result is important in order to establish the fact that a worn tool causes chipping. Additionally, since tool wear governs the occurrence of chipping, a high amount of tool wear should increase panel chipping.
  
  - **Effect of Varying Spindle Speed on Tool Wear, Panel Chipping, and Tool Spindle Vibration**
    The objective was to determine the effect of varying the spindle speed on tool wear, chipping and tool spindle. The results are crucial for the feedback control technique that would be designed to modify tool life.
  
  - **Effect of the Variability in the Density of Different Boards on Tool Wear, Panel Chipping, and Tool Spindle Vibration**
    The objective was to determine the effect of the variability in board density on tool wear, chipping and tool spindle. The effect is important as the melamine-coated particleboard panels were purchased in batches from the same store (Lowe’s Home Improvement in Cary, North Carolina) throughout the completion of the preliminary tests. The different batches seemed to have different characteristics when machining, thus, the density variability was investigated.
  
  - **Effect of Cutting Configuration on Panel Chipping**
    In most of the preliminary work, each test was done with 200 cutting passes. It was found that there was a drop in panel chipping at the 120th pass. This test was done to evaluate possible causes of the drop in chipping.
• **Effect of Cutting at Different Positions on the CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration**

  This test investigated the different positions of the tool on the CNC router table during cutting. Different levels of vibration affect chipping formation. Thus, it is crucial to identify the effect, if any, of tool location on the vibration levels in order to help explain the occurrence of chipping.

• **Effect of Cutting at Different Cutterhead Diameters on Tool Wear, and Tool Spindle Vibration**

  The effect of cutterhead diameter on tool wear and tool spindle vibration was evaluated. The cutterhead diameter is an important factor that determines the amount of tool wear as well as spindle vibration.

• **Effect of Cutting at Different Number of Cutting Flutes on Tool Wear, and Tool Spindle Vibration**

  The effect of cutting with a one flute and two flute cutters on tool wear and tool spindle vibration was investigated. This is to show whether or not the number of cutting flutes is a critical factor in determining the amount of tool wear.

• **Effect of Cutting at Different Feed Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration**

  The test was conducted to determine the effect of feed speeds on tool wear, panel chipping and tool spindle vibration. Varying the feed speed produced different chip load (i.e. the thickness of a chip that is removed by a tool cutting edge as the tool advances). The size of chip load affects machining quality, particularly the amount of panel chipping.
• **Effect of Cutting at Different Spindle Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration**

The test was conducted to determine the effect of different spindle speeds on tool wear, chipping and tool spindle vibration. Similar to feed speed, varying the spindle speed also produced different chip load. It was also to observe whether or not higher spindle speed would reduce panel chipping and at the same time increase the rate of tool wear. This is important in order to establish the relationship between tool wear and panel chipping. Once the relationship is established, the information can be used to perform cutting with the feedback control technique. A feedback control system that can regulate the spindle speed is needed to optimize tool life and product quality.

• **Effect of Cutting at Different Carbide Grades on Tool Wear, Panel Chipping, and Tool Spindle Vibration**

The amount of cobalt determines the grades (and hardness) of the carbide tools. Thus, the rate of wear is different for each grade. This test was done to establish a wear curve for each grade, and also to determine the grade’s effect on panel chipping and spindle vibration. The information is important as carbide grade is one of the key factors to be considered in machining.

3.2. **Experimental Work**

A series of preliminary tests was done in order to establish a relationship of the effect of tool grade and spindle speed on tool wear, the degree of chipping of melamine-coated particleboard, and tool spindle vibration. The chipping occurrence is governed by the amount of wear on the cutting tool, and the effect could be worsened with the presence of excessive vibration from the cutting tool. Meanwhile, combination of machining parameters and tool grade significantly affects the rate and amount of wear on tools during machining.

In terms of the spindle vibration signal, an accelerometer was placed on the lower bearing housing of the spindle and three frequency bands were selected and analyzed to determine the one that was sensitive to tool wear and panel chipping. The three frequency
bands were chosen after a series of preliminary experiments where the frequency bands were observed during the wearing of the cutting tools. Based on the correlation between the vibration signal and panel chipping, a single frequency band was then chosen to monitor the condition of the cutting tool in order to optimize cutting operations on a CNC router.

The following sections describe the equipment, raw materials, data acquisition process, methods of measuring tool wear, and panel chipping as well as vibration signal analysis. Preliminary studies as well as their results are also presented.

### 3.2.1. Equipment and Raw Materials

Preliminary experiments were conducted at the Hodges Wood Products Laboratory, Department of Forest Biomaterials at North Carolina State University in Raleigh, North Carolina, USA. Machining of melamine-coated particleboard was performed by a Thermwood CNC model 40 turret router with a 5 × 5 foot table as shown in Figure 3.2.1.

Cutting tools were in the form of inserts made of tungsten carbide. The carbide grades that were used in the study were produced by TIGRA Company: T02SMG (SMG for Sub Micro Grain), T06MG (MG for Micro Grain), and T10MG, and one carbide grade from Sandvik company (grade name: H6N). These carbide grades are specifically made for machining wood-based composite materials, and differ in terms of their carbide size, and the percentage of cobalt binder. The combination of carbide size and cobalt percentage determines the performance of each carbide grade. Carbide grade T02SMG has a grain size of 0.5 – 0.7 µm, and 2.5% cobalt binder; T06MG and T10MG have a grain size of 0.7 – 1.0 µm with 6% and 10% cobalt binder, respectively; and H6N has 6 % of cobalt content and medium fine grain size (below 3.0 µm).
Figure 3.2.1 Thermwood CNC model 40 turret router.

Figure 3.2.2 shows the tungsten carbide insert with its holder and how it was inserted in the tool spindle of the CNC router. In Figure 3.2.3, the drawing of the tungsten carbide insert with its dimensions is shown. Tool nose width was used as the wear parameter to quantify tool wear as illustrated in Figure 3.2.4 (Sheikh-Ahmad et al., 2003). After series of cutting, the nose width was increased as depicted in Figure 3.2.5. Tungsten carbide inserts were inspected using an optical microscope that was attached to a computer prior to machining on the CNC router. After the machining was completed, tool wear was measured as described in detail in the Experimental Work section.
Figure 3.2.2 Tooling for the study: (a) tungsten carbide insert with tool holder, (b) tool holder inserted into the tool spindle.

Figure 3.2.3 Drawing of tungsten carbide insert (dimensions are in mm).
Figure 3.2.4 Location of nose width on carbide insert (Nose width diagram: Sheikh-Ahmad et al., 2003).

Figure 3.2.5 Nose width measurements (Sheikh-Ahmad et al., 2003).
Melamine-coated particleboards panels (Figure 3.2.6) with dimensions of 61 cm × 124 cm × 2 cm (2 ft. × 4.5 ft. × 0.75 in.) were cut using each grade of the carbide inserts at different spindle speeds; 12,000 rpm, 15,000 rpm, and 18,000 rpm (rpm = revolutions per minute). The composite panels were selected for several reasons; first, it was due to their high abrasive contents that can expedite the wearing of the cutting tools; second, chipping of the melamine can easily aid in the determination of surface quality assessment; additionally, it is a common wood-based product material that is used in many applications in furniture and cabinet making.

Figure 3.2.6 Melamine-coated particleboards: (a) before; and (b) after cutting.

LabVIEW™; a graphical programming software, which stands for Laboratory Virtual Instrumentation Engineering Workbench, was used to write a program for the data acquisition process as explained in the next section. It was also an important tool in the analysis and representation of the data that was acquired from the cutting process. LabVIEW™ applies the concept of data flow programming. As opposed to text-based programming, LabVIEW™ uses icons to create applications, and dataflow is used to determine the order of the execution of the program. A LabVIEW™ program consists of a front panel and a block diagram.

The front panel serves as the user interface where it contains controls and indicators that can be used to adjust the data acquisition process, perform signal analysis, as well as displaying, and saving the results. The block diagram contains the graphical source code that
controls the front panel objects. Figure 3.2.7 shows the front panel of the LabVIEW™ program that acquired the vibration and tachometer signals, and its corresponding block diagram is shown in Figure 3.2.8.

![Figure 3.2.7 Front panel of the LabVIEW™ program for the data acquisition process.](image-url)
3.2.2. Data Acquisition

In a tool condition monitoring study, a data acquisition system is an integral part of the process. The data acquisition system for this study was composed of a vibration sensor or accelerometer, a tachometer with attached optical sensor, an A/D converter by National Instruments™, and a computer with the LabVIEW™ software installed.

During the cutting process, the tool cut the particleboard at one corner, and traveled horizontally about 99 cm (39 in.) along the length of the panel to make a buried cut before it retracted and returned back to complete 20 cutting passes either in conventional or climb cutting direction (Figure 3.2.9). Four more sets of the same cutting operation were done for a total of five sets of 20 passes per board sample. The depth of cut (or tool advancement) was 0.32 cm (0.125 in.), which was selected to accommodate the 200 cutting passes within the melamine-coated particleboard panel size. The feed speed and spindle speed were varied depending on the tests. For the feed speed, it was either at 7.62 m/min (300 ipm), 10.16 m/min (400 ipm), or 12.7 m/min (500 ipm). As for the spindle speed, it was either at 12,000 rpm, 15,000 rpm, or 18,000 rpm. These spindle speeds were selected to represent the spindle speed range of the CNC router, which is from 0 to 18,000 rpm.
Vibration data was collected by clicking a start button in the LabVIEW™ program on the first, second, and third passes in each 20 pass set. In each of the three cutting passes, vibration signals were acquired from the sensor and relayed to the A/D converter, which converted the analog signals into digital signals. At the same time, tachometer signals were also collected as it provided the rotational reference of the router spindle, and was required in conducting the order analysis. In order to acquire the tachometer signals, a reflective tape was placed on the spindle. The coincidence between the tape and the optical sensor generated pulses signals, which were captured by the sensor, and saved on the computer.

The vibration and tachometer data were collected at a sampling rate of 250,000 samples per second (Hertz) with a total sample size of 16,384. Data or waveform averaging was done in which, at each click of the start button, ten data sets of 16,384 samples per channel were taken and averaged. The purpose of the average was to reduce the effect of random and spurious signals during the data acquisition process.

In each cutting pass, data were collected and stored in the computer. These data were: (1) the **spindle speed** (in rpm) of the router spindle provided by the tachometer; (2) the **averaged power spectrum** of the vibration signals; (3) the **root mean square (RMS)** values
for both time and frequency of the time waveform signal. The RMS values are commonly used when using accelerometer; (4) the 10th time waveform of the vibration signal; (5) the delta frequency (df) of the power spectrum; (6) the delta time (dt) of the spindle speed, and (7) the dt of the sampling rate for acquiring the time waveform signal. Figure 3.2.10 shows a graphical representation of the data acquisition process.

![Data Acquisition Flow Chart](image)

**Figure 3.2.10** Flow chart of data acquisition process.
The data was stored on the hard drive of the computer. The LabVIEW™ software was then used to perform post analysis such as filtering, the FFT algorithm, and the order spectrum for the order analysis. In the filtering process, bandpass filter was used to extract frequency bands. The FFT algorithm was performed in order to identify the frequency contents of the vibration signal, and the order spectrum was used to identify a significant order. These processes were further discussed in the results.

a) Application of LabVIEW™ in Acquiring Tool Spindle Vibration Signal

Tool spindle vibration signal was collected during the machining of melamine-coated particleboard panels. As described in the Data Acquisition section under the Methodology and Preliminary Work chapter, the data was acquired and stored into the computer using LabVIEW™ program. Two separate programs were specifically written for the study in which one was used to collect the vibration signal during the machining tests, and the second program was used to read the stored data and to perform post analysis.

Displaying the program codes is difficult as the LabVIEW™ style code does not lend itself well to documentation and showing the actual code flow. Thus, due to the complexity and the huge codes used in building the two programs, only a general description is provided.

Figure 3.2.11 shows the front panel of the LabVIEW™ program that was used to collect the tool spindle vibration signal. At the top portion of the program, the “Data Log” toggle switch was turned on in order to save the acquired vibration signal in a location that was specified in the “Destination File Name” box. The “Start” button was used to acquire the vibration signal and the “Stop” button was used to immediately stop the entire LabVIEW™ program.

The bottom portion of the program shows two graphs placed in a tab control. A tab control consists of pages and tabs that can be used to overlap the front panel controls and indicators in a much smaller area. The vibration signal can be viewed through the graph indicators while it was being collected during the machining process. Several commercially available subroutines (i.e. instructions frequently used) were used in the LabVIEW™ program. Additionally, tasks such as displaying graphs, performing FFT, filtering and some
calculations, were custom written within LabVIEW™. The controls and indicators on the front panel were arranged accordingly for easy viewing.

![Figure 3.2.11 Front panel of LabVIEW™ program used to collect tool spindle vibration.](image)

The tool spindle vibration data that had been collected and stored in the computer can be read or retrieved using another LabVIEW™ program as shown in Figure 3.2.12. A specific file can be read by entering the location and name of the file in the “Filename to Read” box. The “Start” button was pressed in order to read the data. The top portion of the program also had graph indicators that were used to display the vibration signal that was previously collected. Meanwhile, the bottom portion of the program had a tab control, which contained the controls and indicators that were used to display and analyze the vibration data.
b) **Experimental Setup and Placement of Sensors**

Figures 3.2.13 and 3.2.14 show the experimental setup, and the placement of the tachometer optical sensor as well as the accelerometer. Following paragraphs describe each component as shown in the experimental setup.
Figure 3.2.13 Experimental setup.

Figure 3.2.14 Placement of the optical and vibration sensors.
The type of vibration sensor or accelerometer that was used in this study is shown in Figure 3.2.15. The Model 621B51 manufactured by Industrial Monitoring Instrumentation (IMI Sensors) is a high-frequency industrial accelerometer equipped with 10-32 coaxial connector. It has a frequency range between 0.8 to 20,000 Hz.

Figure 3.2.15 Vibration sensor: (a) vibration sensor showing its relative size, and magnetic base, (b) close-up view of the vibration sensor with the 10-32 coaxial connector.

The signal from the vibration sensor was sent to an amplifier (Model Number 484B10; high frequency response 200 kHz) by PCB Piezotronics Inc. where it was amplified before being digitized by the A/D converter (Figures 3.2.16b and 3.2.17). The A/D converter used in the study was a National Instruments™ analog input module model NI 9201 with the following specifications: eight analog input channels, 12 bits analog to digital conversion (ADC) resolution, and a maximum aggregate sampling rate of 500 kilo sample per second or kS/s. Figure 3.2.17 shows a close-up view of the module.
Figure 3.2.16 (a) Model 484B10 amplifier, (b) A/D converter (with analog input module inserted into a chassis).

Figure 3.2.17 Close-up view of NI 9201: (a) right view, (b) left view.

The rotational speed of the tool was captured using a tachometer by Monarch Instrument model ACT-3 coupled with an optical sensor as shown in Figure 3.2.18. It has a speed range of 5 rpm to 999,990 rpm, and an input frequency range of 0.083 Hz to 250 KHz.
3.2.3. Panel Chipping Observation and Measurement

After machining, the edge that was produced by the 20th cut in each of the five sets was observed, and measured for chipping in order to determine the quality of cut. Figure 3.2.19 shows a comparison between a chipped edge and an edge with no chipping.

The panel chipping was measured by counting the number of chips per 25 mm (1 in.) that were at least 2 mm (0.08 in.) in width or 2 mm (0.08 in.) in height. Prior to counting the chips, the number of observations were first determined by taking into account the effect of
the CNC router spindle acceleration and deceleration. Based on the information from the manufacturer, the CNC router’s acceleration and deceleration value was 15 inch per second squared (in/s²). The value was used in calculating the length for both acceleration and deceleration using the motion equation below (Equation 3.2.1).

\[ v^2 = v_i^2 + 2a(s - s_i) \]  

\textbf{Equation 3.2.1}

Where:
- \( v \) = velocity at the end of the interval
- \( v_i \) = initial velocity
- \( a \) = constant acceleration
- \( s \) = position at the end of the interval or displacement
- \( s_i \) = initial position

Given:
- \( v = 500 \text{ in/min (8.333 in/sec)} \)
- \( v_i = 0 \text{ in/sec} \)
- \( a = 15 \text{ in/ s}^2 \)
- \( s_i = 0 \text{ in} \)

Required:
- \( s \) = position at the end of the interval or displacement

Calculation:

\[(8.333 \text{ in/sec})^2 = 0 \text{ in/sec} + 2\left(15 \frac{\text{in}}{\text{s}^2}\right)(s - 0 \text{ in})\]

\[(8.333 \text{ in/sec})^2 = 30 \frac{\text{in}}{\text{s}^2} (s)\]

\[ s = \frac{(8.333 \text{ in/sec})^2}{30 \frac{\text{in}}{\text{s}^2}} \]

\[ s = 58.7 \text{ mm (2.31 in.)} \]
Based on the calculation, the length to be accounted for was 58.7 mm (2.31 in.). This value was rounded off, and doubled where the number of chipping was counted in the center portion of the 1 m (39 in.) edge after subtracting 101.6 mm (4 in.) from each end, leaving a length of 0.787 m (31 in.). This was to ensure that chipping measurements were only taken in the section where the tool feed speed was at its maximum. The next step was to determine the number of observations to be taken along the edge.

A paired t-test using JMP® 8 statistical package was conducted in order to justify for taking a smaller sample size rather than measuring the entire length (i.e. 1 m). Two sets of chips measurements were taken at the 200th pass on two randomly selected boards. The first set was measuring the number of chips per 25 mm (1 in.) with 26 number of observations, and the second set was counting the number of chips per 25 mm (1 in.) at five random equally-spaced locations (n = 5) as shown in Figure 3.2.20.

![Figure 3.2.20 Panel edge chipping measurement.](image-url)
The chip counts are shown in Figure 3.2.21, and in Figure 3.2.22, the paired t-test result showed a P-value of 0.338, which meant that the two group of observations (n = 26 vs. n = 5) were not different from each other. With this result, it was therefore justified to take a smaller number of observations, i.e. counting the number of chips at five locations along the 20th pass edge in each set.

![Figure 3.2.21 Chip counts on the 200th pass of two boards.](image)

*Figure 3.2.21 Chip counts on the 200th pass of two boards.*
A systematic sampling was performed in which the first location or observation was randomly selected among the 31 observations. Then, a sampling fraction was obtained by dividing the total number of observations (n = 31 referring to 31 in.) with the sample size (n = 5). The result of the sampling fraction (i.e. 31/5 ≈ 6) was used as the constant difference or interval between the observations. Thus, if the first observation is located at 0.15 m (6 in.), the next four observations would be taken placed at the 0.3 m (12 in.), 0.46 m (18 in.), 0.6 m (24 in.), and 0.8 m (30 in.) locations. The amount of chips per 25 mm (1 in.) was related to the amount of wear (measured in microns) on the carbide inserts. A close-up view at how the measurement was taken is shown in Figure 3.2.23.
The panel chipping measurement was considered as a weak area and possible source of error in the research project that needed to be further investigated. The original method was done by counting the number of chips at the five observations. A new method was considered, which was conducted through measuring the length of chips within the five observations at the 20th pass in each set.

Figures 3.2.24 and 3.2.25 show the results of panel chipping that were counted as average number of chips per 25 mm and also based on the average of chip length per 25 mm from five observations, respectively. The chip length method showed a smoother pattern as compared to the chip count method.
Figure 3.2.24 Average number of chips per 25 mm for 10% cobalt grade tungsten carbide inserts cutting in climb direction at 12,000 rpm and 18,000 rpm of spindle speeds and 12.7 m/min (500 ipm) of feed speed.
Figure 3.2.25 Total length of chips from five observations at each 20\textsuperscript{th} pass for 10\% cobalt grade tungsten carbide inserts cutting in climb direction at 12,000 rpm and 18,000 rpm of spindle speeds and 12.7 m/min (500 ipm) of feed speed.

3.2.4. Tool Wear Measurement

Tool wear on the carbide inserts were inspected. The nose width measurement was done based on previous work by Sheikh-Ahmad et al. (2003). Prior to cutting, the initial nose width or NW of the sharp tool was inspected under the microscope (Figure 3.2.26) for any chips on the cutting edge or tool nose. In order to choose the best cutting edge, a cutting edge having a chip that measured more than 10 microns, horizontally or vertically, was rejected.
Figure 3.2.26 Tool wear measurement with optical microscope: a) overall view of microscope; and b) tungsten carbide insert placed under the microscope lens.

The microscope was first calibrated at 500× magnification using a stage micrometer as shown in Figure 3.2.27. As illustrated, the calibration was done where the smallest division on the stage micrometer was used. The smallest division is 0.01 mm and is equal to 96 pixels on a 640 × 480 pixels window size. Figure 3.2.28 shows the second window of the nose width. In Figure 3.2.29 images of a sharp and worn carbide insert are illustrated.
Figure 3.2.27 View of a stage micrometer for calibrating the microscope at 500× magnification; i.e. 0.01 mm = 96 pixels with camera size: 640 × 480 pixels.

Figure 3.2.28 Four equally-spaced nose width measurements were taken on the second window as viewed from the microscope.
Using a micro-measurement tool software, the nose width was measured at several positions along the worn cutting edge of the tool that cut at the high density area of the melamine-coated particleboard. The high density area location is shown in Figure 3.2.30. The results were reported as the average values from the four measurements that were taken from the second window as shown in Figures 3.2.28 and 3.2.31.

Figure 3.2.30 High density area is located at the top and bottom surfaces of the melamine-coated particleboard. The carbide insert cut the entire depth of the high density area at the top surface and only slightly at the bottom surface.
3.3.  Sensitivity and Accuracy of Tachometer

A test was performed to determine the sensitivity of the optical sensor of the tachometer in capturing the coincidence with the reflective tape that was placed on the router’s tool spindle.

3.3.1. Methodology

Two objectives were first established. The first objective was to determine if the width of the reflective tape affected the rpm reading. The reflective tape (Figure 3.3.1) was cut into three widths i.e. 4 mm, 8 mm, and 12 mm. During the test, the 4 mm piece was placed on the spindle holder, and the spindle was rotated at 9,000 rpm. The actual spindle speed that was obtained from the tachometer was recorded. The test was repeated for the 8 mm and 12 mm reflective tapes.

The second objective was to verify the reliability and accuracy of the tachometer reading. In the test, the optical transducer of the tachometer was pointed towards the spindle, and a hand held optical tachometer was set up and pointed towards the router spindle. The spindle was rotated at 9,000 rpm, and the readings from both tachometers were observed. Similar readings from both tachometers would help confirm the reliability and accuracy of the tachometer that was used in the study.
3.3.2. Results and Discussion

It was found that all three reflective tape pieces produced the exact same tachometer reading, which was 9,376 rpm. Thus, a 4 mm width was selected and applied in all of the cutting tests. Figure 3.3.2 shows the location of the reflective tape on the spindle. It was also observed that both tachometers showed similar readings. The optical transducer tachometer’s reading was 9,376.6 rpm while the handheld tachometer displayed 9,377 rpm. Based on both tests, it was observed that the actual rpm reading (from the tachometers) was higher than the spindle speed that was set in the G-code program. This difference could be attributed to the variation in the motor controller of the router.

Figure 3.3.1 Reflective tapes.

Figure 3.3.2 Tape’s placement near the cutting tool.
3.4. Tool Spindle Vibration during Idling for Different Cutterhead Diameters, Number of Cutting Flutes, and Spindle Speeds

3.4.1. Introduction

Vibration signals during idling were collected for two types of cutterheads with different diameters in order to see the difference in the vibrations patterns caused by these cutterheads. Besides cutterhead diameter, other factors investigated include the number of cutting flute (i.e. cutter blade), and spindle speed. The objective was to observe the vibration patterns of these factors that can later be used for comparing with the data from cutting operation.

3.4.2. Methodology

Vibration data was acquired during idling of the CNC machine. Effects for the following factors were investigated: cutterhead diameters, number of cutting flutes, and spindle speeds. Two types of cutterheads with diameters of 19.1 mm (0.75 in.), and 50.8 mm (2 in.) were compared. These cutterheads are shown in Figure 3.4.1. The small cutterhead had one cutting insert slot whereas the larger cutterhead had two slots for insertion of the blades.

In all tests, the cutterhead was inserted into the CNC router tool spindle, and rotated at a specific spindle speed without performing any cutting. A total of 10 readings of the vibration signal were acquired. In each reading, the vibration signal was sampled at a sampling rate of 250 kHz with 16,384 samples.

For the effect of cutterhead diameter, new carbide inserts were used to ensure that the rotation was derived from a well-balanced tool. The small cutterhead had one new carbide insert attached to it prior to acquiring its vibration signal while the large cutterhead had two carbide inserts attached to it (note: one was worn, and the other was new). Both cutterheads were rotated at 15,000 rpm.

The large cutterhead was used to demonstrate the effect of the number of cutting flutes. For a one-flute effect, a worn blade was inserted in one of the slots in the large...
cutterhead while the other slot had a new cutting blade in order to represent a one-flute vibration. As for a two-flute effect, two new carbide inserts were placed in the slots.

The effect of spindle speed was determined by rotating the small cutterhead at different spindle speeds of 9,000 rpm, 12,000 rpm, 15,000 rpm, and 18,000 rpm.

The vibration signals produced were analyzed. The results of the series of tests helped in identifying the vibration patterns caused by the different cutterheads through analyzing the ribbon plots in the LabVIEW™ program. A ribbon plot is a 3D graph of parallel lines with x-, y-, and z- axes. In the study, the frequency was represented by the X axis, the number of readings was represented by the Y axis and the magnitude of the power spectrum was represented by the Z axis.

![Figure 3.4.1 Configuration of the large cutterhead: (a) overall view, (b) bottom view.](image)

**3.4.3. Results and Discussion**

Following are the analyses of the vibration signal data of the cutterheads during idling (i.e. tool rotating without cutting and turret head not moving).

a) **Effect of Cutterhead Diameters**

Figure 3.4.2 shows the power spectra of the vibration signal from the two different cutterheads rotated at 15,000 rpm. It was found that the small cutterhead produced a larger
power spectrum (i.e. higher amplitudes) at the beginning compared to the large cutterhead. This could be due to the fact that a larger cutterhead having two cutting blades (note: one was new, and one was worn) attached to it resulted in a more well-balanced tool, hence, it reduced the vibration.

It can also be observed that the frequency band around 6 kHz had larger amplitudes as pointed by the arrows. Since a power spectrum represents the energy distribution of the vibration signal, it suggests that any frequency bands with higher amplitudes may contain important information such as those that can be related to the progression of tool wear.

![Figure 3.4.2 Three dimensional ribbon plots of power spectra: (a) power spectrum for small cutterhead, (b) power spectrum for large cutterhead.](image)

Figure 3.4.2 Three dimensional ribbon plots of power spectra: (a) power spectrum for small cutterhead, (b) power spectrum for large cutterhead.
Figure 3.4.3 further illustrates the initial higher amplitudes for the smaller diameter cutterhead as compared to the large cutterhead. The RMS values were changing as the number of cutting passes increased. A t-test was performed using JMP® Pro 9 from SAS® to assess the statistical difference between means. Based on the test, it was found that the means of the tool spindle vibration between the small and large cutterhead sizes were not significantly different with a P-value of 0.3793. It can be concluded that the tool spindle vibration during idling was not affected by cutterhead size.

![RMS of Small and Large Cutterhead Sizes during Idling and Rotating at 15,000 RPM](image)

Figure 3.4.3 RMS of small and large cutterhead sizes during idling rotating at 15,000 rpm.

b) Effect of Number of Flutes

In determining the effect of the number of flutes on the vibration signal, the large cutterhead was used. In Figure 3.4.4, the two-blade rotation produced lower vibration than the one-flute rotation. The phenomenon can be explained based on the fact that a cutterhead having two new blades is more well-balanced compared to the worn and new blades.
combination. Since the two new blades had thinner cutting edges, they caused less air resistance during rotation. Additionally, a two-flute will wear equally and thus, keeping it well-balanced.

![Three dimensional ribbon plots of power spectra](image)

Figure 3.4.4 Three dimensional ribbon plots of power spectra: (a) power spectrum for one blade, (b) power spectrum for two blades.

In Figure 3.4.5, it can be observed that the RMS for the cutterhead with two new blades was much lower.
c) **Effect of Spindle Speeds**

Spindle speed was varied in order to determine the effect of spindle speeds on the vibration signal of the tool spindle. The tool was rotated at 9,000 rpm, 12,000 rpm, 15,000 rpm, and 18,000 rpm without cutting, and a total of ten readings were taken for each spindle speed. The ribbon plots in Figure 3.4.6 shows that the 9,000 rpm spindle speed produced the lowest vibration magnitude.

Figure 3.4.5 RMS of cutterhead with one blade and two blades during idling and rotating at 15,000 rpm.
Figure 3.4.6 Three dimensional ribbon plots of power spectra during machine idling. Spindle rotated at different speeds: (a) at 9,000 rpm, (b) at 12,000 rpm, (c) at 15,000 rpm, and (d) at 18,000 rpm.

Figure 3.4.7 confirms that the 9,000 rpm produced the lowest vibration. Tool spindle vibration was high at 12,000 rpm, and 15,000 rpm. However, the spindle speed at 15,000 rpm showed a more inconsistent peaks pattern. This could be due to resonance. In Figure 3.4.8: (a) to (f), the 15,000 rpm fell within the resonance region where high amplitude of the power spectrum between 14,000 rpm to 16,000 rpm can be observed. The 15,000 rpm was initially selected as it was a value that fell in the middle range of the CNC router spindle speed that was used in the study. The test was conducted prior to the knowledge of the resonance region of the CNC router.
Figure 3.4.7 RMS of tool during idling and rotating at different spindle speeds.
Figure 3.4.8 Tool spindle vibration during idling at different spindle speeds: (a) 12,000 rpm, (b) 13,000 rpm, (c) 14,000 rpm, (d) 15,000 rpm, (e) 16,000 rpm, and (f) 17,000 rpm.
3.5. Vibration Signal Analysis: Frequency Band Selection and Extraction Processes

3.5.1. Introduction

Vibration signals were collected during the machining process using the data acquisition system. Three frequency bands were initially selected to identify which frequency spindle vibration that changes the most as a tool becomes worn. The frequency bands were selected based on their high energy in the power spectrum, and they were filtered using a bandpass filter. The RMS ratio between the selected frequency bands, and centroid frequency (CF) were also determined to see if these values were more accurate in representing the relationship between the vibration signal and panel chipping. The CF or spectral centroid is defined as the barycenter (or center of mass) of a spectrum (Peeters, 2004; Schubert et al., 2004). It is used to show a shift in frequency. Additionally, order analysis was also done to see if it can provide the right information for the feedback control system. Detailed procedures are described below.

3.5.2. Methodology

Vibration signal data were read and analyzed with a LabVIEW™ program that was written specifically to analyze the collected vibration signal data. The vibration analysis was done in order to identify a frequency band that was sensitive to the change in the cutting tool condition and can be correlated with the chipping of the melamine-coated particleboard. A frequency band that shows significant changes as tool wear increases could be used to monitor the cutting tool condition for optimizing machining operation on a CNC router. In the LabVIEW™ program, the vibration signal can be viewed both in the time domain as well as in the frequency domain. A ribbon plot was used to provide a three dimensional view of the power spectrum of the vibration signal. A 3D ribbon plot shows the energy distribution of the vibration signal, and it helps to identify which frequency bands have the most change as the machining progresses.

Figure 3.5.1 shows 3D ribbon plot power spectra of a 10% cobalt grade tungsten carbide insert that performed cutting on the CNC router machine. In this example, the machining was done in conventional cutting direction at spindle speed of 18,000 rpm and
spindle speed of 12.7 m/min (500 ipm). A total of 200 cutting passes (~ 200 m) were completed. In Figure 3.5.1a, the overall power spectrum is presented. The x-axis represents the frequency in Hertz; the y-axis represents the number of cutting passes in which the vibration signal was collected; and the z-axis represents the magnitude of the power spectrum. The 200 cutting passes were divided into 10 sets with 20 cutting passes in each set. The vibration signal was recorded three times in each set (i.e. the first three passes in each set) totaling to 30 readings (i.e. representing the 30 number of passes).

As illustrated in Figure 3.5.1a, there were several frequency bands that showed some changes in its magnitude as the number of cutting passes increased. Lower frequency bands such as the one between 600 Hz to 1,800 Hz had an energy that was almost constant throughout the cutting process. Thus, it was considered as not being sensitive to any changes in the tool condition. A 2D power spectrum can also be used to observe individual spectrum more closely on selected frequency band. Based on these observations, three frequency bands were selected: (1) 3,750 Hz – 5,250 Hz; (2) 5,500 Hz – 6,750 Hz; and (3) 6,750 Hz – 8,000 Hz as illustrated in Figures 3.5.1b, 3.5.1c, and 3.5.1d. All three selected frequency bands are presented with similar y-axis values. A bandpass filter was used to filter the signal frequency in order to obtain the three selected frequency bands.
Figure 3.5.1 Three dimensional ribbon plots showing the power spectra of the vibration signal and frequency bands: (a) overall; (b) 3,750 Hz – 5,250 Hz; (c) 5,500 Hz – 6,750 Hz; and (d) 6,750 Hz – 8,000 Hz.

The three frequency bands were analyzed through their RMS values as shown in Figure 3.5.2. The RMS values were extracted using the LabVIEW™ program. The rows represent the three frequency bands. The two graphs in each row are similar with the first column having the same y-axes values. As can be seen in the figure, the first frequency band of 3,750 Hz – 5,500 Hz seemed to be following the chipping pattern; however, other repetitions showed that it was not always the case. The second frequency band of 5,500 Hz – 6,750 Hz seemed to have an upward trend beyond 100 cutting passes. Meanwhile, frequency
band three of 6,750 Hz – 8,000 Hz showed a decreasing trend. There were five other replications of similar cutting conditions, which generally had the same trend in all three frequency bands. The second frequency band seemed to be promising due to its increasing pattern and it could be used to monitor tool condition for optimizing machining operation on a CNC router. Thus, frequency band two was applied in the study.

Figure 3.5.2 RMS of three frequency bands and melamine chipping after 200 cutting passes (~200 m) with 10% cobalt grade tungsten carbide insert at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.
Figure 3.5.3 shows the RMS data for six 10% cobalt grade tungsten carbide inserts that cut 200 passes at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) in the climb cutting direction. The RMS readings were in a group of three and as mentioned before, the RMS reading was taken during the first, second and third passes in each 20-pass set. It can be observed that there were two distinctive groups among the replications; i.e. Rep 1 to Rep 3 as the first group and Rep 4 to Rep 6 as the second one. The first three replications had lower starting points as compared to the last three repetitions. However, they all had an increasing trend as the cutting progressed after the initial drop at the 40th cutting pass.

In order to further refine the trend of the RMS of the second frequency band, the three RMS readings in each 20-pass set were averaged as plotted in Figure 3.5.4. As can be seen,
through averaging the three RMS values, it shows a more defined line of the two distinctive groups.

![Figure 3.5.4](image)

Figure 3.5.4 Average of three RMS readings at frequency band 2 (5,500 Hz – 6,750 Hz) of six 10% cobalt grade tungsten carbide inserts cutting 200 passes (~200 m) at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.

### 3.5.3. Effect of Panel Density

The cutting operation of the first group (Rep 1 to 3) was done a year earlier. Board properties such as panel density could be the reason for the difference as well as the different batches of boards. Reps 1 to 3 were from the same batch, as well as Reps 4 to 6. Figure 3.5.5 shows the panel density for each replication. It can be observed that the two groups had different level of panel densities. A one-way ANOVA test was performed and showed that the means of the panel density of the different replications and groups were significantly different (P-value = 0.0001, F ratio = 45.5243, and R square = 0.97). Tukey-Kramer HSD
multiple comparisons test was performed to further analyze the significant difference between the groups. Both statistical tests were performed using JMP® Pro 9 software.

Figure 3.5.6 shows the result of the Tukey-Kramer test. As can be observed, the means of the two groups (i.e. Rep 1 to Rep 3 = Group 1; Rep 4 to Rep 6 = Group 2) were significantly different from each other. It can be concluded that the panel density of the two batches of board was different.

Figure 3.5.5 Panel density of different batches of boards.
As the starting points vary for each repetition, the RMS values were normalized by dividing each RMS value to the first RMS reading and multiplied by 100%. The normalized RMS data is shown in Figure 3.5.7. In the normalized graph, the percent of change can be seen for each repetition. Rep 2 had the highest amount of percent change as cutting passes increased. Between the two groups, the first group had a higher percent of change compared to the second group.
Figure 3.5.7 Normalized data of the RMS readings average at frequency band two (5,500 Hz – 6,750 Hz) of six 10% cobalt grade tungsten carbide inserts cutting 200 passes (~200 m) at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.

It can also be observed that the percent of change started to spread out after the 40th cutting pass. This is also clearly shown in Figure 3.5.8, which is a cumulative version of the normalized RMS data. This information will be used in a process control to increase the spindle speed when cutting on the CNC router machine.
In order to determine a reasonable starting point to increase the spindle speed, panel chipping has to be taken into consideration. Panel chipping is quite complex as it varies between boards; carbide tools and machining parameters such as spindle speed and feed speed. Figure 3.5.9 shows the variability in chipping for the six carbide inserts. As cutting passes increased, the cutting tool became dull and causes an increase in panel chipping. A chip amount needs to be selected as a way to determine the quality surface. As an example, one chip per 25 mm (1 in.) can be used and based from Figure 3.5.9, it can be concluded that the spindle speed can be increased between 40th to 60th cutting passes.
Figure 3.5.9 Panel chipping of six 10% cobalt grade tungsten carbide inserts cutting 200 passes (~200 m) at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.

Since there was too much variability in the panel chipping, a cumulative count was used to deal with the variability as shown in Figure 3.5.10.
3.5.4. Sources of Experimental Variation

It is of great interest as to what causes the variability not only on the chipping of the melamine-coated particleboard, but also on the tool wear and the vibration signal. Table 3.5.1 shows a list of the sources of experimental variation that could have some effects on the results on tool wear, chipping, and vibration signal.

In terms of the cutting tool condition, the cutting edge could be chipped during machining, which leaves a sharp serrated surface. The sharp edge would behave like a new cutting edge where it causes a drop in the signal of the spindle vibration as mentioned by Lemaster et al. (2000b), and Lim (1995).

The second source of variation is the effect of the density of the melamine-coated particleboard, which will be discussed in section under the title Effect of the Variability in the Density of Different Boards on Tool Wear, Panel Chipping, and Tool Spindle Vibration.
The tool position effect will be discussed in section under the title Effect of Different Positions on CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration.

The last two sources of variation are related to each other. It had been observed that there was a drop in panel chipping at the 120th pass. As the initial cutting configuration was done by cutting 100 passes twice, it was suspected that in between replacing a new board for the second 100 passes cut, the temperature of CNC router machine cooled down; hence, it might affect the chipping. Therefore, the cutting configuration was modified in which the 200 cutting passes were done at once. The details will be discussed in section under the title Effect of Cutting Configuration on Panel Chipping.
Table 3.5.1 Sources of experimental variation.

<table>
<thead>
<tr>
<th>Source of Experimental Variation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cutting tool condition</td>
<td>• Chipped tool blade affects cutting. A chipped blade can have a sharp serrated surface, which would behave like a new cutting edge.</td>
</tr>
<tr>
<td>3. Position of tool on the CNC router table</td>
<td>• Tool position on the CNC router table could produce different levels of vibration, hence, will also affect tool condition and chipping. • There might be a need to speed up the tool spindle at a certain cutting position.</td>
</tr>
<tr>
<td>4. Cutting configuration (i.e. cutting 100 passes twice or cutting 200 passes at once)</td>
<td>• As each test usually performed 200 cutting passes, there would be a difference between cutting 100 passes twice (i.e. same starting cutting position), and cutting 200 passes at once.</td>
</tr>
<tr>
<td>5. Temperature of the CNC router</td>
<td>• Machine heats up while cutting progresses, thus, temperature might have an effect on the machining performance and the product quality.</td>
</tr>
</tbody>
</table>
3.6. Some Key Results from Preliminary Tests

In this section, some key results from the preliminary tests are presented. There are three key results: (1) the effect of tool wear on chipping; (2) effect of varying spindle speed on tool wear, chipping, and vibration signal; and (3) effect of the variability in the density of different melamine-coated particleboard on tool wear, chipping, and tool spindle vibration. The results are discussed below.

3.6.1. Effect of Tool Wear on Panel Chipping

A machining test was conducted using a 10% cobalt grade of carbide insert. Five new carbide inserts were first inspected to ensure the absence of chipped cutting edge. Each cutting tool performed a machining test on the CNC router machine at 18,000 rpm of spindle speed, and 12.7m/min (500 ipm) in climb direction. Different number of cutting passes was assigned to each cutting tool with increments of 20 passes.

Figure 3.6.1 shows the tool wear results of the five carbide inserts. The carbide insert that completed 20 passes had the lowest tool wear. The highest tool wear was for between the 80 and 100 cutting passes tools. The tool that cut for 60 cutting passes had a lower tool wear than the 40-passes tool. As illustrated in Figure 3.6.2, the second window of the 60-passes tool showed less wear than the 40-passes tool. This could be due to the experimental variation such as board density that affects the tool spindle vibration from the machining operation. Figure 3.6.3 further illustrates that lower tool wear produced less chipping as in the case between the carbide inserts that cut 40-passes and 60-passes.
Figure 3.6.1 Tool wear of 10% cobalt grade tungsten carbide inserts cutting in climb direction at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed.
Figure 3.6.2 Cutting edges images of five 10% cobalt grade tungsten carbide inserts that were worn at a spindle speed of 18,000 rpm and a feed speed of 12.7 m/min (500 ipm) in climb direction: (a) 20 passes; (b) 40 passes; (c) 60 passes; (d) 80 passes; and (e) 100 passes.
Figure 3.6.3 Panel chipping results of five 10% cobalt grade tungsten carbide inserts cutting in the climb direction.

3.6.2. Effect of Varying Spindle Speed on Tool Wear, Panel Chipping, and Tool Spindle Vibration

A preliminary test on varying the spindle speed was conducted. This was done to determine the effect of varying the spindle speed of the CNC router on tool wear, chipping, and vibration signal of the tool spindle. The effect that will help to establish a relationship is crucial for the feedback control technique that is designed to extend the effective tool life.

A 10% cobalt grade tungsten carbide insert was used to perform a climb cutting process with feed speed of 12.7 in/min (500 ipm) and completed 200 passes. The spindle
speed was increased starting from 12,000 rpm until 18,000 rpm. The increased was a step function with the list of the spindle speed as follows: 12,000 rpm, 12,300 rpm, 12,600 rpm, 13,000 rpm, 13,300 rpm, 13,600 rpm, 16,000 rpm, 16,500 rpm, 17,000 rpm, and 17,500 rpm. The spindle speed values for the step function were determined after taking the spindle speed range of the CNC router, as well as the location of the machine resonance into consideration. The interval between the spindle speed values was determined in a way that the resonance region was avoided, and the spindle speed was changed in each set of 20 passes before reaching the maximum spindle speed. Vibration signal of the tool spindle was acquired during cutting. The tool wear and panel chipping were also determined.

The results of the spindle vibration and panel chipping are shown in Figure 3.6.4. The RMS values were extracted from the second frequency band of 5,500 Hz – 6,750 Hz. As illustrated, there was a decrease in chipping when the spindle speed was increased, specifically after the spindle speeds of 12,300 rpm, 13,000 rpm, and 16,000 rpm. This could be due to the ‘self-sharpening effect’ of the cutting tool. The spindle speeds were determined so that the incremental speed ramping was near 18,000 rpm when the 200 cutting passes were completed. However, an exception was made where spindle speed values were skipped, which left a large gap between the 13,600 rpm and 16,000 rpm. This was done in order to avoid the resonance around the 15,000 rpm spindle speed that was noticed during other preliminary tests. It is also important to note that a high increment in spindle speed will accelerate the wear on the cutting tool.

There was an increase in the spindle vibration after 13,300 rpm and beyond 100 cutting passes. A higher vibration was realized as the tool became worn. Additionally, a visibly higher spike can be observed at the 141 pass, which could also be due the ‘self-sharpening effect’ as described by Lemaster et al. (2000b).
Figure 3.6.4 RMS and panel chipping results of a 10% cobalt grade tungsten carbide insert cutting in the climb direction at different spindle speeds and 12.7 m/min (500 ipm) of feed speed.

In order to see the effect of varying the spindle speed in terms of its performance, a comparison was done for cutting at: (1) 12,000 rpm; (2) varying the spindle speed or step function from 12,000 rpm to 17,500 rpm; and (3) 18,000 rpm. Figure 3.6.5 shows that by varying the spindle speed, the panel chipping was reduced. The panel and cumulative chipping was done at the 180th pass as the panel chipping at the 200th cutting pass was when the tool was considered worn out and therefore, could be considered as an outlier in a control scheme.
Figure 3.6.5 Cumulative panel chipping and chipping at 180th cutting pass of 10% cobalt grade tungsten carbide inserts cutting in the climb direction at different spindle speeds and 12.7 m/min (500 ipm) of feed speed.

3.6.3. Effect of the Variability in the Density of Different Boards on Tool Wear, Panel Chipping, and Tool Spindle Vibration

The effect of the variability in density of the different batches of boards on tool wear, chipping, and tool spindle vibration was determined. The investigation of this effect is important as the 1.2 m × 2.4 m (4 ft. × 8 ft.) melamine-coated particleboard panels were purchased in batches throughout the completion of the preliminary tests. The density variation within board could be important as well as batch variation. As there was some variation in some replications of the tests, this section was trying to identify if it was a natural
variation in the board or due to the fact that the boards were purchased at such different times.

a) Methodology

The x-ray densitometry was used to determine the density variation across the board batches. The x-ray vertical density profile (VDP) of the boards was determined using a Quintek Measurement Systems’ (QMS) Tree Ring Scanner (Model QTRS-01X), which is a density profiler as shown in Figure 3.6.6. A VDP can be defined as the density variation across the thickness of a board.

![Figure 3.6.6 Density profiler.](image)

Four 10% cobalt grade tungsten carbide inserts were selected in which each insert was used to machine boards from one of four different batches. The inserts were divided into two groups, with each group having similar machining parameters as detailed in Table 3.6.2. Two parameters that were different between the two groups were the number of batches, and the spindle speed value. The four batches of boards were purchased at different times from Lowe’s Home Improvement store in Cary, North Carolina. The first batch was purchased in
December 2010, the second batch in June 2011, the third batch in July 2011, and the fourth batch was purchased in November 2011. The boards were cut shortly after they were purchased. While the age of these boards may affect its machinability, it should not affect the density gradient. There could be other possible sources of variation.

Table 3.6.1 Machining parameters for tungsten carbide inserts.

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool &amp; Batch Numbers*</td>
<td>A (#2), B (#3)</td>
<td>C (#1), D (#4)</td>
</tr>
<tr>
<td>Cutting Direction</td>
<td>Climb</td>
<td>Climb</td>
</tr>
<tr>
<td>Number of Cutting Passes</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Spindle Speed</td>
<td>15,000 rpm</td>
<td>18,000 rpm</td>
</tr>
<tr>
<td>Feed Speed</td>
<td>500 ipm</td>
<td>500 ipm</td>
</tr>
</tbody>
</table>

* A large batch number represents a batch of boards most recently purchased.

Each carbide insert completed 200 cutting passes (~200 m of length of cut) on the CNC router, which was comprised of two sets of 100-cutting passes. Each 100-pass set was done on a 0.6 m × 1.2 m (2 ft. × 4 ft.) panel. For the purpose of the VDP analysis, five samples with dimensions of 1 cm × 2 cm × 4.5 cm were cut from each of the 0.6 m × 1.2 m (2 ft. × 4 ft.) panel. Thus, each carbide insert was represented by 10 samples. The samples were loaded in a holder (Figure 3.6.7) before they were inserted into the density profiler.
b) Results and Discussion

Following are the results on the effect of density on tool wear, chipping, and tool spindle vibration.

Tool Wear

The panel density results of the board batches from Group 1 and Group 2 are presented in Figures 3.6.8 and 3.6.9, respectively. The average panel density was compared with the amount of tool wear for the carbide insert that had completed 200 cutting passes on the boards. In Figure 3.6.8, the average panel density for Batch 2 was 723.87 kg/m$^3$, where it was higher than Batch 3 with 659.49 kg/m$^3$. The tool wear amount also followed the same pattern where the carbide insert that cut the boards with higher average panel density produced higher tool wear with 294 µm as compared to 55 µm for Batch 3.

As for Group 2, the average panel density for boards from Batch 1 was lower than Batch 4 with 675.96 kg/m$^3$ and 738.33 kg/m$^3$, respectively (Figure 3.6.9). The tool wear for Batch 1 was also slightly higher than Batch 4. It can be seen that for Group 2, the difference in the average panel density between the boards’ batches seemed to cause a small difference in the amount of tool wear. The amount of tool wear of the three carbide inserts that cut
boards from Batch 1, 2, and 4 had a small difference except for tool that cut the boards from Batch 3.

![Graph showing Effect of Panel Density on Tool Wear](image)

Figure 3.6.8 Comparisons of board density and tool wear for Group 1.

**Effect of Panel Density on Tool Wear**
(10% Cobalt Tungsten Carbide Insert, 15,000 RPM Spindle Speed, 12.7 m/min (500 IPM) Feed Speed, Climb Cut Direction, 200 Continuous Passes)

<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Density (Kg/m³)</th>
<th>Tool Wear (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch 2</td>
<td>723.87</td>
<td>294</td>
</tr>
<tr>
<td>Batch 3</td>
<td>659.49</td>
<td>55</td>
</tr>
</tbody>
</table>
Although there was a small difference in terms of the tool wear, the different level of tool wear still produced a varied amount of panel chipping as shown later in this section. The panel density of the boards from different batches could have an effect on the amount of tool wear on the tungsten carbide inserts. The tool with the lowest tool wear could be an anomaly; however, it was worth to further investigate the panel density’s variation. A statistical t-test was done using JMP® Pro 10 by SAS Institute Inc. to see if there was a significant difference in the panel density between Batch 2 and Batch 3, and Batch 1 and Batch 4. Statistical results showed that there was a significant difference in panel density between Batch 2 and 3 with a P-value of <0.0001; t-value = 8.13 and df = 11.3. As for the
comparison between Batch 1 and 4, its panel density was significantly different from each other with a P-value of 0.0002; t-value = 5.38 and df = 11.6.

Figures 3.6.10 and 3.6.11 show the density gradient of the two board batches from Group 1, with and without error bars, respectively. It can be observed that, Batch 3 that had a lower tool wear possessed a lower surface density as compared to Batch 2.

Figure 3.6.10 Comparison of density variation across thickness between Batch 2 and 3.
Figure 3.6.11 Comparison of density variation across thickness between Batch 2 and 3 (with standard error bars).

Figure 3.6.12 shows the mean density of the boards from the four batches. The density for batches 2 and 4 were higher than batches 1 and 3. The VDP in Figure 3.6.13 that shows the variation density of the boards’ thickness verifies this result.
Figure 3.6.12 Panel density of melamine-coated particleboard from different batches.
Panel Chipping

The panel chipping results from the two tungsten carbide inserts that cut the boards from Batch 2 and 3 (Group 1) are illustrated in Figure 3.6.14. The chipping on boards from Batch 2, which had a higher average panel density of 723.87 kg/m\(^3\), was higher than those from Batch 3 (659.49 kg/m\(^3\)), however, the chipping at the 120\(^{th}\) and 140\(^{th}\) passes were much lower. Figure 3.6.15 shows the chipping results for Group 2. The boards from Batch 1 had a higher chipping even though it had a lower average panel density of 675.96 kg/m\(^3\) as compared to Batch 4 (738.33 kg/m\(^3\)). It appeared that the panel density had an effect on panel chipping. Based on the previously stated statistical t-test, there was a significant difference in the panel density between Batch 2 and Batch 3, and Batch 1 and Batch 4. Thus, this could affect the amount of tool wear, which could also being reflected in the amount of panel chipping.
Figure 3.6.14 Effect of panel density on chipping for Group 1.
**Tool Spindle Vibration**

The tool spindle vibration results from both groups are presented in the following figures. Figure 3.6.16 compares the RMS between Tool A that had cut boards from Batch 2, and Tool B that had cut boards from Batch 3. The RMS shown was at the frequency band of 6,750 Hz – 8,000 Hz, which was thought to be sensitive to the tool spindle vibration from other preliminary tests discussed above. The spindle vibration for Tool B was slightly higher than Tool A, although its tool wear and panel density were lower than Tool A.
In Figure 3.6.17, both tools showed similar vibration pattern, and magnitude. From the preliminary test it appeared that the panel density had an effect on the vibration of the tool spindle. As previously stated, there was a significant difference in the panel density between Batch 2 and Batch 3, and Batch 1 and Batch 4. Therefore, the difference could generally affect the tool spindle vibration.
In summary, the experiments showed that density gradients match with the panel densities that were measured directly from the board. The panel density of the boards from different batches appeared to have an effect on the amount of tool wear on the tungsten carbide inserts. It was also found that the panel density appeared to have an effect on panel chipping and the vibration of the tool spindle. Additionally, statistical t-test showed that there was a significant difference in panel density between the board batches (i.e., Batch 2 versus Batch 3, and Batch 1 versus Batch 4), at 0.05 significance level.
3.7. Effect of Cutting Configuration on Panel Chipping

At the very beginning of the preliminary work, cutting tests were done by performing 100 cutting passes twice to obtain 200 cutting passes. It was found that there was a decrease in the number of panel chipping at the 120th pass, which was after a total of cutting of approximately 120 m. This test was done to evaluate the difference between cutting 100 passes twice (i.e. same starting cutting position), and cutting 200 passes at once (placing two words side by side), and also possible causes of the drop in chipping.

The following are the assumptions that were made regarding the drop in panel chipping:

1. During performing the 100 cutting passes twice, the 120th pass was located in the first set of the second panel. Thus, in between changing and placing the second panel (which could take up to more than five minutes), it allowed the cutting tool to cool down. As the cutting for the second board started, the effect of the decreased in temperature of the tool could result in less chipping.

2. There could be a ‘spot’ on the CNC router table that caused the behavior at the 120th pass.

3. The chip load could be the reason for the drop.

In order to address the first assumption, a cutting operation was conducted in which two panels were placed side by side on the CNC router table to reduce the chance of blade cooling. A tungsten carbide insert with 10% cobalt binder was used to cut the panels at a spindle speed and feed speed of 15,000 rpm and 12.7 m/min (500 ipm), respectively. After the degree of chipping was measured, the drop at the 120th pass can still be observed as shown in Figure 3.7.1.

The second assumption was addressed by conducting a test to determine the effect of table position, which can be found in the section entitled Effect of Cutting at Different Positions on the CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration.
As for the third assumption, which was the effect of chip load, cutting tests were done in which three 10% cobalt grade tungsten carbide inserts were used to perform 200 cutting passes on melamine-coated particleboards at 15,000 rpm of spindle speed. Three feed speeds were used: 7.6 m/min (300 ipm), 10.2 m/min (400 ipm), and 12.7 m/min (500 ipm). The different amount of chip load was achieved by varying the feed speeds. Detailed description and results can be found under the section entitled ‘Effect of Feed Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration’. Only the panel chipping result is presented in this section as shown in Figure 3.7.2. In the figure, the drop at the 120th still exists. These results show that the assumptions made earlier did not cause the decrease in panel chipping at the 120th pass.

![Panel Chipping for 10% Cobalt Tungsten Carbide Inserts Cutting in Conventional Direction at 15,000 RPM of Spindle Speed and 12.7 m/min (500 IPM) of Feed Speed](image)

Figure 3.7.1 Panel chipping when cutting 100 passes twice versus 200 passes at once.
3.8. Effect of Cutting at Different Positions on CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration

3.8.1. Introduction

Machining of melamine-coated particleboard was done at three different starting positions on the CNC router table in order to determine the effect of table position on tool wear, panel edge chipping, and tool spindle vibration.

Figure 3.7.2 Panel chipping when cutting at different feed speeds.
3.8.2. Methodology

Three new 10% cobalt grade tungsten carbide inserts were initially inspected for the presence of chipped edge. Each carbide insert completed five sets of 20 passes (i.e. a total of 100 passes ≈ 100 m), in the same pattern as shown in the Experimental Work section. The machining was done using a spindle speed of 18,000 rpm, and 12.7 in/min (500 ipm) of feed speed in the climb direction. The three tungsten carbide inserts represented three cutting scenarios in which each started the cutting at different positions. As shown in Figure 3.8.1, the first cutting scenario started at the farthest point (in the Y-axis direction) from the tool spindle ‘home’ position (i.e. the default position) where the Y-axis was 60 in., the second cutting scenario started at Position 2 with Y-axis was equal to 48 in., and the third one started at Position 3, which was the nearest point from the tool spindle with a Y-axis of 36 in.. Vibration signal data was collected as described in detail in the Experimental Work section. Tool wear was measured with a digital optical microscope, and the panel edge chipping count was also determined. Further details on these two measurements have also been elaborated in the Experimental Work section.

Figure 3.8.1 Starting positions on CNC router table (top view).
3.8.3. Results and Discussion

Following are the results on tool wear, panel edge chipping, and tool spindle vibration from the cutting tests.

Tool Wear

Figure 3.8.2 illustrates the cutting edge wear for the three tungsten carbide inserts that cut at positions 1, 2, and 3, respectively. It can be observed that the third position had the lowest wear. This is confirmed by observing the wear images presented in Figure 3.8.3 (refer to the second window in each tool. The second window is the part of the tool cutting edge that cut the high density area of the melamine-coated particleboard). The cause of Position 3 having a lower tool wear is not known. However, the difference in tool wear results (i.e. about 20 µm) between the first two positions and Position 3 could be considered as too small. Additional tests had been conducted with three replications in each cutting position. The results can be found under the Additional Studies chapter.
Figure 3.8.2 Tool wear of 10% cobalt grade tungsten carbide blades that cut at three different starting positions on the CNC router table.
Figure 3.8.3 Tool wear images of 10% cobalt grade tungsten carbide inserts that cut at: (a) Position 1; (b) Position 2; and (c) Position 3.

**Panel Chipping**

Although the wear on the blade that cut at Position 3 had the lowest wear, it however, produced the highest panel chipping count on the edge of the particleboard panels as compared to the other two tungsten carbide blades (Figure 3.8.4). The low wear and high panel chipping at Position 3 is contradictory to the fact that more chipping is produced due to an increase in tool wear. However, it could be that the difference in the tool wear amount for the three positions was considered small; and there could be a complex interaction that occurs between the cutting tool, spindle vibration and position of table. Additional tests were done with more replications in order to confirm the results. The results from the new test found that the means for tool wear, panel chipping, and tool spindle vibration were not
statistically significant among the three table positions. Thus, it could be stated that tool wear, and panel chipping were not affected by table position.

In Figure 3.8.5, the cumulative panel chipping result was presented. It can be observed that Position 3 had the highest chipping while positions 1 and 2 had a similar panel chipping level.
Figure 3.8.5 Cumulative chipping on particleboard produced by tungsten carbide blades cutting at different starting positions on CNC router table.

**Tool Spindle Vibration**

Tool wear and panel chipping results are needed to be correlated to the vibration signal of the tool spindle. Figure 3.8.6 shows the tool spindle vibration signal for the three starting positions. Each position had three RMS readings in each of the 20-pass set. It can be observed that the RMS readings for each position at each 20-pass set were close to each other. This can be viewed as having less variability, and they could be having the same pattern and level.
In order to determine the vibration pattern for each position, the three RMS readings at each 20-pass set were averaged as can be seen in Figure 3.8.7. In the graph, the first and second positions seemed to have the same pattern whereas the third position had a smooth increased pattern. In order to see the level or the real magnitude of the tool spindle vibration signal, the averaged of three RMS readings were normalized by dividing each averaged RMS value with the first RMS averaged value and then multiplied by 100 to get a percentage value. This is further discussed in the next paragraph.
Figure 3.8.7 Average of three RMS readings of frequency band two (5,500 Hz – 6,750 Hz) of three 10% cobalt grade tungsten carbide inserts that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at different positions on CNC router table (Note: Position 1 – farthest from the tool spindle home position).

Figure 3.8.8 shows the normalized version of the averaged of three RMS readings. It can be observed that Position 3 had a slightly higher vibration than the other two positions. However, it is more meaningful to look at the rate of change for each position through a cumulative count as illustrated in Figure 3.8.9.
Figure 3.8.8 Normalized RMS of frequency band two (5,500 Hz – 6,750 Hz) of three 10% cobalt grade tungsten carbide inserts that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at different positions on CNC router table (Note: Position 1 – farthest from the tool spindle home position).

The cumulative counts of the normalized and averaged of three RMS readings were presented in Figure 3.8.9. As can be seen, positions 2 and 3 seemed to have the same slope, while Position 1 had a less steep slope and a low level of vibration compared to the other two positions. The level of tool spindle vibration of the three positions was reflected in the amount of panel chipping produced. The tool spindle vibration results were initially presented in the forms of the three frequency bands; i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz, that were discussed in the Vibration Signal Analysis:
Frequency Band Selection and Extraction Processes section. The results of the tool spindle vibration at the three frequency bands for this test can be found in Appendix A.

In summary, based on the results of the table position test, Position 3 had the lowest tool wear, however, it produced the highest panel chipping and tool spindle vibration compared to the other two positions. As for Position 1 and 2, both positions followed the
logic of having the amount of tool wear that produced the appropriate amount of panel chipping and tool spindle vibration. Position 2 had a higher tool wear as well as its panel chipping and the vibration signal of the tool spindle as compared to Position 1. Most importantly, the rate of change in the tool spindle vibration as shown in the cumulative graph showed that the three positions had generally the same slope although Position 1 seemed to diverge slightly. Additional tests were conducted to provide further information on the effect of table position on tool wear, panel chipping, and tool spindle vibration. As stated earlier, tool wear and panel chipping were not affected by the table position factor. Tool spindle vibration was also found to be not significant. Details of the results on the additional test for table position can be found under section 4.5.

3.9. Effect of Cutting Using Cutterheads with Different Diameters on Tool Wear and Tool Spindle Vibration

3.9.1. Introduction

Machining on the CNC router was performed using two cutterheads with different diameters. The configurations of the small (20 mm or 0.75 in.) and large (51 mm or 2 in.) cutterheads are shown in Figure 3.9.1. This particular experiment was conducted in order to determine the difference in the vibration signal of the tool spindle. It also allowed for a better understanding of the overall behavior of the vibration of the tool spindle.
3.9.2. Methodology

Each cutterhead had three cutting replications using 10% cobalt grade tungsten carbide inserts. Each carbide insert completed 200 cutting passes totaling to approximately 200 m (650 ft.) of length of cut. Machining of melamine-coated particleboard panels was performed on a CNC router with a spindle speed of 15,000 rpm and 12.7 m/min (500 ipm) of feed speed in the conventional cutting direction. Since the larger cutterhead had two slots for inserting the carbide inserts, a ‘dummy’ blade was placed into the second slot where, prior to the test, it was ground down in order to allow a one-blade cut, and also to provide balance to the tool during cutting. For clarification, the term flute is referring to the cutting edge of the tool. Vibration signals of the CNC router tool spindle were acquired and analyzed, and then comparisons were made. The nose width values of the tools were measured after the cutting was completed in order to determine its wear state.
3.9.3. Results and Discussion

Figure 3.9.2 shows that the average tool wear when cutting with the large cutterhead was higher than the small cutterhead with 227 µm and 168 µm, respectively. This could be due to the higher peripheral or cutting speed for the large cutterhead. Klamecki (1979) in his comprehensive review of wood cutting tool wear, discussed and concluded that decreasing cutting speed can decrease tool wear. However, the cause of the tool wear reduction due to lower cutting speed is not known.

A one-way analysis of variance (ANOVA) was performed using JMP® Pro 9 from SAS® to assess the statistical difference between means. It was found that the means tool wear of the different cutterhead sizes were significantly different with a P-value of 0.009, F ratio of 22.5162, and R² equals to 0.85. It can be concluded that tool wear was affected by cutterhead size.

Figure 3.9.2 Tool wear of 10% cobalt grade tungsten carbide inserts on small versus large cutterheads.
The results of the power spectrum of the small and large cutterheads are shown in Figures 3.9.3 and 3.9.4, respectively. It can be seen that the large cutterhead had a larger vibration spectra. Additionally, as will be shown below, the RMS of the replications for both cutterheads confirms that the vibration signal of the large cutterhead was higher than the small cutterhead size. The higher spindle vibration could be due to the higher mass or the larger cutterhead or flute design.

**Small Cutterhead**

(Spindle Speed = 15K RPM, Feed Speed = 12.7 m/min (500 IPM))

![Ribbon plots showing spindle vibration of small cutterhead](image)

Figure 3.9.3 Ribbon plots showing spindle vibration of small cutterhead: (a) replication 1; (b) replication 2; and (c) replication 3.
Large Cutterhead
(Spindle Speed = 15K RPM, Feed Speed = 12.7 m/min (500 IPM)

Figure 3.9.4 Ribbon plots showing spindle vibration of large cutterhead: (a) replication 1; (b) replication 2; and (c) replication 3.

The tool spindle vibration for both cutting with the small and large cutterheads was further analyzed and presented in the next few graphs. Figure 3.9.5 shows the tool spindle vibration signal for all replications. Generally, the vibration data were similar, although some of the RMS readings were much higher than the rest of the data. Each replication had three RMS readings in each of the 20-pass set. In order to determine the statistical difference between the means, a one-way ANOVA test was performed. Results showed that the means of different cutterhead sizes were not significantly different from each other at each cutting
pass in which the vibration data were acquired. Therefore, it can be concluded that the vibration level was not affected by the cutterhead sizes. Further graphs are presented just for the purpose of describing the pattern of vibration for the two different cutterhead diameters.

Figure 3.9.5 RMS of frequency band two (5,500 Hz – 6,750 Hz) of six 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed using different cutterhead sizes.

The three RMS readings at each 20-pass set were averaged as presented in Figure 3.9.6. It can be observed that most of the replications seemed to have a consistent pattern except Rep 2 of the large cutterhead, which had several higher peaks. This could be due to the ‘self-sharpening effect’ of the tungsten carbide insert in which the breaking off of the tool leaves a sharp edge as described in a study by Lemaster et al. (2000b). Although Lemaster et
al. (2000b) could not explain the increase and drop of the vibration signal, Lim (1995) speculated the cause but it was not verified.

Figure 3.9.6 Average of three RMS readings of frequency band two (5,500 Hz – 6,750 Hz) of six 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed using different cutterhead sizes.

The RMS was then normalized where the first data point started at the same point for comparison purpose as illustrated in Figure 3.9.7. In the figure, Rep 2 of the large cutterhead was higher than the other replications. The reason is unknown, although, board density could be the reason.
Figure 3.9.7 Normalized RMS of frequency band two (5,500 Hz – 6,750 Hz) of six 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed using different cutterhead sizes.

The normalized and averaged of three RMS reading were presented in a cumulative form as shown in Figure 3.9.8. All three replications for the small cutterhead seemed to have the same slope or rate of change and they were also close to each other in value. As for the large cutterhead, Rep 2 had a higher rate of change, which was due to its steeper slope as compared to the other two replications. Additionally, Rep 3 of the large cutterhead had the lowest rate of change, and it can be speculated that this could be due to board density.
Figure 3.9.8 Cumulative RMS of frequency band two (5,500 Hz – 6,750 Hz) of six 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed using different cutterhead sizes.

In order to further illustrate which cutterhead size had the highest vibration level, the three replications in each cutterhead type were averaged. The result is presented in Figure 3.9.9. As illustrated, the large cutterhead produced the highest rate of change in its vibrations, which could be due to the large mass of the cutterhead. In addition, the larger cutterhead may not be as balanced as the smaller one, which could compound the mass difference.
Figure 3.9.9 Average cumulative RMS at frequency band two (5,500 Hz – 6,750 Hz) of small cutterhead versus large cutterhead that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (average of three replications).

This test was conducted to show the effect of cutterhead size on tool spindle vibration. Tool wear was significantly different in which the larger cutterhead produced higher tool wear than the smaller cutterhead. Additionally, although the larger cutterhead seemed to produce high vibration level compared to the small one, it was found that the means of different cutterhead sizes were not significantly different. Thus, it can be stated that the vibration level was not affected by the cutterhead sizes.
3.10. Effect of Cutting with Different Number of Cutting Flutes on Tool Wear and Tool Spindle Vibration

3.10.1. Introduction

Tests were conducted to determine the effect of cutting with one-flute and two-flute cutting tools on the vibration signal of the tool spindle.

3.10.2. Methodology

A large cutterhead (51 mm or 2 in. in diameter) with two slots for inserting blades was used in the test. Two cutting scenarios were conducted in which the first scenario involved cutting using only one flute (the other slot had a ‘dummy’ blade inserted), and the second scenario had a carbide insert in each of the two slots. Tungsten carbide inserts with 10% cobalt binder were used. Each cutting scenario had three replications in which each cutting operation was done with a spindle speed of 15,000 rpm, and 12.7 m/min (500 ipm) of feed speed in the conventional direction. Each replication completed 200 passes (ten sets of 20-passes) on melamine-coated particleboard, totaling to 200 m (650 ft.) in length of cut. Vibration signals were acquired from the first three passes in each of the 20-pass set. After the machining tests were completed, tool wear was measured and the vibration signals were analyzed. Comparisons were made between the one- and two-flute cutting.

3.10.3. Results and Discussion

The tool wear result is shown in Figure 3.10.1. The two-flute cutting had a lower tool wear. This is due to the fact that a cutterhead with two flutes produces a smaller chip load for each insert. However, based on the one-way ANOVA test, the means of the tool wear for the different number of cutting flutes were not significantly different (P-value = 0.4194, F Ratio = 0.7735, and R² = 0.13). This could mean that tool wear is not affected by the number of cutting flutes in this case.
Figure 3.10.1 Tool wear of one- and two-flute cutting.

Tool spindle vibration result is presented next, which further describes the nature of cutting with one-flute and two-flute.

Figure 3.10.2 shows the distribution of the tool spindle vibration signal for all replications for both cutting with one flute and two flutes. It can be observed that the vibration when cutting with two flutes seemed to be lower than the one-flute cutting.

However, a one-way ANOVA statistical test showed that the means of different number of cutting flutes were not significantly different from each other at each cutting pass in which the vibration data were acquired. Thus, it can be concluded that the vibration level was not affected by the number of cutting flutes. The following graphs are presented for the purpose of describing the vibration pattern of the cutterheads with different number of cutting flutes.
Figure 3.10.2 RMS at frequency band two (5,500 Hz – 6,750 Hz) of six replications of cutting with one-flute and two-flute using 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed.

In order to view the data clearly, the three RMS readings that were acquired in each set of 20 passes were averaged as illustrated in Figure 3.10.3. The figure shows that Rep 2 of the one-flute cutting had several peaks, and as mentioned before, this could be explained by due to the ‘self-sharpening effect’, which is the breaking off of the tool that leaves a sharp edge as described in a study by Lemaster et al. (2000b). Although Lemaster et al. (2000b) work could not explain the cause behind the increase and drop of the vibration signal, Lim (1995) speculated the relationship between vibration amplitude and flank wear and cutting time but did not further verify.
Figure 3.10.3 Average of three RMS readings of frequency band two (5,500 Hz – 6,750 Hz) of six replications of cutting with one-flute and two-flute using 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed.

The average of three RMS readings was normalized so that all replications start at the same point. Figure 3.10.4 shows the normalized data, and it can be seen that the two-flute cutting replications maintained at the lower level of the group, except that Rep 3 of the one-flute cutting had the lowest vibration. The cause is unknown, although this could be due to the effect of board density.
Figure 3.10.4 Normalized RMS of frequency band two (5,500 Hz – 6,750 Hz) of six replications of cutting with one-flute and two-flute using 10% cobalt grade tungsten carbide inserts that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed.

Figure 3.10.5 shows a cumulative version of the previous graph. This is to determine the pattern and the slope of the RMS for each replication. The highest and the lowest rate of changes came from Rep 2 and Rep 3 of the one-cutting flute, respectively. Board effect could play a role, although the actual cause is not known.
The three replications in each cutting scenario were averaged. As illustrated in Figure 3.10.6, the one-flute cutting produced the highest rate of change compared to the two-flute cutting, which means it had higher level of tool spindle vibration as the cutting process progressed.
Figure 3.10.6 Average cumulative RMS of frequency band two (5,500 Hz – 6,750 Hz) of one-flute versus two-flute cutting that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (average of three replications).

The objective of this test was to determine the effect of cutting with one-flute and two-flute cutting tools on the vibration signal of the tool spindle. Tool wear for the different number of cutting flutes were not significantly different. In the case of the vibration level, results showed that the number of cutting flutes were not significantly different from each other at each cutting pass. As a conclusion, the vibration level was not affected by the number of cutting flutes. Additionally, a two-flute cutterhead produced a well-balanced tool condition that caused a lower tool wear and tool spindle vibration based on the results of this test.
3.11. Effect of Cutting at Different Feed Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration

3.11.1. Introduction

The experiment was done in order to determine the effect of cutting at different feed speeds of the cutterhead. When the spindle speed is kept constant and the feed speed is varied, than a varying chip load is produced. Chip load can be defined as the thickness of the chip in every cut. Chip load also determines the amount of heat being removed from the cutting zone. This is because chip removal creates heat on the material surface through the action of the cutting tool (Dagenais and Salenikovich, 2008). Chip load is also related to cutting force. An increased in chip thickness (i.e. chip load size) results in increased cutting force (Csanády and Magoss, 2013). This will eventually cause an increase in wear rate of the cutting tools.

This test was preliminary and exploratory in nature, which was why a more thorough and detailed study was not conducted at this time. Additional test with more replications were done later and reported in a later section.

3.11.2. Methodology

Three 10% cobalt grade tungsten carbide inserts were used in which each cut 200 passes (200 m or 656 ft. of length of cut). Machining was done in the conventional direction with a spindle speed of 15,000 rpm. Three feed speeds were used; 7.6 m/min (300 ipm), 10.2 m/min (400 ipm), and 12.7 m/min (500 ipm). Vibration signals were acquired and analyzed, and then comparisons were made between cutting with different feed speeds. Tool wear was determined by measuring the changes in the nose width of the blade using a digital optical microscope. The number of chips in the melamine coating of the particleboard was also measured.

3.11.3. Results and Discussion

Following are the results on tool wear, panel chipping, and tool spindle vibration from the cutting test.
**Tool Wear**

In Figure 3.11.1, it can be observed that the lowest feed speed produced the highest tool wear, while the highest feed speed produced the lowest in the amount of tool wear on the tungsten carbide insert. Figure 3.11.2 shows a normalized graph of the amount of tool wear. It can be observed that the percent of difference was 3% and 6% for 10.2 m/min (400 ipm) and 12.7 m/min (500 ipm), respectively.

The highest tool wear was produced by the lowest feed speed, which can be visually confirmed in Figure 3.11.3. The lowest feed speed had the smallest chip load. Thus, the heat from the cutting zone does not being removed effectively when cutting at low feed speed (i.e. chip load for the three feed speeds: lowest = 0.0200 in.; medium = 0.0267 in.; and highest = 0.0333 in.). Tool wear may not be significantly different; however, additional work would be needed to verify this.

Figure 3.11.1 Tool wear of tungsten carbide inserts that cut at different feed speeds.
Figure 3.11.2 Percent difference of tool wear of carbide inserts cutting at different feed speeds.

Figure 3.11.3 Cutting edge images of blades cutting at feed speed of: (a) 7.6 m/min (300 ipm); (b) 10.2 m/min (400 ipm); and (c) 12.7 m/min (500 ipm).
The high amount of tool wear for the lowest feed speed can be further explained by the number of tool engagement per inch. Figure 3.11.4 shows that the lowest feed speed of 7.2 m/min (300 ipm) produced the highest number of tool engagement per inch (50). This was followed by 37.5 for feed speed of 10.2 m/min (400 ipm), and 30 for feed speed of 12.7 m/min (500 ipm). The numbers were calculated by dividing the spindle speed (i.e. 15,000 rpm) by the feed speed.

![Number of Tool Engagement of Different Feed Speeds at Spindle Speed of 15000 RPM](image)

Figure 3.11.4 Number of tool engagement per inch for different feed speeds.

**Panel Chipping**

Figure 3.11.5 shows that machining at the highest feed speed with the highest chip load produced the lowest chipping, meanwhile, cutting a low feed speed that has the lowest chip load resulted in a higher chipping on the melamine-coated particleboard. This is in line with the tool wear result. Figure 3.11.6 illustrates the same panel chipping in a cumulative version. It can be concluded that a high chip load could reduce the panel chipping. Although
changing the feed speed could reduce panel chipping, it was not being investigated in this study due to the reluctance of the industry to reduce production speeds. Thus, spindle speed was selected in order to optimize the cutting process on the CNC router, and also to conduct a research product which can be related and more useful to the industry application.

Figure 3.11.5 Panel chipping when cutting at different feed speeds and 15,000 rpm of spindle speed in the conventional direction with 10% cobalt grade tungsten carbide inserts.
Figure 3.11.6 Cumulative panel chipping when cutting at different feed speeds and 15,000 rpm of spindle speed in the conventional direction with 10% cobalt grade tungsten carbide inserts.

**Tool Spindle Vibration**

The tool spindle vibration for the cutting that was produced by the three feed speeds is shown in Figure 3.11.7. The distribution of the RMS readings for each feed speed seemed to follow a similar pattern, and the values were close to each other.
Figure 3.11.7 RMS of frequency band two (5,500 Hz – 6,750 Hz) of three 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 15,000 rpm of spindle speed and different feed speeds on CNC router table.

A better observation can be made through obtaining the average of the three RMS readings from each set of the 20 passes as shown in Figure 3.11.8. It can be observed that the highest feed speed seemed to produce the lowest vibration compared to the other two feed speeds. This is in line with the lowest tool wear and panel chipping that a feed speed of 12.7 m/min (500 ipm) produced.
Figure 3.11.8 Average of three RMS readings of frequency band two (5,500 Hz – 6,750 Hz) of three 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 15,000 rpm of spindle speed and different feed speeds on CNC router table.

A normalized version of the tool spindle vibration is presented in Figure 3.11.9. It shows that the first RMS average starts at the same position that could show the real level of vibration for each feed speed. As can be seen, the tool spindle vibration for the three feed speeds were very close to each other, and could be considered as having the same level of tool spindle vibration. Additional replications are needed to confirm this result.
Figure 3.11.9 Normalized RMS of frequency band two (5,500 Hz – 6,750 Hz) of three 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 15,000 rpm of spindle speed and different feed speeds on CNC router table.

In Figure 3.11.10, a cumulative version of the previous graph is shown. It can be observed that all three feed speeds had similar slopes. This could be explained by the small differences in terms of the amount of tool wear. An additional test was done with three replications for each feed speed in order to determine if it shows a similar trend. The tool spindle vibration results were initially presented in the forms of the three frequency bands; i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The results can be found in Appendix B.
It can be summarized that the lowest feed speed of 7.6 m/min (300 ipm) produced the highest tool wear as well as panel chipping. Meanwhile, the highest feed speed of 12.7 m/min (500 ipm) had the lowest amount of tool wear and panel chipping. However, the tool spindle vibration for the three feed speeds seemed to have similar slopes. Additional tests had been done to provide further information on the effect of different feed speeds on tool wear, panel chipping, and tool spindle vibration. The results can be found under the Additional Studies chapter.
3.12. Effect of Cutting at Different Spindle Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration

3.12.1. Introduction

Machining was conducted with varying spindle speeds i.e. 12,000 rpm, 15,000 rpm, and 18,000 rpm. The experiment was done in order to determine its effect on tool wear, panel chipping, and vibration signal of the tool spindle.

3.12.2. Methodology

This experiment used three 10% cobalt grade tungsten carbide inserts for each spindle speed (nine tungsten carbide inserts in total). Each tool completed 200 cutting passes (i.e. 200 m of total cutting length) in conventional direction with 12.7 m/min (500 ipm) of feed speed. The data from the three spindle speeds were evaluated. The ribbon plot was used to observe the vibration frequency components that changed with time. Panel chipping and tool were measured after tests were completed. The amount of panel chipping and tool wear were correlated with the results observed from the vibration signals of the tool spindle.

3.12.3. Results and Discussion

Tool Wear

Figure 3.12.1 shows that the highest spindle speed produced the highest amount of tool wear. This is due to the fact that at 18,000 rpm, the number of impact or tool engagement per inch is also higher than the other two spindle speeds (i.e. tool engagement per inch = spindle speed (rpm) / feed speed (ipm); 12,000 rpm = 24; 15,000 rpm = 30; and 18,000 rpm = 36).

In order to assess the significant effect of spindle speed on tool wear, a one-way analysis of variance (ANOVA) was performed using JMP® version 9 statistical software package. There were significant differences in the means of the three spindle speeds with P-value of 0.001 (F ratio = 26.7377, $R^2 = 0.90$). A Tukey honestly significant difference (HSD) test was performed with the same statistical software and found that spindle speeds of 15,000 rpm and 18000 rpm were not significantly different from each other. However,
spindle speed of 12,000 rpm was significantly different from the other two. It can be concluded that higher spindle speeds result in an increase in tool wear.

Figures 3.12.2, 3.12.3 and 3.12.4 illustrate similar results in the form of images of the tool wear on the cutting edges of the tungsten carbide inserts.

![Tool Wear of 10% Cobalt Grade Tungsten Carbide Inserts Cutting at Different Spindle Speeds](image)

Figure 3.12.1 Tool wear of tungsten carbide inserts cutting at different spindle speeds and feed speed of 12.7 m/min (500 ipm) in the conventional direction. Note: Different letters indicate statistical significance.
Figure 3.12.2 Cutting edge images of blades that cut at spindle speed of 12,000 rpm:
(a) Rep 1; (b) Rep 2; and (c) Rep 3.
Figure 3.12.3 Cutting edge images of blades cutting at spindle speed of 15,000 rpm: (a) Rep 1; (b) Rep 2; and (c) Rep 3.
Figure 3.12.4 Cutting edge images of blades cutting at spindle speed of 18,000 rpm: (a) Rep 1; (b) Rep 2; and (c) Rep 3.

Panel Chipping

The panel edge chipping result as illustrated in Figure 3.12.5 shows that the 18,000 rpm of spindle speed was the highest, while the 12,000 rpm was the lowest. This could be due to the degree of tool wear as a higher spindle speed produces a higher amount of tool wear. The chip loads for spindle speeds of 12,000 rpm and 18,000 rpm were 0.0417 in. and
0.0278 in., respectively. Another interesting observation can be seen in that there was a drop in the amount of panel chipping at the 120\textsuperscript{th} pass for all the spindle speeds. It had been speculated that this could be due to the board density, cutting configuration, position of cutting on the CNC router table, cooling off of the tool, and etc. This particular issue is fully discussed under the Additional Studies chapter.

Figure 3.12.5 Panel chipping of melamine-coated particleboard when cutting at different spindle speeds and 12.7 m/min (500 ipm) of feed speed in the conventional direction with 10% cobalt grade tungsten carbide inserts.
The cumulative panel chipping is shown in Figure 3.12.6 in which similar result can be seen where the 18,000 rpm still produced the highest panel chipping. The other two spindle speeds seemed to produce the same level of panel chipping; however, the 15,000 rpm of spindle speed was slightly higher towards the end of the cutting passes.

Figure 3.12.6 Average cumulative panel chipping of melamine-coated particleboard when cutting at different spindle speeds and 12.7 m/min (500 ipm) of feed speed in the conventional direction with 10% cobalt grade tungsten carbide inserts.
**Tool Spindle Vibration**

Figure 3.12.7 shows the tool spindle vibration during the cutting test that was produced by the three different spindle speeds. It can be observed that the three replications for the 18,000 rpm of spindle speed generally dominated the upper portion of the graph beyond halfway through the cutting process. This could be contributed by the high amount of tool wear and the steep increase in panel chipping, which occurred halfway through the cutting process. Meanwhile, spindle speeds of 12,000 rpm and 15,000 rpm seemed to produce the same level of tool spindle vibration. Several higher data points can be seen for the 15,000 rpm, which could be due to experimental variation.
Figure 3.12.7 RMS of frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 12.7 m/min (500 ipm) of feed speed and at different spindle speeds on CNC router table.

Average of the three RMS readings from each set of 20 passes is shown in Figure 3.12.8. The highest spindle speed seemed to produce the highest vibration when cutting towards the end of the cutting process.
Figure 3.12.8 Average of three RMS readings of frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 12.7 m/min (500 ipm) of feed speed and different spindle speeds on CNC router table.

Figure 3.12.9 shows a normalized version of the tool spindle vibration. As illustrated, the highest spindle speed produced a higher level of tool spindle vibration while the 12,000 rpm and 15,000 rpm seemed to have similar magnitude. This could be attributed to the higher amount of tool wear and panel chipping that the 18,000 rpm produced.
Figure 3.12.9 Normalized RMS of frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 12.7 m/min (500 ipm) of feed speed and different spindle speeds on CNC router table.

Figure 3.12.10 depicts a cumulative version of the previous graph. The results remain the same in that the 18,000 rpm of spindle speed produced the highest tool spindle vibration. The tool spindle vibration results were initially presented in the forms of the three frequency bands; i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The results can be found in Appendices C and D. Appendix C shows the tool spindle vibration for individual replication, while Appendix D shows the average RMS from the three replications of each spindle speed.
Figure 3.12.10 Cumulative RMS of frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the conventional direction at 12.7 m/min (500 ipm) of feed speed and different spindle speeds on CNC router table.

Figure 3.12.11 shows the average of the cumulative RMS shown previously. It confirms that the highest tool spindle vibration was produced by the 18,000 rpm. Spindle speeds of 12,000 rpm and 15,000 rpm showed similar percent of change in terms of the vibration of the tool spindle.
It can be summarized that the highest spindle speed of 18,000 rpm produced the highest tool wear, which could be due to the higher number of tool engagement per inch. Meanwhile, the lowest spindle speed of 12,000 rpm produced the lowest tool wear. The 18,000 rpm of spindle speed also produced a higher degree of panel edge chipping compared to the other two spindle speeds of 12,000 rpm and 15,000 rpm. This could be due to the higher tool wear amount. Different spindle speeds produce different chip load or chip thickness. The chip load for 12,000 rpm, 15,000 rpm, and 18,000 rpm is 0.0417 in., 0.0333 in., and 0.0278 in, respectively. A faster spindle speed reduces the chipping on the panel (in
the short term) since it cuts a smaller chip; however, it accelerates tool wear. As for the vibration of the tool spindle, 18,000 rpm produced the highest level of vibration, and spindle speeds of 12,000 rpm and 15,000 rpm produced similar magnitude.

From the test, the second frequency band at 5,500 Hz – 6,750 Hz appears to show a good correlation with the panel chipping, and thus, it can be used as the indicator to monitor the tool condition and the quality of the machined workpiece (refer to section 3.5). A previous study by Lemaster et al. (2000b) found a frequency band of 1,000 Hz – 7,000 Hz to be the best frequency to perform the monitoring and control on a CNC router to reduce melamine chipping. The frequency band in that study had a wider range, and it was performed on a different CNC router model and configuration. However, it is interesting to note that frequency band two of the current study was within the frequency range of the older study.

3.13. Effect of Cutting with Different Carbide Grades on Tool Wear, Panel Chipping, and Tool Spindle Vibration

3.13.1. Introduction

Machining was conducted using different tungsten carbide grades. The grades represent the different degree of hardness based on the amount of the cobalt binder. The experiment was done in order to determine its effect on tool wear, panel chipping, and vibration levels of the tool spindle.

3.13.2. Methodology

Tungsten carbide inserts were used to cut melamine-coated particleboard on the CNC router. Three tungsten carbide grades were used, which were classified according to the percentage amount of cobalt binder: (1) T02SMG (2.5%), (2) H6N (6%), and (3) T10MG (10%). The H6N grade was manufactured by Sandvik, while the other two grades were manufactured by Tigra. The lowest amount of cobalt binder increases the hardness of the tool; however, it is more brittle. The machining was done in the climb direction at a constant spindle speed and feed speed of 15,000 rpm, and 12.7 m/min (500 ipm), respectively. A total
of 200 cutting passes representing 200 m of length of cut were completed. Tool spindle vibration signals were collected during each machining set. Analysis on the data was performed to see the effect of using different percentages of cobalt binder. Tool wear was measured using a digital optical microscope while the degree chipping on the edge of melamine-coated particleboard was measured by counting chips that were larger than 2 mm in width and height.

3.13.3. Results and Discussion

**Tool Wear**

In Figure 3.13.1, it can be observed that the T10MG grade or 10% cobalt grade tungsten carbide inserts had the highest wear of 282 µm; meanwhile the 2.5% (T02SMG) had the lowest with 95 µm. Having a high cobalt content makes a tool soft but tough. A 10% cobalt grade tungsten carbide tool has a higher wear rate than tools containing 2.5% and 6% of cobalt binder.

The effect of tungsten carbide grade on tool wear of tungsten carbide inserts was assessed and also presented in Figure 3.13.1. A statistical software package; JMP® version 9 was used to perform a one-way analysis of variance (ANOVA). It was found that there were significant differences between the tool grades (P-value = 0.0006, F ratio = 31.6720, R² = 0.91). Further analysis using the Tukey honestly significant difference (HSD) test showed that all three carbide grades were significantly different from each other. It can be concluded that tool grade affected the amount of tool wear, and that the higher the percentage of cobalt binder, the higher is the tool wear. Figures 3.13.2, 3.13.3, and 3.13.4 show the images of the tool wear of these cutting tool inserts with different tungsten carbide grades. The difference between the wear rates for the different grades of carbide is as expected. This showed that the grade of carbide was statistically significant.
Figure 3.13.1 Tool wear of different grades of tungsten carbide inserts cutting in the climb direction at 15,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed. Note: Different letters indicate statistical significance.
Figure 3.13.2 Tool wear images of 2.5% cobalt grade tungsten carbide inserts: (a) Rep 1, (b) Rep 2, and (c) Rep 3.

Figure 3.13.3 Tool wear images of 6% cobalt grade tungsten carbide inserts: (a) Rep 1, (b) Rep 2, and (c) Rep 3.
Figure 3.13.4 Tool wear images of 10% cobalt grade tungsten carbide inserts: (a) Rep 1, (b) Rep 2, and (c) Rep 3.

Panel Chipping

Figure 3.13.5 shows the average of panel chipping results from three replications for each tungsten carbide grade. The T10MG grade or 10% cobalt grade tungsten carbide tools produced the highest panel chipping average whereas the lowest chipping was produced when cutting with T02SMG grade or 2.5% cobalt grade tungsten carbide inserts for the same amount of cutting.

A tool with a higher wear rate such as the T10MG grade produced a high amount of total tool wear. Additionally, the result confirms the relationship where higher tool wear causes a higher amount of chipping on the melamine-coated particleboard. This is due to the fact that a dull cutting edge can no longer perform the cutting effectively. Figure 3.13.6 shows a cumulative version of the panel chipping result. The 10% cobalt grade tungsten carbide inserts produced the highest percent of change.
Figure 3.13.5 Averaged panel chipping produced by different grades of tungsten carbide inserts at 15,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in the climb direction (average of three replications for each tungsten carbide grade).
Figure 3.13.6 Cumulative panel chipping produced by different grades of tungsten carbide inserts at 15,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in the climb direction (average of three replications for each tungsten carbide grade).

**Tool Spindle Vibration**

Figure 3.13.7 illustrates the vibration of the tool spindle during the machining test that was produced by the different grades of tungsten carbide inserts. As can be seen from the figure, the different carbide grades seemed to have similar pattern of tool spindle vibration.
The tool spindle vibration data were further analyzed by averaging the three RMS readings from each set of 20 passes as shown in Figure 3.13.8. It can still be observed that the vibration data for the different tungsten carbide grades seemed to have a similar pattern, although Rep 1 of the 10% cobalt grade tool behaved differently towards the end of the cutting process.
Figure 3.13.8 Average of three RMS readings of frequency band two (5,500 Hz – 6,750 Hz) of different grades of tungsten carbide inserts that cut at 15,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in the climb direction.

A normalized version of the previous graph is shown in Figure 3.13.9. It can be seen that Rep 3 of the 6% cobalt grade tool and Rep 1 of the 10% cobalt grade tool had the highest and the lowest tool spindle vibration, respectively. However, overall, the different tungsten carbide grades showed similar level of tool spindle vibration. In order to assess the difference in means of the tool spindle vibration on the different tungsten carbide grades, a one-way ANOVA was performed. It was found that the means were not significantly different for all cutting passes in which the vibration data was acquired.
Figure 3.13.9 Normalized RMS of frequency band two (5,500 Hz – 6,750 Hz) of different grades of tungsten carbide inserts that cut at 15,000 rpm of spindle speed and 500 ipm of feed speed in the climb direction.

A cumulative version of the previous normalized RMS graph is shown in Figure 3.13.10 where the same two replications can be seen as having the results in tool spindle vibration as previously presented. Most of the replications showed the same rate of change in terms of their tool spindle vibration.
Figure 3.13.10 Cumulative RMS of frequency band two (5,500 Hz – 6,750 Hz) of different grades of tungsten carbide inserts that cut at 15,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in the climb direction.

The three replications in each carbide grade were averaged and the result is shown in Figure 3.13.11. As illustrated, the 6% cobalt grade tool showed a slightly higher rate of change in terms of its tool spindle vibration compared to the other two grades. However, it can be concluded the vibration of the tool spindle was not sensitive enough to detect the difference between carbide grades. The tool spindle vibration results were initially presented in the forms of the three frequency bands; i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The results can be found in Appendices E and F. Appendix E
shows the tool spindle vibration for individual replication, while Appendix F shows the averaged RMS from the three replications of each carbide grade.

Figure 3.13.11 Averaged cumulative RMS of frequency band two (5,500 Hz – 6,750 Hz) of different grades of tungsten carbide inserts that cut at 15,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in the climb direction.

In summary, the tungsten carbide inserts with the highest percentage of cobalt binder of 10% produced the highest amount of tool wear and edge chipping of the melamine-coated particleboard. Meanwhile, the tools with the lower percentage of cobalt binder of 2.5% produced the lowest in both measurements. Additionally, it was found that the tool spindle
vibration had not enough sensitivity to detect the difference between the tungsten carbide grades.
4. ADDITIONAL STUDIES

4.1. Introduction

Additional tests were conducted in order to: (1) further investigate several issues that were found in the previous tests, such as the drop in panel chipping at the 120th pass, inaccuracies in the panel chipping measurement method, and the lack of number of replications; and (2) achieve the goal of this study, i.e. improving the CNC router performance. These tests are summarized below:

- **Effect of Tool Cooling on Tool Wear of Tungsten Carbide Inserts, Panel Chipping, and Tool Spindle Vibration**
  
  The tool cooling effect was investigated in order to determine on whether or not it can modify the tool life. Previous study (Gisip et al., 2007) showed that tool life was prolonged when tool was cooled when machining medium density fiberboard (MDF).

- **Measuring Panel Chipping Area using Image Analysis**
  
  Panel chipping was initially determined by measuring the number of chips per 25 mm. The chip count method counted chips that were measured 2 mm in width or height. It could not represent the exact characteristics of a chip. As an example, when a large chip exceeding the 2 mm in width or height requirement, it can be counted as one and this could introduce a false representation of the extent of the panel chipping level. The chip area method measures the area of the chips using an image analysis software. It represents the actual magnitude of the panel chipping.

- **Analysis of Tool Spindle Vibration using Order Analysis**
  
  Order analysis is a technique for analyzing noise and vibration signals produced by rotating or reciprocating machinery. A common analysis such as FFT, cannot detect mechanical characteristics with changes in spindle speed. Thus, order analysis could be used to analyze the vibration signal of the tool spindle.
• **Additional Test on the Effect of Cutting at Different Positions on CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration**

A test was done earlier with one replication for each of the three positions on the CNC router table. However, it was decided that more replications were needed. This test had three replications for each position in order to validate the results from the initial test. The test was a part of a series of tests that were conducted in order to investigate the drop in panel chipping at the 120th pass.

• **Additional Test on the Effect of Cutting at Different Feed Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration**

Similar test was conducted earlier with one replication for each of the three feed speeds. Additional test with more replications was done in order to validate the initial results.

• **Additional Tests to Investigate the Drop in Panel Chipping at 120th Pass**

Several tests were conducted to further investigate the drop in the panel chipping level. These tests include: (1) a cutting operation in which tool wear on a tungsten carbide insert cutting edge was captured at the 20th, 40th, 60th, 80th, 100th, 120th, 140th, 160th, 180th, and 200th; (2) machining tests that were performed to address the effect of board weight on panel chipping.

• **Process Control Test: Machining of Melamine-Coated Particleboard using Feedback Control**

A machining test using feedback control was used to determine the effect of controlling the spindle speed using the tool spindle vibration on the overall performance of cutting on the CNC router. Tool wear and panel chipping results were used to showcase the improvement in terms of machining quality by using the feedback control system.
Cost-Benefit Analysis on Different Cutting Scenarios Using Feedback Control Process in Machining of Melamine-Coated Particleboard on CNC Router Machine

A cost-benefit analysis (CBA) was conducted on three cutting scenarios: (1) standard cutting operation that served as a control; (2) step function in which the spindle speed was increased from 12,000 rpm to 18,000 rpm in a regular interval; and (3) feedback control in which the spindle speed was started at 12,000 rpm, and it was increased whenever the cumulative RMS (i.e. tool spindle vibration level) increased at a certain percentage. The CBA was done in order to decide whether or not these cutting scenarios were worthwhile.

Details of the tests described above are presented next, followed by the conclusion and future work as the final chapter of this study.

4.2. Effect of Tool Cooling on Tool Wear of Tungsten Carbide Inserts, Panel Chipping, and Tool Spindle Vibration

4.2.1. Introduction

A tool cooling method was investigated in order to be compared with the feedback control system’s performance. Based on previous work by Gisip et al. (2007), tool cooling application has shown promise in extending the life of cutting tools. In the study, a vortex tube was used to produce cold air, which was blown onto a solid tungsten carbide router bit during machining medium density fiberboard (MDF). The tool wear results of the study are presented in Table 4.2.1. The total wear was defined as the sum of the percentages of wear void and wear scar areas to the area of the original clearance face of the tool. Readers are directed to the work by Gisip (2005) for details in the methods of measuring the tool wear.

From Table 4.2.1, the total wear was lower for tools that had cold air during cutting, i.e. at 4.4°C and -6.7°C with 60.03% and 66.31%, respectively. The tool that cut at ambient temperature (21°C) had the highest total wear. It is important to note that the temperatures of the cold air were measured by placing a thermometer at the end of the air hose that was attached to the vortex tube. The surface condition of the three tools that cut at ambient, at cold air temperature of 4.4°C, and at -6.7°C, are shown in Figure 4.2.1. The tool that cut at
21°C exhibited the worst condition with a formation of a black layer carbon and other material residues near the cutting edge of the tool.

Table 4.2.1 Wear void, wear scar and total wear as a percentage of the original clearance face area. Superscript letters indicate the significant difference at the 0.05 level (Gisip et al., 2007).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Wear void (%)</th>
<th>Wear scar (%)</th>
<th>Total wear (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>32.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>44.09&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.16&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>4.4</td>
<td>25.39&lt;sup&gt;a&lt;/sup&gt;</td>
<td>34.64&lt;sup&gt;b&lt;/sup&gt;</td>
<td>60.03&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>-6.7</td>
<td>25.68&lt;sup&gt;a&lt;/sup&gt;</td>
<td>40.63&lt;sup&gt;b&lt;/sup&gt;</td>
<td>66.31&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Figure 4.2.1 Solid tungsten carbide tools after cutting at: (a) -6.7°C; (b) 4.4°C; and (c) 21°C (Gisip, 2005).

The current study attempted to cool tungsten carbide inserts during machining of melamine-coated particleboard. An air powered vortex tube (by Exair®, Model 3200 series) was used to chill the edge of the cutting tool (Figure 4.2.2). In a vortex tube, compressed air is ejected into a vortex spin chamber. This air stream spins up to 1,000,000 rpm toward the hot end where some air escapes through the control valve. The remaining air, still spinning, is forced back through the center of the outer vortex. The inner stream gives off kinetic energy in the form of heat to the outer stream and exits the vortex tube as cold air. The outer stream exits the opposite end as hot air (www.exair.com). Chilled temperatures as low as 10°C (50°F) below ambient is possible.
Figure 4.2.2 (a) Air powered vortex tube by Exair®, and (b) close-up view of the vortex tube with a hot muffler attached at the hot end.

Controlling the cold air temperature and cold airflow of the vortex tube can be done by adjusting the hot air valve as shown in Figure 4.2.3. The hot air valve is located at one of the ends of the vortex tube as can be seen in Figure 4.2.4. By opening the hot air valve, the cold airflow and the cold air temperature are reduced whereas closing the valve will increase the cold airflow as well as the cold air temperature (Exair®’s vortex tubes and spot cooling catalog).
The airflow can be adjusted by using a generator or also known as “top hat” (Figure 4.2.5), which is an internal plastic part. The size of the opening of the generator determines the amount of the airflow of the vortex tube. A generator is marked with a number and a letter that represent the capacity of air consumption, and the type of operation, respectively. As an example, a 10R generator indicates a capacity of 10 scfm (standard cubic feet per minute), and “R” stands for maximum refrigeration. The location and placement of the generator are shown in Figure 4.2.6.
A test was conducted to investigate the temperature of the cold air from the vortex tube as detailed in the following section.

4.2.2. Cooling Effect of Vortex Tube at Different Tool Conditions

The cooling effect of the cold air from the vortex tube was first investigated at different tool conditions. The objective was to determine the temperature differential on the cutting tool when blown with cold air. Cold air from the vortex tube was directed to a tungsten carbide insert at the CNC router tool spindle while the tool was in stationary,
rotating and cutting conditions. The distance between the opening of the flexible air hose of the vortex tube and the tool was 0.1 m (4 in.). The procedure was repeated without having the cold air directed to the tool. Thermal images of the tool were captured using a handheld RAZ-IR PRO thermal infrared camera (by Sierra Pacific Innovations or SPI Corp.) as shown in Figure 4.2.7. A thermal infrared camera is a device that produces image of heat energy (Sierra Pacific Innovations, 2014).

Figure 4.2.7 Thermal camera.

Figure 4.2.8 shows images of the cutting tool in a stationary condition, with (Figure 4.2.8(b)) and without (Figure 4.2.8(c)) the presence of cold air. These thermal images were transferred to a computer using an imaging software called Guide IrAnalyser (Wuhan Guide Infrared Co., Ltd., 2009). The imaging software was also used to obtain temperature values. From the figure, the small rectangle on the tool, which was denoted as R1, represented an area in which a mean average temperature was taken.

Similar procedures were performed on the tool during rotating and cutting. In the rotating condition, the tool was rotated at 18,000 rpm. Meanwhile, for the cutting condition, the tool cut a melamine-coated particleboard in the climb direction at a spindle speed of
18,000 rpm, and 12.7 m/min (500 ipm) of feed speed. The normal and thermal images for the rotating and cutting conditions were shown in Figures 4.2.9, and 4.2.10. Results of the temperature measurements for the three tool conditions are presented in Table 4.2.2.

Figure 4.2.8 Tool in stationary condition: a) normal view; b) with cold air (R1 = 21.7°C average); c) without cold air (R1 = 23.5°C average).

Figure 4.2.9 Tool in rotating condition: a) normal view; b) with cold air (R1 = 19.4°C average); c) without cold air (R1 = 25.1°C average).
The tool in the cutting condition without the cold air generated the highest average temperature due to the extreme heat generated from the cutting in addition to the absence of the cooling effect. The difference of the average temperature between with and without cold air was (7.8°C). It can be concluded that the effect of cooling was greater when the tool was cutting.
Table 4.2.2 Average temperature measurements on tungsten carbide inserts for three tool conditions.

<table>
<thead>
<tr>
<th>Tool Condition</th>
<th>Average Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With Cold Air</td>
</tr>
<tr>
<td>Stationary</td>
<td>21.7</td>
</tr>
<tr>
<td>Rotating</td>
<td>19.4</td>
</tr>
<tr>
<td>Cutting</td>
<td>32.3</td>
</tr>
</tbody>
</table>

From Table 4.2.2, the difference of the average temperature between with and without cold air for the stationary tool condition was small (1.8°C). As for the rotating tool condition, the temperature difference was large (5.7°C). This could be due to the heat that came from the bearing of the tool spindle as depicted in the thermal image. The tool in the cutting condition had higher mean temperatures for both with and without the cold air due to the cutting interaction between the tool and material. This resulted in a huge amount of heat being generated.

The average “ambient” temperature of the tungsten carbide insert was also determined using an image that was captured using the thermal camera. This was done in order to obtain the average temperature of the tungsten carbide insert without being attached to the tool holder. Based from Figure 4.2.11(b), the average temperature; R1, was 18.9°C. When comparing the value with the average temperature for the tool in the stationary condition with cold air (R = 21.7°C), the difference was small. This showed that the effect of the tool holder on the temperature of the carbide insert was negligible.
4.2.3. Methodology

A series of tests was conducted to determine the effect of cooling and increased air flow on tungsten carbide inserts during machining of melamine-coated particleboard. Three types of treatments were selected namely; vortex tube – 10R, vortex tube – 40R, and high velocity air jet. Each of these devices produced different air temperatures, and amount of air flow, which was directed towards the cutting tool. In each of the machining test, three replications were conducted using 10% cobalt grade tungsten carbide inserts to cut 10 sets of 20 passes. Each pass was 1 m totaling to 200 m of cutting passes on melamine-coated particleboard panels in a climb cutting direction. The machining was done at 18,000 rpm of spindle speed, and 12.7 m/min (500 ipm) of feed speed. A similar cutting test was conducted without a cooling application. It served as a control to be compared with the tests that had a cooling treatment. Vibration signal of the tool spindle was collected for the first three passes in each set. Final tool wear was measured as well as panel chipping.

Vortex tube – 10R and the vortex tube – 40R used 10R and 40R generators, respectively. The two generators are shown in Figure 4.2.12.

Figure 4.2.11 Cold air on carbide insert 4 in. from cold gun nozzle: a) normal view; b) thermal view (R1 = 18.9°C).
Compressed air was first passed through a PROdry™ model PD35 compressed air dryer to remove moisture before entering the vortex tube. The setup of the vortex tube, and the compressed air dryer is shown in Figure 4.2.13.
The third cooling type was a high velocity air jet model 6013 that has an air consumption of 22 scfm. The air jet produces a large volume air stream. Figure 4.2.14 shows the air jet and its set up during the cutting process.

![Figure 4.2.14 (a) High velocity air jet; (b) set up for cutting with air jet; (c) close up of the air jet.]

Temperature of the air that was exiting the cold end of the vortex tube and the end of the air jet was measured with a thermocouple that was plugged into a Fluke model 179 digital multimeter (Figure 4.2.15). The thermocouple was inserted all the way through the cold muffler, to where the tip was inside the cold cap of the vortex tube. As for the air jet, the tip of the thermocouple was held in front of its blowing end.
The results of the temperature are presented in Table 4.2.3. It can be observed that the air jet produced the highest temperature of 14.5°C, while the vortex tube – 10R produced the lowest with -19°C. The different temperatures could be due to the cooling effects of each device, which has a different amount of air flow exiting the ends. This will be discussed further in the following air flow measurement section.

Table 4.2.3 Temperature of air exiting vortex tube and air jet.

<table>
<thead>
<tr>
<th>Device</th>
<th>Temperature (°C)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex tube - 10R</td>
<td>-19</td>
</tr>
<tr>
<td>Vortex tube - 40R</td>
<td>7.5</td>
</tr>
<tr>
<td>High velocity air jet</td>
<td>14.5</td>
</tr>
</tbody>
</table>

*Temperature for the vortex tube was taken at the generator tip inside the cold muffler.

The air flow of the vortex tube and air jet was measured with a flow meter as shown in Figure 4.2.16. A flow meter measures the rate of the air speed that flows through it. Air flow can be expressed in standard cubic feet per minute or scfm.
Different configurations were used to determine the amount of air flow in and out. Figure 4.2.17 shows the configuration for measuring the air flow into the vortex tube. Compressed air entered the system by first passing through the filter and regulator. The filter ensured that the air was free from impurities, and the pressure regulator enabled the compressed air pressure to be maintained at 100 psi. The compressed air passed through the flow meter in which the measurement was taken. It then exited through the end of the flow meter before entering the vortex tube via the air hose. The path of the air flow is depicted by red arrows as seen in the figures.

The configuration for the air flow out of the vortex tube is shown in Figure 4.2.18. In this configuration, the flow meter was attached at the cold end of the vortex tube in order to measure the amount of air flow that was exiting the vortex tube. Figure 4.2.19 shows a
configuration to measure the air flow in of the air jet, which was similar to the vortex tube. The air flow out was not measured due to the end design of the air jet.

Figure 4.2.17 Air flow in measurement setup for vortex tube.
Figure 4.2.18 Air flow out measurement setup for vortex tube.
The air flow measurement was taken three times and the values were averaged. The results of the average air flow in and out of the vortex tube and the air jet are presented in Table 4.2.4. Vortex tube – 10R values were contradictory to the fact that the air that is consumed or coming in should be more than what is being produced or coming out from a device. Also, it should be noted that the amount of air flow in the table is less than what is stated in the Exair® product catalog. This could be due to the setup of the measurement, which involves the placement of the flow meter. The use of quick disconnects may introduce excessive back pressure or resistance to the air flow throughout the configuration. Additionally, the length and diameter of the air hose that was used to deliver the compressed air from the air compressor to the device could affect its performance (personal communication with Exair®’s application engineer).

It can be observed that the vortex tube – 40R had higher amounts of air flow in and out as compared to the vortex tube – 10R. A high rate of air flow resulted in a warmer air temperature as demonstrated, where the air temperatures of vortex tube – 10R and vortex tube – 40R were -19°C and 7.5°C, respectively.
Table 4.2.4 Average air flow in and out of vortex tube and air jet.

<table>
<thead>
<tr>
<th>Device</th>
<th>Air Flow In (scfm*)</th>
<th>Air flow Out (scfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vortex tube - 10R</td>
<td>4.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Vortex tube - 40R</td>
<td>8.4</td>
<td>7.4</td>
</tr>
<tr>
<td>High velocity air jet</td>
<td>7.0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*scfm = standard cubic feet per minute

The next section discusses the tests on the application of different air temperature and air flow on tool wear, panel chipping and tool spindle vibration when machining melamine-coated particleboard on a CNC router. The effect of cooling the tool will also be discussed.

4.2.4. Results and Discussion

After the cutting tests were completed, the tungsten carbide inserts were inspected under the microscope for measuring the tool wear. Panel chipping was measured, and the vibration signal was analyzed with the LabVIEW™ software. Results for the tool wear, panel chipping and vibration of the tool spindle are presented and discussed.

**Tool Wear**

Tool wear results are presented in Figure 4.2.20. It can be observed that the test without the cooling treatment produced the lowest tool wear amount of 114 µm. Meanwhile, tool wear for the air jet treatment was the highest with 299 µm. The cooling treatments with vortex tube – 10R and vortex tube – 40R performed differently with the 40R resulting in a higher tool wear of 173 µm.

The tool wear between the control test (i.e. no cooling) and the vortex tube – 10R showed a small difference. This could indicate no improvement on the cutting process when cooling the tool at temperature level produced by the vortex tube – 10R. It can also be observed that the amount of tool wear increased with an increase in air flow exiting the vortex tube and air jet ends. However, this will need further investigation in order to determine if there is any relationship between tool wear and air flow.
Figure 4.2.20 Tool wear results of 10% cobalt grade tungsten carbide that cut at different treatments. Different bar colors refer to different batch of boards.

Figures 4.2.21, 4.2.22, 4.2.23 and 4.2.24 show the images of tool wear on the 10% cobalt grade tungsten carbide inserts that cut without cooling treatment (control), vortex tube – 10R, vortex tube – 40R, and air jet, respectively. Tool wear images supported the amount of tool wear as presented earlier.
Figure 4.2.21 Tool wear images of 10% cobalt grade tungsten carbide inserts that cut without cooling treatment (From top to bottom: first, second, and third replications).

Figure 4.2.22 Tool wear images of 10% cobalt grade tungsten carbide inserts that cut with cooling treatment using vortex tube – 10R (From top to bottom: first, second, and third replications).

Figure 4.2.23 Tool wear images of 10% cobalt grade tungsten carbide inserts that cut with cooling treatment using vortex tube – 40R (From top to bottom: first, second, and third replications).
Another point to be considered is that the different amount of tool wear in each treatment could be due to the different panel density of the melamine-coated particleboard panels. Figure 4.2.25 shows the average panel density of six panels (each replication cut two boards) for each treatment. It can be observed that the average panel density corresponds to the amount of tool wear produced in each treatment.

It can be concluded that the panel density could affect the amount of tool wear in this experiment as well as in all of the machining tests performed in the study. The panel density may account for some of the tool wear in this particular test as the average panel density figure shows there was a difference between the first three bars on the left, and the air jet was slightly higher. Further, the tool wear graph shows that the tool wear using the vortex tube – 40R seemed to be greater than the tool wear from the no air and vortex tube – 10R.

Other possible sources of differences in tool wear could be due to the interaction between the cutting tool and materials, which related to chip and panel chipping formation, as well as tool spindle vibration as discussed below.
Figure 4.2.25 Average density of melamine-coated particleboard panels that were cut with different treatments using 10% cobalt grade tungsten carbides at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed.

**Panel Chipping**

Figure 4.2.26 shows the panel chipping for each replication in each treatment. Due to the variability in chipping, a cumulative count was performed as shown in Figure 4.2.27.
Figure 4.2.26 Panel chipping of melamine-coated particleboard panels that were machined with different treatments using 10% cobalt grade tungsten carbides at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed.

As depicted in Figure 4.2.27, Rep 3 of the air jet treatment had the steepest slope. It also produced the lowest panel chipping as in the case of its Rep 1.
Further, the three replications in each treatment were averaged, and the average cumulative result is presented in Figure 4.2.28. It can be seen that all treatment seemed to have similar slope, except that the vortex tube – 40R diverged a little towards the end of the cutting process. Overall, the panel chipping seemed to be not following the trend in tool wear. The air temperature, amount of air flow as well as panel density could be affecting the panel chipping result. Additionally, foreign matter or localized density effects could also be the source of variation in the panel chipping behavior. However, the main source of variation is not known.
Figure 4.2.28 Averaged cumulative panel chipping of melamine-coated particleboard panels that were machined with different treatments.

**Tool Spindle Vibration Signal**

The vibration signal of the CNC router tool spindle was analyzed with the LabVIEW™ software, and the result is presented in Figure 4.2.29. Three RMS readings of frequency band 5,500 Hz to 6,750 Hz, which correspond to the first, second, and third pass in each of the 20-pass set, were plotted for each replication. Based on the scatter plot, it can be observed that the replications for cutting without cold air had the highest tool spindle vibration. Meanwhile, the vortex tube – 40R produced the lowest vibration.
The three RMS readings for each replication were averaged. As a result, a clearer trend can be obtained as illustrated in Figure 4.2.30. The replications for cutting without cold air maintained the highest level of tool spindle vibration. The cause of this trend is not known but it could be due to the condition of the different treatments such as the air temperature, and amount of air flow. Panel density could be affecting the result.
Figure 4.2.30 Average of three readings of vibration signal of tool spindle during machining for different treatments.

The averaged RMS were normalized to accommodate the different starting points of the replications by dividing each RMS value by the first RMS reading and multiplying it by 100%. This was also to accommodate the small variation in the initial tool sharpness, and the panel density. Thus, all replications had the same starting point to begin with as shown in Figure 4.2.31. The graph shows the percent change for each replication as the cutting progressed. Rep 2 of the vortex tube – 10R had the highest percent of change followed by Rep 1 of the cutting without cold air, and Rep 1 of the vortex tube – 10R. As mentioned before, this could be due to the effect of panel density, and the condition of the different treatments such as the air temperature, and amount of air flow.

The rest of the replications showed minimal percent of change in terms of the vibration signal. Thus, the two most extreme temperatures; i.e. two of the coldest reps and one of the warmest, had the most vibration change. This could be due to the cooling and air
flow effect of the vortex tube – 10R and also the absence of it. Additionally, the drastic difference between Rep 2 of vortex tube – 10R from the rest could not be explained even after looking the board density, tool chipping, and visual inspection on the blade.

Figure 4.2.31 Normalized vibration signal of tool spindle during machining for different treatments.

The next step is to produce a cumulative graph of the normalized RMS data. Figure 4.2.32 shows a trend for each replication with varying slopes. Rep 2 of the vortex tube – 10R had the steepest slope. It can also be observed that the control and vortex tube – 10R groups had steeper slopes compared to the vortex tube – 40R and air jet groups.
The average cumulative result is presented in Figure 4.2.33. The low vibration level for the vortex tube – 40R and air jet groups could be due to the huge amount of air flow that was produced by the device in each treatment. The large air flow could provide a cleaner environment at the cutting edge and material intersection by blowing away the chips and dusts during cutting, thus, clearing the pathway for the cutting tools to make a smooth cutting. However, the real cause is still unknown.
In summary, the application of tool cooling did not reduce tool wear. The cutting without cold air produced the lowest tool wear. The result of the panel chipping did not follow the tool wear trend. In terms of the tool spindle vibration results, the groups (cutting without cold air and vortex tube – 10R) that had lower tool wear produced higher level of tool spindle vibration. A definitive reason for this could not be found even with additional inspection of the test boards for contaminants, panel density, tool chip, and so on.

Based on the results of the tests, it can be concluded that the application of tool cooling did not effectively improve the cutting operation of melamine-coated particleboard on a CNC router. Although a study by Gisip et al. (2005) showed improvement in the life of tungsten carbide tools when cutting MDF, the different outcome when cutting melamine-coated particleboard in this particular study could be due to the different types of material. Additionally, the total cutting length could also affect the result in which the former study...
had a total of 166,000 m length of cut, while the latter had 200 m of cutting length per cutting flute.

4.3. Measuring Panel Chipping Area Using Image Analysis

4.3.1. Introduction

A chip area method was evaluated to address the problems found in the chip count and length methods. Measuring the chip area could provide a true representation of the magnitude of the panel chipping as cutting progresses. In the chip count method, chips that were measured 2 mm in width or height were counted. This may introduce an erroneous representation of the panel chipping condition. As an example, a panel chip, which measures 4 mm in width, will be counted as one chip as with a panel chip that measures 2 mm. This shows that the chip count method could not represent the exact magnitude of the panel chipping. In the case of the length method, two chips with similar length could have different shapes; either deeper or narrower, and this method could not illustrate this.

4.3.2. Methodology

In the chip area method, panel chipping images were first captured with a digital camera as shown in Figure 4.3.1. Ten images were taken across a length of 0.8 m (30 in.) of each of the 20th pass edge of the melamine-coated particleboard, after subtracting 101.6 mm (4 in.) from each end (similar to the chip count method). White paper and broad area linear array illumination were used to produce images with high brightness and contrast. A sample image of the panel chipping is shown in Figure 4.3.2.
An image analysis software called SigmaScan Pro 5™ by Systat Software Inc. was used to measure and analyze the digital images of the panel chipping. In order to measure the area of the panel chipping, the measurement setting was first determined by selecting the area option found in the “Measurement Setting” dialog box as shown in Figure 4.3.3.
The next step was to perform a calibration for an area measurement. The calibration was performed using an image of a ruler, which was taken at the same distance and camera settings with the panel chipping images. As shown in Figure 4.3.4, the calibration was done by selecting a 1 mm division on the ruler.
A SigmaScan Pro 5™ macro was used to analyze the panel chipping images in batches. A macro language based on Visual Basic within the SigmaScan Pro 5™ was used to automate the image analysis procedures. The image analysis procedures or steps were recorded to which a macro was generated. The resulting macro was then edited to allow for batch analyzing of the panel chipping images. A batch contained a total of ten images for the edge of each of the 20-pass set on the melamine-coated particleboard.

The following descriptions provide details of the image analysis tasks that were performed before the panel chipping area can be measured. These image analysis tasks were manually selected from within the SigmaScan Pro 5™ and recorded in order to generate a macro for analyzing the images in batches as described earlier.

Figure 4.3.5 shows the first image analysis task, which was to perform “Histogram Stretch” on the image. In Figure 4.3.6, the intensity of the image was modified to obtain an optimum combination of brightness and contrast that separates the panel chipping areas from the melamine-coated particleboard.
Figure 4.3.5 Performing histogram stretch to modify the intensity of the image.

Figure 4.3.6 Adjusting the brightness and contrast using histogram stretch control.
The next step was to perform “Intensity Threshold” in order to fill in the dark areas with red color as illustrated in Figure 4.3.7. Additional step was done in which the remaining holes and gaps left by the “Intensity Threshold” step was filled by selecting the overlay filter function named “Fill Holes” (Figure 4.3.8).

Figure 4.3.7 Performing intensity threshold to fill in the dark areas with red color.
Figure 4.3.8 Performing overlay filter to fill in the holes within the dark areas that were missed by the intensity threshold step.

After executing the macro on images in batches, the next step was to measure the red-colored areas. The areas were numbered, and the area values in squared millimeters were shown in a column with its respective number (Figures 4.3.9 and 4.3.10). The panel chipping areas, which exceeded 1 mm$^2$ value, were identified and the area values were transferred to a Microsoft Excel™ spreadsheet for further calculation and analysis.
Figure 4.3.9 Performing area measurement of the red-colored areas.

Figure 4.3.10 Enlarged parts of the red-colored areas representing the panel chipping with its area value in squared millimeter (Example: $2585^{th}$ area measured 9.95 mm$^2$).
A paired t-test was conducted using JMP® 10 statistical package on the same board in which the count and length methods used. A comparison was made between measuring chip areas in seven (out of 10, i.e. 10 images) number of observations versus three. In paired t-test, it was found that there was no statistical difference between measuring chip areas in seven observations versus three observations (P-value = 0.4624).

Figure 4.3.11 shows a comparison of the three panel chipping quantification, i.e. length, count, and area methods for the same 10% cobalt grade tungsten carbide insert that cut in climb direction at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed. Based on the figure, unlike the count and length methods, the chip area method showed that panel chipping was greatly increased after approximately 200 m of cutting.

![Comparison of Panel Chipping Measurement Methods](image)

Figure 4.3.11 Comparison of panel chipping measurement methods for a 10% cobalt grade tungsten carbide insert that cut in climb direction at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed.
Due to the increased accuracy and with the help of semi-automated process of conducting the image analysis procedures, it was an advantage to measure all ten images that were captured from the 20th pass of each set. Further tests such as the process control tests used the chip area measurement method using image analysis to quantify the panel chipping.

In summary, the three methods of panel chipping quantification have their own advantage and disadvantage. The count and length method could be done faster than the chip area using image analysis. However, as described earlier, accuracy is greatly reduced especially for the chip count method where a large chip exceeding the 2 mm in width or height requirement can be counted as one and this could introduce a false representation of the extent of the panel chipping level. Meanwhile, the length method could not illustrate the amount of chipping between two chips having similar length but different shapes. The chip area method using image analysis is highly accurate as it measures the areas that represent the actual magnitude of the panel chipping.

4.4. Analysis of Tool Spindle Vibration Using Order Analysis

4.4.1. Introduction

Order analysis is an advanced technique for analyzing noise and vibration signals produced by rotating or reciprocating machinery (National Instruments, 2007). Unlike FFT, which is a traditional and the most commonly used method for analyzing sound and vibration signal, order analysis can detect mechanical characteristics with changes in spindle speed (National Instruments, 2007).

The rotational speed vibration of the tool shaft can be represented in the frequency domain. Orders are the harmonics nature of the frequency domain, which can be related to the rotational speed. The first order is the harmonic at the same frequency of the rotational speed; the second order is the harmonic at twice the frequency of the rotational speed and so on (National Instruments, 2003).

As in the case of the current study, the spindle speed can be correlated to the machine’s vibration signal in order to generate information about the order components of the machine. Order components found in an order power spectrum represent parts of a
machine. The first order can correspond to the frequency at which a tool is rotating. The second order can be bearings of the tool spindle. Significant orders can be identified and characterized from an order power spectrum. These orders are those that can be characterized by having high amplitudes.

The potential of this technique to be used in a process control system for a CNC router was investigated.

4.4.2. Methodology

The order analysis was performed on the vibration signal while it was being collected during the machining operation. The order analysis toolkit that was a part of the Sound and Vibration Measurement Suite in LabVIEW™ was used to perform the task. The data from the order analysis was obtained from several machining tests that were described in this study. A machining test was selected to illustrate the application of the order analysis as discussed in the next few paragraphs.

A 10% cobalt grade tungsten carbide insert was used to cut two sheets of melamine-coated particleboard with measurement of 0.6 m (2 ft.) × 1.2 m (4 ft.) each. A total of 200 m of length of cut was completed with a cutting pattern that has been described in details in the Methodology chapter. The cutting pattern consisted of 10 sets of 20 passes. Vibration signals were collected from the first three cutting passes in each 20-pass set. A program that was written in LabVIEW™ was used to record and analyze the tool spindle vibration signal. A plot called order power spectrum contains the information about the orders found in the vibration data of the CNC router tool spindle.

The machine rotational speed is known as the source of the noise as well as the vibration signals. Rotating components such as blades, bearings, and gears contribute the noise and vibration. Thus, the orders are the harmonics (i.e. frequencies that are integer multiples of a fundamental frequency) of the machine rotational speed (National Instruments, 2003). In this study, the rotational speed was captured using a tachometer with an optical sensor, which was directed to the reflective tape that was placed on the CNC router tool
spindle. Further details of the tachometer as well as the set up can be found in the Methodology and Preliminary Work chapter.

4.4.3. Results and Discussion

Figure 4.4.1 shows an order power spectrum plot of the machining test that was discussed earlier. An order power spectrum is an order analysis function in the National Instruments™ (NI) Sound and Vibration Measurement Suite found in LabVIEW™. It is a graph that shows the amplitude of the orders that are found in a signal. Significant orders can be identified and the level of different order components can be compared using the order power spectrum. A total of 30 plots were viewed from the test, which represented the vibration signals that were collected from the first three passes of each of the 10 sets of 20 passes.

Each peak in the plot represents a rotating component of the machine. Although the magnitude of the order is an important characteristic, each peak was observed throughout the 30 passes. The yellow arrow in the figure points to an order, i.e. order 21.6, which was thought to have the most changes throughout the cutting process. The changing characteristic is of interest because it could be due to the cutting process, where it could be caused by chipped blades, and panel density variability as well as the interaction between the cutting blade and the formation of the panel chipping.

Both Figures 4.4.1 (first pass) and 4.4.2 (second pass) illustrate this drastic change for order 21.6 in which the second figure shows that the magnitude had increased.
Figure 4.4.1 Order power spectrum of the first pass. Arrow points to the order that had the most change throughout the cutting process.
Figure 4.4.2 Order power spectrum of the second pass. Arrow points to the order that had the most change throughout the cutting process.

The amplitude values for all 30 passes for order 21.6 were extracted from the order power spectrum, and then plotted on a graph. The RMS for frequency band two (5,500 Hz – 6,570 Hz) was also plotted on the same graph as a comparison.

Figure 4.4.3 shows the RMS and amplitude of order 21.6. It can be observed that the RMS had an increasing pattern whereas the amplitude of order 21.6 had a decreasing shape.
Figure 4.4.3 Comparison between RMS at frequency band two (5,500 Hz – 6,750 Hz) and amplitude of order 21.6 for cutting test of melamine-coated particleboard at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.

The RMS values and the order amplitudes were averaged and displayed in Figure 4.4.4. Smoother lines can be seen, and each line maintained the same pattern as the previous graph. It can also be observed that the RMS had more drastic changes compared to the order amplitude. This could be due that the RMS was more sensitive to the changing throughout the cutting process.
Figure 4.4.4 Comparison between averaged RMS at frequency band two (5,500 Hz – 6,750 Hz) and amplitudes of order 21.6 for cutting test of melamine-coated particleboard at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.

In Figure 4.4.5, the averaged RMS values and amplitudes of order 21.6 were normalized. It can be seen that the average RMS values pattern had more drastic changes or sensitivity compared to the order amplitude as stated before.
Figure 4.4.5 Comparison between normalized averaged RMS at frequency band two (5,500 Hz – 6,750 Hz) and amplitudes of order 21.6 for cutting test of melamine-coated particleboard at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction.

Figure 4.4.6 shows the cumulative plot of the averaged RMS values and amplitudes of order 21.6. As illustrated, both RMS and order 21.6 for the tool spindle vibration had the same linear upward shape. This could indicate that other than RMS, order analysis could also be used in a process control system for a CNC router.
Figure 4.4.6 Comparison between cumulative RMS at frequency band two (5,500 Hz – 6,750 Hz) and amplitudes of order 21.6 for cutting test of melamine-coated particleboard at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed in climb direction. The cumulative amplitudes of order 21.6 and the RMS values were then plotted with the panel chipping to observe its pattern and relationship as shown in Figure 4.4.7. Based from the graph, it was found that the RMS values as well as the amplitudes of order 21.6, seemed to be following the panel chipping pattern.
An order (i.e. order 21.6) from the order power spectrum graph was selected based on its changing pattern throughout the cutting process. Both the RMS values and the amplitudes of order 21.6 followed the panel chipping pattern. Thus, it can be concluded that order analysis could be used in a process control system for this CNC router setup; although it was initially thought that order analysis could be more sensitive (i.e. having a steeper slope) than FFT. The feasibility of order analysis in a process control system on a CNC router could be pursued as a future work.
4.5 Additional Test on the Effect of Cutting at Different Positions on CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration

4.5.1. Introduction

A preliminary test on the different table positions on the CNC router was conducted with one replication for each position. Additional replications were required in order to verify the results that were obtained from the preliminary test. Thus, the test was repeated in which each position had three replications. The objective was to determine the effect of table position on tool wear, panel edge chipping, and tool spindle vibration.

4.5.2. Methodology

Nine new 10% cobalt grade tungsten carbide inserts were inspected for the presence of chipped edge. Each carbide insert completed 100 m of length of cut (i.e. five sets of 20 passes). The machining was done using a spindle speed of 18,000 rpm, and 12.7 in/min (500 ipm) of feed speed in the climb direction. The tungsten carbide inserts were divided into three groups, which represented the cutting at three different starting positions on the CNC router table. The location for each of the starting position can be seen in Section 3.8 of the preliminary test. As illustrated, Position 1 started at the farthest point (in the Y-axis direction) from the tool spindle ‘home’ position where the Y-axis was 60 in., Position 2 had Y-axis, which was equal to 48 in., and Position 3 was started at the nearest point from the tool spindle with Y-axis of 36 in. Vibration signal data was collected during the first three passes in each of the 20-pass set. Tool wear was measured with a digital optical microscope, as well as indirectly using the panel edge chipping count. Details on the methodology can be found in section 3.8 under the Methodology and Preliminary Work chapter.

4.5.3. Results and Discussion

Following are the results on tool wear, panel edge chipping, and tool spindle vibration from the table position test.
**Tool Wear**

In Figure 4.5.1, the cutting edge wear for the three groups of tungsten carbide inserts that cut at positions 1, 2, and 3 are presented. It can be observed that the third position had the highest average tool wear compared to the other groups. A one-way analysis of variance (ANOVA) test was performed to assess whether or not table position had a significant effect on the amount of tool wear. It was found that the means of the tool wear at the three table positions were not significantly different from each other (P-value = 0.2559, F ratio = 1.7253, $R^2 = 0.37$). Thus, it can be concluded that tool wear was not affected by the position on the CNC router table.

The tool wear images are illustrated in Figures 4.5.2, 4.5.3, and 4.5.4. Based on the figures, Rep 1 and Rep 3 for Position 3 showed higher tool wear, which resulted in a higher tool wear average. This had been confirmed with the tool wear values for both replications.

![Tool Wear of 10% Cobalt Grade Tungsten Carbide Inserts Climb Cutting at Different Starting Positions on CNC Router Table](image)

*Figure 4.5.1 Tool wear of three groups of 10% cobalt grade tungsten carbide inserts that cut at three different starting positions on the CNC router table.*
Figure 4.5.2 Tool wear images of 10% cobalt grade tungsten carbide inserts that cut at table Position 1.

Figure 4.5.3 Tool wear images of 10% cobalt grade tungsten carbide inserts that cut at table Position 2.
Panel Chipping

As for the panel chipping result, Figure 4.5.5 shows the result for all groups. The panel chipping for Position 3 seemed to show a higher amount although Rep 2 generally showed the lowest.
Panel Chipping for 10% Cobalt Grade Tungsten Carbide Inserts Cutting at Three Different Starting Positions on CNC Router Table

Figure 4.5.5 Panel chipping on melamine-coated particleboard produced by 10% cobalt grade tungsten carbide inserts that cut at three starting positions on CNC router table.

A one-way ANOVA test was also performed to determine if table position had a significant effect on the panel chipping amount. It was found that the means of the three table positions were not significantly different from each other at the 20\(^{th}\), 40\(^{th}\), 60\(^{th}\), 80\(^{th}\), and 100\(^{th}\) cutting passes. Table 4.5.1 summarizes the statistics details. Thus, it can be concluded that panel chipping was not affected by the position on the CNC router table.
Table 4.5.1 One-way ANOVA result on the effect of table position on panel chipping.

<table>
<thead>
<tr>
<th></th>
<th>Panel Chipping at 20th Pass</th>
<th>Panel Chipping at 40th Pass</th>
<th>Panel Chipping at 60th Pass</th>
<th>Panel Chipping at 80th Pass</th>
<th>Panel Chipping at 100th Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-value</td>
<td>0.5477</td>
<td>0.7065</td>
<td>0.9860</td>
<td>1.7731</td>
<td>0.1112</td>
</tr>
<tr>
<td>F ratio</td>
<td>0.6667</td>
<td>0.3684</td>
<td>0.0141</td>
<td>0.93778</td>
<td>3.2388</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.18</td>
<td>0.11</td>
<td>0.005</td>
<td>0.37</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The cumulative amount of the panel chipping is shown in Figure 4.5.6. As can be observed in Figure 4.5.6, two replications for Position 3 had a higher level of panel chipping after the 60th pass, which was 60 m in length of cut.

![Cumulative Panel Chipping](image)

Figure 4.5.6 Cumulative panel chipping on melamine-coated particleboard produced by 10% cobalt grade tungsten carbide inserts that cut at three starting positions on CNC router table.
In order to easily understand the pattern, the panel chipping amount was averaged for each position. Figure 4.5.7 shows the panel chipping averaged result. As illustrated, Position 3 had a higher panel chipping level, which corresponds to its higher tool wear amount as shown earlier.

Figure 4.5.7 Average cumulative panel chipping on melamine-coated particleboard produced by 10% cobalt grade tungsten carbide inserts that cut at three starting positions on CNC router table.

**Tool Spindle Vibration**

The purpose of the study was to control the machining process via changing the spindle speed using the vibration signal of the tool spindle. Hence, the correlation between
tool wear, panel chipping, and tool spindle vibration needed to be established. Figure 4.5.8 shows the result of the vibration signal of the CNC router tool spindle for the three starting positions. Three RMS readings were acquired in each of the 20-pass set for each position. In terms of the vibrational pattern, it can be seen that the vibration signal for two of the replications for Position 1 deviated from the rest of the group. It could be speculated that the panel density of the melamine-coated particleboard affected the vibration level. However, based on the one-way ANOVA test, the panel density was found to be not significant (P-value = 0.0727, F ratio = 4.1886, $R^2 = 0.58$).

Figure 4.5.8 RMS at frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at different positions on CNC router table (Note: Position 1 – farthest from the tool spindle home position).
The three RMS readings at each 20-pass set were averaged as can be seen in Figure 4.5.9. In the graph, the pattern for each replication can be clearly observed. Some of the replications went up while others went down, and this could be due to experimental variation.

![Graph showing averaged RMS values for frequency band two (5,500 Hz – 6,750 Hz).](image)

**Figure 4.5.9** Average of three RMS at frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at different positions on CNC router table (Note: Position 1 – farthest from the tool spindle home position).

In Figure 4.5.10, the averaged RMS values were further normalized in order to determine the real magnitude of the tool spindle vibration signal for each replication. This was done through dividing each averaged RMS value with the first RMS averaged value and then multiplied by 100 to get a percentage value.
Figure 4.5.10 Normalized RMS at frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at different positions on CNC router table (Note: Position 1 – farthest from the tool spindle home position).

Figure 4.5.11 presented a cumulative version of the normalized RMS shown previously. It can be observed that each position had its replications in the higher and lower levels. Position 1 showed the most variability among its replications with Rep 1 and Rep 2 having the highest rate of change while Rep 3 had the lowest. The actual reason for the difference between the replications is unknown; however, it could be due to board and experimental variation.
Further analysis was done in which the three replications in each position were averaged as presented in Figure 4.5.12. Position 1 had a higher vibration level, and a steeper slope due to two of its replication having the highest rate of change. Position 1 could be having a different level of vibration on the table compared to the two other positions.

A one-way ANOVA was performed to assess the difference in means of the tool spindle vibration on the three table positions. The statistical test was done on vibration of each cutting passes that was acquired during the cutting test (i.e. first pass until the 15\textsuperscript{th} pass, which was the first three passes in each of the five sets of 20 passes; e.g. 1, 2, 3, 21, 22, 23…etc.). The third cutting pass (i.e. the third pass of all replications for the three table
positions) was significant (P-value = 0.0487, F ratio = 5.2169, $R^2 = 0.63$) while the majority of the large cutting passes were not.

![Averaged Cumulative RMS of Frequency Band Two (5,500 Hz - 6,750 Hz)](image)

Figure 4.5.12 Average cumulative RMS at frequency band two (5,500 Hz – 6,750 Hz) of nine 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at different positions on CNC router table (Note: Position 1 – farthest from the tool spindle home position).

Different levels of vibration that present on the CNC router table would need a process control system that can regulate the spindle speed in order to improve the machining performance. However, since the one-way ANOVA on the tool spindle vibration were not significant, the variation among the replications should not be a concern.
Since the means of the tool wear, panel chipping, and tool spindle vibration were not significantly different, it can be concluded that table position does not have any effect on the results, and mapping the vibration level of the CNC router table is not needed.

4.6 Additional Test on the Effect of Cutting at Different Feed Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration

4.6.1 Introduction

The feed speed test as discussed in the previous section under the methodology and preliminary work chapter was conducted in a conventional direction at a spindle speed of 15,000 rpm. The spindle speed of 15,000 rpm was initially selected due to it being in the middle of the CNC router’s spindle speed range. However, after it was discovered that it was near the machine resonance, all other tests were done at 18,000 rpm of spindle speed. The cutting direction was also switched from conventional to climb cutting in order to provide the worst cutting conditions that will affect the amount of panel chipping and tool wear. Previous work has shown that more chipping occurs on melamine-coated particleboard (Lemaster et al., 2000b) in the climb cutting direction. This trend was also observed in preliminary cutting tests. Additionally, the previous feed speed test had a single replication for each feed speed since it was not the main factor that was going to be changed during the cutting operation in this study. The initial test was just to observe the effect of feed speed on tool wear and panel chipping.

4.6.2 Methodology

In order to obtain a full overview of the effect of cutting at different feed speeds, a new test was performed in the climb direction at a spindle speed of 18,000 rpm. This was done in order to provide similar cutting conditions with the majority of tests that were done in this study. Similar feed speeds were used, i.e. 7.6 m/min (300 ipm), 10.2 m/min (400 ipm), and 12.7 m/min (500 ipm). Each feed speed had three replications using 10% cobalt grade tungsten carbide tool inserts. The tool spindle vibration signals were collected during the machining process where each tool completed 200 m of length of cut. A similar cutting
pattern was conducted in which each tool cut 10 sets of 20 cutting passes as discussed previously in the experimental work section. Chipping of the melamine-coated particleboard was measured as well as the amount of tool wear on the tool cutting edge after the test was completed.

4.6.3 Results and Discussion

The following sections present the results on tool wear, panel chipping and the vibration signals.

Tool Wear

Figure 4.6.1 shows the tool wear result for the feed speed test. It can be observed that it had similar results as the early test in determining the effect of cutting at different feed speeds. Due to the higher number of impacts between the cutting tool and the material per inch, a feed speed of 7.6 m/min (300 ipm) produced the highest amount of tool wear (317 µm). Meanwhile, the highest feed speed of 12.7 m/min (500 ipm) had the lowest tool wear of 298 µm. A feed speed of 7.6 m/min (300 ipm) at 18000 rpm of spindle speed produced 2,340 impacts in a single cutting pass (21.2 m or 39 in.). Meanwhile, 12.7 m/min (500 ipm) produced 1404 number of tool impacts. Thus, the difference in the number of impacts was 936 impacts. As a comparison, with a constant feed speed of 12.7 m/min (500 ipm), a 12000 rpm of spindle speed would produce 936 impacts, and at 18,000 rpm, 1404 impacts would be produced in a single pass. The difference would then be 468 impacts, which is half of the difference when changing the feed speed (i.e. 936 impacts).

A normalized version of the tool wear result is shown in Figure 4.6.2. A 1% difference between feed speeds of 10.2 m/min (400 ipm) and 12.7 m/min (500 ipm) can be observed. The percent difference between 7.6 m/min (300 ipm) with the highest tool wear, and 12.7 m/min (500 ipm) with the lowest tool wear was 6%.

Earlier test showed that tool wear was significantly different when changing the spindle speed. In this feed speed test, the higher difference in the number of impacts should be expected to produce a significantly different result in tool wear. However, based on a
one-way analysis of variance (ANOVA), it was found that the means of the three feed speeds were not significantly different from each other with a P-value of 0.2729, F ratio of 1.625, and $R^2$ value of 0.35. Thus, it can be concluded that tool wear was not affected by feed speed.

Figure 4.6.1 Tool wear of 10% cobalt grade tungsten carbide inserts cutting at different feed speeds.
Figures 4.6.3 to 4.6.5 show the tool wear images of the 10% cobalt grade tungsten carbide inserts that cut at different feed speeds. Each figure is composed of three replications of its respective feed speed. In each replication of the carbide insert, the image of the cutting edge was captured into several ‘windows’. As depicted in the figure, each replication shows windows that also cover the part of the tool cutting edge that cut the high density area of the melamine-coated particleboard. As described in the main methodology section of this document, the tool wear was measured on the second window (counted from the left side of the figure).

Results showed that the tool wear images seemed to support the one-way ANOVA result in which the means were not significantly different, although Rep 2 of the 12.7 m/min (500 ipm) of feed speed showed lower tool wear.
Figure 4.6.3 Tool wear images of 10% cobalt grade tungsten carbide inserts cutting at 7.6 m/min (300 ipm) of feed speed.

Figure 4.6.4 Tool wear images of 10% cobalt grade tungsten carbide inserts cutting at 10.2 m/min (400 ipm) of feed speed.

Figure 4.6.5 Tool wear images of 10% cobalt grade tungsten carbide inserts cutting at 12.7 m/min (500 ipm) of feed speed.
Panel Chipping

Figure 4.6.6 shows the panel edge chipping that was produced by the 10% cobalt grade tungsten carbide inserts cutting at different feed speeds. The edge chipping pattern was highly variable. However, it is important to note that Rep 3 of the 7.6 m/min (300 ipm) feed speed had a substantial increase at the 80\textsuperscript{th} cutting pass, and a huge drop at the 160\textsuperscript{th} pass. The increase and drop pattern in the panel edge chipping could be due to a “self-sharpening effect” of the tool cutting edge in which the carbide insert chipped leaving a sharp edge. It could also be due to experimental variation. A cumulative count of the panel edge chipping was done in order to smooth the data is shown in Figure 4.6.7.

A one-way ANOVA test was performed to assess the effect of feed speed on the panel chipping amount. Results showed that the means of the panel chipping for the three feed speeds were not significantly different from each other for the majority of the sets of 20-passes except at the 80\textsuperscript{th} cutting pass (P-value = 0.0032; F ratio = 17.3333; $R^2 = 0.85$). It can be concluded that panel chipping was not affected by feed speed.
Figure 4.6.6 Panel chipping produced by 10% cobalt grade tungsten carbide inserts cutting at different feed speeds.

As shown in Figure 4.6.7, Rep 3 of the 7.6 m/min (300 ipm) test had the steepest slope that also translated to a higher amount of panel edge chipping of the melamine-coated particleboard. This was in agreement with the result in Figure 4.6.6. Rep 1 for both the 10.2 m/min (400 ipm) and 12.7 m/min (500 ipm) of feed speeds showed a lower amount of chipping.
The panel chipping amount was averaged to assist a better observation of the overall panel chipping level. Figure 4.6.8 shows that the lowest feed speed produced a slightly higher amount of panel chipping. However, the one-way ANOVA test showed that the means were not significantly different.
Figure 4.6.8 Averaged cumulative panel edge chipping produced by 10% cobalt grade tungsten carbide inserts cutting at different feed speeds.

**Tool Spindle Vibration**

The tool spindle vibration signal of the replications at different feed speeds is illustrated in Figure 4.6.9. Three RMS readings were recorded during the cutting operation, which corresponded to the first, second, and third cutting passes in each of the 20-pass set. It can be seen that Rep 3 of the 12.7 m/min (500 ipm) had a higher vibration; however, it also had a higher variation among its three RMS readings at each cutting pass.

The higher vibration for Rep 3 of 12.7 m/min (500 ipm) could be due to the large chip load (0.028 in.) produced by 12.7 m/min (500 ipm) compared to other feed speeds (i.e. 0.017 in. for 7.6 m/min (300 ipm); 0.022 in. for 10.2 m/min (400 ipm)). The size of the chip determines the amount of heat being carried away during cutting. The larger the chip size, the better the heat dissipates; hence, the lower tool wear. Higher tool wear is supposed to cause higher vibration; however, in the case of different size of chip loads, the chip load...
formation could also affect the level of vibration. Panel density could also complicate the interaction between the cutting tool and the resulting tool spindle vibration. Thus, in this particular test, removing a larger chip load could potentially produce higher tool spindle vibration.

Figure 4.6.9 Tool spindle vibration signal at frequency band between 5,500 Hz – 6,750 Hz of 10% cobalt grade tungsten carbide inserts cutting in the climb direction at spindle speed of 18,000 rpm and at different feed speeds.

The three RMS readings were averaged for a clear interpretation of its pattern as shown in Figure 4.6.10. It can still be observed that Rep 3 of the 12.7 m/min (500 ipm) had a higher vibration. Due to the different starting point of the RMS levels for each replication, the RMS readings were normalized by dividing each RMS value by the first RMS reading,
and then multiplied by 100%. This resulted in all replications having the same starting point as shown in Figure 4.6.11.

![Averaged RMS of Frequency Band Two (5,500 Hz - 6,750 Hz)](image)

Figure 4.6.10 Average of three RMS readings of frequency band between 5,500 Hz – 6,750 Hz of 10% cobalt grade tungsten carbide inserts cutting in the climb direction at spindle speed of 18,000 rpm and at different feed speeds.

All replications for the 12.7 m/min (500 ipm) of feed speed had a higher percent of change in vibration as compared to the 7.6 m/min (300 ipm) of feed speed. A cumulative of the normalized RMS data was also done in order to see how the RMS data increased as the cutting progressed (Figure 4.6.12). The RMS percent of change through observing the slope steepness could give an understanding of the vibration level and pattern of the CNC tool spindle vibration.
Figure 4.6.11 Normalized RMS of frequency band between 5,500 Hz – 6,750 Hz of 10% cobalt grade tungsten carbide inserts cutting in the climb direction at spindle speed of 18,000 rpm and at different feed speeds.

As represented in Figure 4.6.12, Rep 1 and 2 of the 10.2 m/min (400 ipm) of feed speed had the highest and steepest slopes. The cumulative effect showed that these two replications had a very drastic change in its pattern during the machining operation. The cause of the steep slopes is unknown. The effect of vertical density gradient and panel density on the tool spindle vibration behavior had been investigated in the previous tests. However, they did not provide any explanation. It can be concluded that this could be due to board and experimental variation.
Figure 4.6.12 Cumulative RMS of frequency band between 5,500 Hz – 6,750 Hz of 10% cobalt grade tungsten carbide inserts cutting in the climb direction at spindle speed of 18,000 rpm and at different feed speeds.

The three replications in each feed speed were averaged in order to provide an overview of the tool spindle vibration level as illustrated in Figure 4.6.13. The 10.2 m/min (400 ipm) feed speed had the highest vibration level followed by 10.2 m/min (400 ipm) and 12.7 m/min (500 ipm). The high vibration level for 10.2 m/min (400 ipm) was due to its two replications with the highest magnitude.
Based on the findings from both tests (i.e. conventional at 15,000 rpm and climb at 18,000 rpm), it can be concluded that the 7.6 m/min (300 ipm) of feed speed was the highest in terms of tool wear and panel chipping, and feed speed of 12.7 m/ min (500 ipm) was the lowest. As for the tool spindle vibration, preliminary results showed that the 12.7 m/min (500 ipm) of feed speed had the lowest spindle vibration. The results from the latest series of tests, however, showed that the averaged RMS of the vibration signal was higher for the 12.7 m/min (500 ipm) of feed speed.

However, the 12.7 m/min (500 ipm) was the lowest in the cumulative version of the vibration signal. This shows that the vibration of the 12.7 m/min (500 ipm) of feed speed had a small rate of change even after a 200 m length of cut as compared to the other feed speeds. This could be due to the panel density in which the average panel density that was
cut by the 12.7 m/min (500 ipm) tools was higher (i.e. 763 kg/m$^3$ compared to 752 kg/m$^3$ and 760 kg/m$^3$ for 7.6 m/min (300 ipm) and 10.2 m/min (400 ipm), respectively). A higher density could provide a dampening effect, which could lower the variability in vibration.

It was expected that this section could be confusing. A heavier chip load associated with a faster feed speed could cause more vibration, which results in more panel chipping while a slower feed speed results in a greater tool wear, which can also result in greater panel chipping. In addition, more vibration caused by a heavier chip load can also cause an increase in tool wear. This results in many experimental interactions, which are difficult to separate out as well as the confounding due to experimental variation in the melamine panels.

### 4.7. Investigation on the Drop in Panel Chipping

#### 4.7.1. Introduction

A test was done to track the changes in tool wear during the machining process. This was also to identify if there were any unusual changes in tool wear at the 120$^{th}$ cutting pass, as most results in the study consistently showed a drop in the amount of panel chipping (either for the count or area methods) at or near the 120$^{th}$ cutting pass.

#### 4.7.2. Methodology

A 10% cobalt grade tungsten carbide insert was used to cut two 0.6 m × 1.2 m × 19 mm (2 ft. × 4 ft. × 0.75 in.) melamine-coated particleboard panels on a CNC router. A total of 200 m length of cut was completed in the climb cutting direction at 18,000 rpm of spindle speed and 500 ipm of feed speed. The cutting pattern was done similar to the one described in the experimental work section in which the tool completed 20 cutting passes in each set. Each of the 0.6 × 1.2 m (2 × 4 ft.) panel had five sets of 20 passes.

As the cutting tool completed the first set of 20 passes, the router was stopped. Then, the CNC router machine was set back to its home position. At the home position, the image of the tool wear was captured with a digital microscope that was attached to a mini tripod as shown in Figure 4.7.1. The digital microscope was attached to a computer that had image
analysis software that was used to capture and analyze the image. This procedure was done at every 20th pass until the 10th set, i.e. 200 total cutting passes (200 m).

Figure 4.7.1 Setup for capturing tool wear image on CNC router table.

At the completion of the machining test, the panel chipping was determined by measuring the chip area using image analysis procedures. The final tool wear was measured and the tool spindle vibration was also analyzed.

4.7.3. Results and Discussion

The tool wear images that were taken at every 20th pass in each set are shown in Figure 4.7.2. It can be observed that there was a drastic increase in tool wear beginning from the first 20 cutting passes up until the 100th pass. However, the change in tool wear was small between the 100th pass until the 180th pass. This tool behavior pattern follows the standard or typical tool wear curve for carbide tools as described by Aknouche et al. (2009) as shown in Figure 4.7.3. The paper described that the tool wear curve had two separate zones; i.e. 1) running zone that had abrupt wear, and 2) linear zone or known as stability period. The tool wear behavior did not help explain the drop in panel chipping at the 120th pass.
Figure 4.7.2 Tool wear images at different cutting passes.
The final pass, i.e. 200th pass showed a high amount of tool wear (368 µm). A close-up of the final tool wear is shown in Figure 4.7.4. The tool wear measurement for this test was slightly higher than previous tests. This could be due to the effect of the interrupted cutting at every 20th pass in which the CNC router was stopped after each set of 20 passes was completed. This could introduce a rapid temperature change from hot to cold and vice versa.

Figure 4.7.4 Close-up view of tool wear at 200th cutting pass.

Figure 4.7.5 shows the panel chipping area on the melamine-coated particleboard. It can be observed that there was a drop in the panel chipping at the 120th pass. The panel chipping had a sharp increase at the 160th pass and slightly dropped after that. Similar panel chipping area patterns were observed in other tests in that the change or variation in the panel...
chipping area was small at the beginning of the cutting and become large beyond the 100\textsuperscript{th} cutting pass. The large change in panel chipping area could be due to the effect of the dullness of the cutting tool. As tool wear increases, so does the panel chipping.

In Figure 4.7.6, the tool spindle vibration level was high and highly variable at the beginning of the cutting and then leveled off as the cutting tool became worn. There was a slight increase at the 100\textsuperscript{th} cutting pass. Similar patterns were seen in several other tests in this study. Additionally, previous work by Lemaster et al. (1985) in acoustic emission (AE) during woodcutting showed that the AE levels decreased with the increase in tool wear. It
was suggested that this was due to the reduction in AE energy from producing a long continuous chip formation by a worn cutting tool.

However, since the test was done for a wood turning process, which is a type of orthogonal cutting, the behavior of the AE energy could be different than a peripheral milling such as routing and circular sawing processes. Chip formation also contributes to the difference between the two types of cutting in which a long continuous chip is produced in orthogonal cutting, and a peripheral milling produces a single curved chip. Lemaster and Dornfeld (1988) monitored a circular sawing process with AE and found that the RMS increased as tooth advancement (i.e. feed speed) increased (increased tool wear). It is not known as to why the RMS of the current study resembled the result from an orthogonal cutting process.

![Figure 4.7.6 Averaged RMS of a 10% cobalt grade tungsten carbide insert cutting in climb direction at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed.](image)
Thus, in order to further analyze and for a better understanding of the vibration data, a cumulative method was used to determine the change in the panel chipping area and tool spindle vibration level as the machining progressed. This method proves to be valid as demonstrated in the work by Saloni (2007), in which the study applied the cumulative method to determine the threshold of a control system in abrasive machining. Figure 4.7.7 shows that both had a similar initial slope, although the cumulative chipping area had a sharp increase after the 140th cutting pass. This could be caused by the high amount of tool wear at 140th pass and beyond as can be seen in the tool wear images of different cutting passes.

![Cumulative Chip Area versus Cumulative RMS for Cutting Stopped at Every 20 Passes](image)

Figure 4.7.7 Panel chipping versus tool spindle vibration for a 10% cobalt grade tungsten carbide insert cutting in climb direction at 18,000 rpm of spindle speed and 12.7 m/min (500 ipm) of feed speed.
Based on the results of the test, there were no unusual changes in tool wear as shown in the images of different cutting passes. Therefore, it can be suggested that the drop in panel chipping at the 120th pass was not caused by tool wear. Several preliminary tests were conducted in order to address the regular occurrences of the drop in panel chipping at the 120th pass. These have been described in details in earlier sections. One test was done to investigate if the cutting of particleboard panels in different configurations could potentially cause the drop. This was done by performing 100 cutting passes twice (i.e. 100 passes on each of the 0.6 × 1.2 m (2 × 4 ft. panel)), and cutting 200 passes at once (i.e. two 0.6 × 1.2 m (2 × 4 ft.) panels were placed side by side), which resulted in a different starting cutting position for the second 0.6 × 1.2 m (2 × 4 ft.) panel.

Another test was done to investigate if chip load caused the drop. The different chip loads were achieved through varying the feed speed at 300 ipm, 400 ipm, and 500 ipm. The panel chipping results from these tests still showed the drop at the 120th pass. Panel density as well as visual observation of the cutting blades and the panels that had been cut from the machining tests also did not provide any explanation as to why the drop had occurred.

Another factor that could be considered is board mass. As the cutting progresses, the overall mass of the particleboard panel gradually decreases. Thus, in order to investigate the effect of board mass factor on the drop in panel chipping, two tests were conducted where the 200 cutting passes were done on panels with different sizes. Details of the tests are described in the next section.

### 4.7.4. Effect of Board Mass on the Drop in Panel Chipping

In the previous section, a test was conducted to determine whether or not tool wear affected the occurrence of the drop in panel chipping at the 120th pass. During the cutting, the CNC router machine was stopped after each set of 20 passes was completed. The tool wear image was captured of the tungsten carbide insert that was attached to the tool spindle. It was found that there were no unusual changes on the tool wear that could possibly affect the drop in panel chipping.
In the preliminary tests that were conducted earlier in the study, the 200 cutting passes (200 m of length of cut) were completed on two melamine-coated particleboard panels with dimensions of 0.6 × 1.2 m (2 × 4 ft.) each. The 200 cutting passes were either completed at once (with the two panels placed side by side) or each panel had 100 cutting passes done separately on the CNC router table. As the drop in panel chipping at the 120th pass occurred at the first set of the second panel, it can be speculated that board mass could play a role. As stated earlier, the overall mass of the particleboard panel is gradually decreased as the cutting progresses.

An explanation is needed regarding what is behind the drop in panel chipping in relation to board mass. It is crucial to point out that in discussing the board mass factor, it is no longer important to observe whether or not there is a drop in panel chipping at the 120th pass. The key is to find out if there is any evidence that shows board mass causes the drop in panel chipping. The next few paragraphs will further elaborate the tests, and discuss the results on the effect of board mass on the drop in panel chipping.

(a) Methodology

Two tests were done in order to determine the effect of board mass on the panel chipping behavior. In the first test, a 10% cobalt grade tungsten carbide insert was used to cut a 1.2 × 1.2 m (4 × 4 ft.) melamine-coated particleboard panel on the CNC router in climb cutting direction at 18,000 rpm of spindle speed, and 12.7 m/min (500 ipm) of feed speed. A cutting pattern, which consisted of ten sets of 20 cutting passes were completed, resulting in 200 m of total length of cut. The cutting pattern illustration and further details on the cutting operation can be found in the Methodology and Preliminary Work chapter under the Experimental Work section. The vibration of the tool spindle was also collected from the first three passes in each set.

As for the second test, the ten sets of 20 cutting passes were distributed evenly among five melamine-coated particleboard panels with each measured at 0.3 × 1.2 m (1 × 4 ft.). The machining parameters were similar with the first test, as well as the acquiring of the tool spindle vibration. The thickness of the melamine-coated particleboard panels in both tests
was 2 cm (0.75 in.). The second test was conducted in order to address the issue that the drop in panel chipping occurred at the edge (i.e. 20th pass) of the first set in every board. Figure 4.7.8 illustrates the cutting pattern for the second test.

![Figure 4.7.8 Pattern for cutting five melamine-coated particleboard panels.](image)

After both tests were completed, tool wear for the two tungsten carbide inserts was measured with an optical digital microscope. Panel chipping images at the edges of each set were taken from all the particleboard panels, and the chip areas were measured. The tool spindle vibration data from both tests was also analyzed. The results and discussion are presented in the next few paragraphs.

(b) Results and Discussion

Following are the results on the effect of board mass on tool wear, panel chipping, and tool spindle vibration for tests of cutting 200 passes on a 1.2 × 1.2 m (4 × 4 ft.) panel versus five 0.3 × 1.2 m (1 × 4 ft.) panels.
Tool Wear

Figure 4.7.9 shows the tool wear result from the two tests. As illustrated, the amount of tool wear for the test of cutting one 1.2 \times 1.2 \text{ m} (4 \times 4 \text{ ft.}) panel was 255 \mu\text{m}. Meanwhile, the cutting of five 0.3 \times 1.2 \text{ m} (1 \times 4 \text{ ft.}) particleboards panels was the highest with 391 \mu\text{m}. The higher amount of tool wear for the second test could be due to the rapid temperature change from hot to cold and vice versa, as well as the frequent stops of the cutting process. The cutting process was interrupted at every 40 passes after which the board was being replaced.

![Figure 4.7.9 Tool wear for cutting of different sizes of boards.](image)
Panel Chipping

Panel chipping area was measured according to the procedures that had been described earlier under the “Measuring Panel Chipping Area using Image Analysis” section. In Figure 4.7.10 below, the panel chipping results are presented. The main objective of the tests was to observe for evidence that shows board mass affecting the drop in panel chipping.

In the first test where a 1.2 × 1.2 m (4 × 4 ft.) panel was cut, it showed no pattern in terms of the drop in panel chipping. As for the second test where five 0.3 × 1.2 m (1 × 4 ft.) panels were cut, it can be observed that the panel chipping increased as the cutting progressed. In the second test, each board had two of the 20-pass sets, i.e. the 20th and 40th cutting passes were on the same first board (Board 1), 60th and 80th passes were located on Board 2, and so on.

It is interesting to note that in the second test, the panel chipping amount for the first 20-pass set was lower than the second 20-pass set on each board. Thus, it can be concluded that the effect of board mass on the drop in panel chipping was not noticeable in the first test; however, it was evident in the second test. The second test exaggerated the effect of board mass on the drop in panel chipping, and was able to demonstrate the board mass effect better.

The explanation behind this could be that higher board mass will produce less vibration due to the dampening effect, hence, less panel chipping is produced. The correlation between tool spindle vibration and panel chipping had been demonstrated and established in earlier tests in which higher vibration caused higher panel chipping. Thus, it would also be interesting to know the tool spindle vibration level for both tests, which will be presented and discussed in the next section.
Figure 4.7.10 Panel chipping for cutting different sizes and masses of boards.

Figure 4.7.11 shows the cumulative panel chipping for both tests. A comparison can be made in terms of the level or magnitude of the panel chipping. The level of panel chipping for the first test (cutting one 4 × 4 ft. panel) had a steady increase beyond the 80th cutting pass. Meanwhile, the second test (cutting five 1 × 4 ft. panels) had a sharp increase after the 80th cutting pass.

The sharp increase in the second test could be due to the effect of the interrupted cutting. This has been discussed in the earlier part of this chapter in which the interrupted cutting could introduce a rapid temperature change from hot to cold and vice versa. This had caused a higher tool wear, which had resulted in a higher amount of panel chipping. This could also be caused by the boards weighing less and thus, vibrating more.
Tool Spindle Vibration

The tool spindle vibration of the CNC router was collected during the first three cutting passes in each of the 20-pass set. Figure 4.7.12 shows the vibration of the tool spindle for both tests. It can be observed that both tests had the same pattern. The second test (i.e. cutting five 1 × 4 ft. panels) had a higher vibration magnitude. The higher level of vibration from the second test correlated with its higher amount of tool wear, and panel chipping as previously presented.
Figure 4.7.12 RMS at frequency band two (5,500 Hz – 6,750 Hz) of two 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed for tests of cutting different sizes and masses of boards.

In order to better represent the tool spindle vibration data, the three RMS readings at each of the 20-pass set were averaged as shown in Figure 4.7.13. A better shape of the graph can be observed in which the second test of cutting five 1 × 4 ft. panels had a higher vibration level.
Figure 4.7.13 Average of three RMS readings at frequency band two (5,500 Hz – 6,750 Hz) of two 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed for tests of cutting different sizes and masses of boards.

Due to the different board density and initial break of the tool cutting edge during cutting, each tungsten carbide insert had a different initial vibration level. Thus, the averaged RMS values were normalized in order to make a better comparison of each tool’s vibration level. The normalized data was done by dividing each averaged RMS value with the first RMS averaged value and multiplying it by 100%. Figure 4.7.14 presents the normalized version of the vibration data, which confirms the higher level of vibration for the second test.
Figure 4.7.14 Normalized RMS at frequency band two (5,500 Hz – 6,750 Hz) of two 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed for tests of cutting different sizes and masses of boards.

Successive additions of the normalized RMS data produced a cumulative version of the vibration signal as illustrated in Figure 4.7.15. The cumulative RMS graph provides a better comparison of the magnitude, shape and slope. As can be observed, both tests had a steady increase in the vibration signal. As expected, the second test had a higher vibration signal compared to the first test. The next two figures will compare the cumulative RMS and the cumulative panel chipping for both tests.
Figure 4.7.15 Cumulative RMS at frequency band two (5,500 Hz – 6,750 Hz) of two 10% cobalt grade tungsten carbide inserts that cut in the climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed for tests of cutting different sizes and masses of boards.

Figure 4.7.16 shows the cumulative version for the vibration of the tool spindle as well as the panel chipping area for the two tests of cutting a 1.2 × 1.2 m (4 × 4 ft.) and five 0.3 × 1.2 m (1 × 4 ft.) melamine-coated particleboard panels. It can be observed that for the first test (one 4 × 4 ft.), both cumulative RMS and chipping area had the same slope, and it can be concluded that the cumulative version of the vibration signal could reflect the general condition of the panel chipping when cutting is in progress. As for the second test of cutting five 0.3 × 1.2 m (1 × 4 ft.) panels, the cumulative RMS and chipping area showed a sharp increase as the cutting progressed. The higher vibration as the cutting progressed agreed with the steep increase in panel chipping.
In summary, this section investigated the effect of tool wear on the drop in panel chipping initially for the drop at the 120th cutting pass. It was found that there were no unusual changes on tool wear. Consequently, board mass factor came into consideration as it was observed that the drop in panel chipping occurred at the first 20-pass set on each board. Two tests were conducted where the cutting of 200 passes (~200 m) were done on different sizes of melamine-coated particleboard panels: (1) cutting on one 1.2 × 1.2 m (4 × 4 ft.) panel; and (2) cutting on five 0.3 × 1.2 m (1 × 4 ft.) panels. The second test prevailed in demonstrating the effect of board mass on the drop in panel chipping. It showed that the first
20-pass set on each of the five boards had a lower chipping compared to the second 20-pass set. Therefore, it can be concluded that board mass was the main factor that had caused the drop in panel chipping at the initial cutting of a board.

4.8. **Application of Feedback Control Technique in Extending Tool Life**

4.8.1. **Introduction**

The relationship between tool wear, panel chipping, and tool spindle vibration had been established through conducting extensive preliminary work. It was found that when cutting at a constantly low spindle speed of 12,000 rpm, tool wear rate was decreased but at a cost of a higher panel chipping due to a larger chip load. Meanwhile, cutting at a constantly high spindle speed of 18,000 rpm produced a lower panel chipping, although it caused an increase in tool wear rate. Additionally, increasing the spindle speed at regular intervals such as in the step function technique produced a lower tool wear and panel chipping; however, it provided no clue as to when to systematically increase the spindle speed. The feedback control technique utilized the tool spindle vibration to regulate the spindle speed that could greatly extend the useful life of the cutting tool; while at the same time could produce a good surface quality.

The main objective was to determine the extent of tool life by the feedback control technique, which could suggest its potential to be used as a process control strategy. Additionally, it was to demonstrate by how much a computer-controlled spindle speed process could extend tool life as compared to cutting without controlling the spindle speed.

The test using the feedback control system was compared with three other tests: (1) cutting with a constantly low spindle speed of 12,000 rpm; (2) cutting with a constantly high spindle speed at 18,000 rpm; and (3) a step function cutting with the spindle speed being increased at regular intervals. Details on the methodology are presented in the following section.
4.8.2. Methodology

Four tests were conducted involving different spindle speed settings: (1) 12,000 rpm; (2) 18,000 rpm; (3) step function; and (4) feedback control. In all four tests, a 10% cobalt grade tungsten carbide insert was used to machine two 2 × 4 ft. panels of melamine-coated particleboard in a climb cutting direction at a feed speed of 12.7 m/min (500 ipm) on the CNC router. The cutting pattern on the panel was similar to the one as described, and illustrated in the main methodology chapter where each of the 2 × 4 ft. panel had five sets of 20 cutting passes. The total length of cut for each test was 198 m, and there were three replications for each test.

After the tests were completed, tool wear and panel chipping area were measured. Based on the tool wear amounts from the tests, the percentage of tool wear reduction or usable tool life was calculated for use in tooling cost calculation in the cost-benefit analysis section.

The first two tests were cutting at constant spindle speeds of 12,000 rpm and 18,000 rpm. The step function cutting had a spindle speed increased by 500 rpm at each step; i.e. after every 20 cutting passes. The following paragraphs elaborate the methods for performing the feedback control technique.

(a) Feedback Control Technique

The feedback control technique utilized a P controller, which indicated only the proportional control action was taken placed. In the cutting test, the spindle speed, which began at 12,016 rpm (corresponded to 6.43 volts), was automatically increased by 2.5% whenever a 25% increase in the tool spindle vibration level was reached. At the beginning of the cutting, the tool spindle vibration level (i.e. RMS value) for the first three cutting passes were collected, and averaged. From then onwards, the averaged RMS value was used as a setpoint in which the 25% increase in the normalized cumulative RMS was based on.

The tool spindle vibration level was monitored and controlled by a LabVIEW™ program written specifically for the process control test. A wire connector from the data acquisition (DAQ) board was attached to a 10 hp variable speed drive or VSD (brand
MagneTek, model GPD 515), which was located inside the CNC router control unit (Figure 4.8.1(a)). A close-up view of the VSD is shown in Figure 4.8.1(b). The VSD was used to control or regulate the speed of the tool spindle. It received a voltage value from the DAQ board and converted it into its corresponding spindle speed value in rpm.

Figure 4.8.1 Variable speed drive: (a) inside the CNC router control unit; (b) close-up view.

The following paragraphs present the results of all tests as well as a conclusion of the findings.

4.8.3. Results and Discussion

As illustrated in Figure 4.8.2, the 12,000 rpm test produced the lowest averaged tool wear with a 120 µm nose width. This is expected as a constantly low spindle speed has a lower number of impacts between the tool and the workpiece. As for the highest averaged
tool wear, it was produced by the 18,000 rpm test (209 µm) due to a higher number of tool-workpiece impacts. Both the feedback control (FC) technique and the step function (ST) showed comparably low averaged tool wear amounts with 139 µm and 144 µm, respectively; due to the effect of controlling the spindle speed by increasing it systematically. Based on the results, the 12,000 rpm, step function, and feedback control technique tests caused 43%, 31%, and 33% increase in tool life, respectively, when compared to the 18,000 rpm test.

Figure 4.8.2 Averaged tool wear of 10% cobalt grade tungsten carbide inserts cutting at different spindle speed settings; i.e. 12,000 rpm (12K), 18,000 rpm (18K), feedback control (FC), and step function (ST).
Figure 4.8.3 shows machining quality as presented in the form of panel edge chipping area of the melamine. Although the 12,000 rpm test had the lowest averaged tool wear, the board quality was not as good due to the higher chip load it produced. As for 18,000 rpm test, it produced the worst panel chipping level, as expected, which is due to its higher tool wear rate. The best machining quality was produced by FC and ST tests due to the effect of controlling the spindle speed, which was increased as the cutting progressed. In the FC and ST tests, it started off with a low spindle speed, which caused a lower rate of tool wear, and as the cutting progressed, the spindle speed was increased; hence, increase in tool wear rate.

![Cumulative Panel Chipping Area for Cutting at Different Spindle Speed Settings](image)

Figure 4.8.3 Cumulative panel chipping area for cutting at different spindle speed settings; i.e. 12,000 rpm (12K), 18,000 rpm (18K), feedback control (FC), and step function (ST).
The relationship of tool wear, panel chipping, and spindle speed can be best presented in a diagram as depicted in Figure 4.8.4. It shows the effect of high and low spindle speeds on the surface quality (i.e. panel chipping), and tool life (i.e. tool wear).

In summary, a lower spindle speed causes more panel chipping due to the larger chip load; however, it causes a slower tool wear rate. A higher spindle speed produces a small tool chip load but causes a higher rate of tool wear. A step function technique would compromise the combined effect of a higher panel chipping due to lower spindle speed, and also a higher rate of tool wear due to higher spindle speed; however, one would not really know when is the right time to increase the spindle speed in order to greatly extend the tool life. In fact, a range of high machine resonance corresponding to a spindle speed of 15,000 rpm was avoided using the step function since it was discovered during preliminary tests. For the feedback control method, no prior knowledge was provided to the system, and it automatically skipped over the high vibration spindle speeds. This illustrated a further benefit of the feedback method.

A feedback control system takes all the aspects of cutting into consideration and performs the cutting accordingly in order to improve the cutting process, and at the same time, increases the usable life of the cutting tool. A cost-benefit analysis would further analyze the opportunity for the feedback control to be utilized in the wood-based industry.
4.9. Cost Analysis of Different Cutting Settings on a CNC Router

4.9.1. Introduction

The performance of machining processes on a CNC router or other cutting equipment depend on several important machining parameters such as spindle speed, feed speed, as well as raw materials, and cutting tools. This particular section analyzes the effect of different cutting scenarios on the cost of machining a product using a high speed CNC router.

For simulation purposes, a product was selected to demonstrate how much it would cost to operate under the different cutting settings. Four cutting settings had been conducted: (1) a control, which was a cutting operation at a constant spindle speed of 18,000 rpm; (2) a cutting operation at a constant spindle speed of 12,000 rpm; (3) a step function cutting with the spindle speed being increased at regular intervals; and (4) a cutting operation that utilized a feedback control system, in which the spindle speed was increased based on the tool spindle vibration level.

Figure 4.8.4 Combined effects of tool wear, panel chipping, and spindle speed.
All of the cutting operations with different settings were conducted on a CNC router using a 10% cobalt grade tungsten carbide insert, which cut a melamine-coated particleboard in a climb cutting direction at 12.7 m/min (500 ipm) of spindle speed.

As demonstrated in previous tests, a higher spindle speed produced lower panel chipping on the melamine-coated particleboard; however, it caused higher tool wear (i.e. shorter tool life). As for the test with a lower spindle speed, tool life was increased; i.e. lower tool wear rate, but adversely affected the level of the panel chipping due to larger tool chip load.

Additionally, a test which increased the spindle speed at regular intervals showed a lower tool wear, and panel chipping. However, the stepping up technique provides no clue about when to increase the spindle speed that could greatly extend tool life. The feedback control system utilized the tool spindle vibration to regulate the spindle speed. It increased the spindle speed in order to optimize the CNC cutting operation through extending the life of the cutting tool.

A cost analysis was conducted in order to weigh in the implications of performing each of the cutting conditions. The different cutting settings affected the amount of tool wear, which translated to the amount of savings on tooling cost. As the feedback control system could contribute to a higher productivity due to extended tool life, a comparison was made with polycrystalline diamond (PCD) cutting tools via a cost-benefit analysis.

4.9.2. Product Description and Assumptions

Due to time and financial constraints, the cost analysis was performed based on an imaginary product. A complete set of kitchen cabinet doors to be fit into a 3 × 2 m (10 × 7 ft.) kitchen cabinet design was used as the imaginary product. Only the doors were considered due to the different materials involved in building the entire kitchen cabinet. The kitchen cabinet was divided into wall and base cabinets. Additionally, depreciation and other financial accounting methods were not considered for this analysis. Operator rate was $35 per hour, and all other economic and plant conditions remained the same.
Figures 4.9.1 to 4.9.4 illustrate detailed drawing views of the kitchen cabinet consisting of isometric, top, front, and right views. The design was drawn using SketchUp™; a 3D drawing application software.

Figure 4.9.1 Isometric view of a simple kitchen cabinet.
Figure 4.9.2 Top view of a simple kitchen cabinet.
Figure 4.9.3 Front view of a simple kitchen cabinet.

Figure 4.9.4 Right view of a simple kitchen cabinet.
The detailed dimensions are shown in Figures 4.9.5 and 4.9.6. As illustrated in Figure 4.9.5, each cabinet door is marked with an abbreviated name. As an example, W1830 refers to a single door wall cabinet with dimensions of 18 in. in width and 30 in. in height. Table 4.9.1 lists the dimensions for each part in details.
Figure 4.9.6 Width dimensions of kitchen cabinet.
As can be seen in Table 4.9.1, the total cabinet doors was 17. The total perimeter was 36.27 m (1,428 in.), and this value was used in calculating the cost of producing the imaginary product.

Table 4.9.1 Cutting list for kitchen cabinet doors.

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Total Quantity per Kitchen Cabinet</th>
<th>Thickness (inches)</th>
<th>Width (inches)</th>
<th>Length (inches)</th>
<th>Perimeter per Part (inches)</th>
<th>Total Perimeter (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3630</td>
<td>2</td>
<td>0.75</td>
<td>18</td>
<td>30</td>
<td>96</td>
<td>192</td>
</tr>
<tr>
<td>Double door wall cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1830</td>
<td>1</td>
<td>0.75</td>
<td>18</td>
<td>30</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>Single door wall cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC2430</td>
<td>1</td>
<td>0.75</td>
<td>24</td>
<td>30</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>Corner wall cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1530L</td>
<td>1</td>
<td>0.75</td>
<td>15</td>
<td>30</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Single door wall cabinet</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W3015</td>
<td>2</td>
<td>0.75</td>
<td>15</td>
<td>15</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Double door wall cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1530R</td>
<td>1</td>
<td>0.75</td>
<td>15</td>
<td>30</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Single door wall cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>696</td>
</tr>
<tr>
<td>B18L</td>
<td>4</td>
<td>0.75</td>
<td>18</td>
<td>8.75</td>
<td>53.5</td>
<td>214</td>
</tr>
<tr>
<td>Drawer base cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SB36</td>
<td>2</td>
<td>0.75</td>
<td>18</td>
<td>35</td>
<td>106</td>
<td>212</td>
</tr>
<tr>
<td>Sink base cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B18R</td>
<td>1</td>
<td>0.75</td>
<td>18</td>
<td>35</td>
<td>106</td>
<td>106</td>
</tr>
<tr>
<td>Single door base cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.9.1 Continued.

<table>
<thead>
<tr>
<th></th>
<th>B15L</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single door</td>
<td>1</td>
<td>0.75</td>
<td>15</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>base cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>B15R</td>
<td>Single door</td>
<td>1</td>
<td>0.75</td>
<td>15</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>base cabinet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>732</td>
</tr>
<tr>
<td>Total Parts</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,428</td>
</tr>
</tbody>
</table>

4.9.3. Nesting Process

Sheets of 1.2 × 2.4 m (4 × 8 ft.) melamine-coated particleboard panels with thickness of ¾ in. were assumed to be used in the production of the kitchen cabinet doors. The panels were cut with 10% cobalt grade tungsten carbide inserts on a CNC wood router. A process called nesting was assumed to be applied in the cutting process. Nesting is a technology that optimizes yield, which originally invented for the leather industry (Vollmers, 2011). It performs a geometric optimization, in which parts that need to be cut out from a sheet of material are arranged in such a way that would reduce material waste.

Table 4.9.2 shows the nesting process (adapted from Vollmers, 2011). The approximate time for each process is also listed. During the cutting process, a panel was automatically loaded on the spoil board, after which the program was selected and started immediately. A spoil board, usually MDF, is a material placed underneath the actual board that needs to be cut in order to accommodate through cuts. It was assumed that the process of loading the board, and the selection of the cutting program were completed approximately in 30 seconds.

Next, the routing operation was done using the machining parameters as follows: 500 ipm of feed speed, and depth of cut of 0.5 in. (note: spindle speed was varied according to the respective cutting setting). The machining process was assumed to be completed approximately in 1.5 minutes based on the calculation of the total perimeter of the wall cabinet doors or base cabinet doors to be cut out divided by 500 ipm. After the cutting process was completed, the entire sheet was automatically pushed off from the machine, and
the process of cleaning the spoil board took place in about **30 seconds**. The total time to finish the cycle was approximately **2.5 minutes**.

Table 4.9.2 also includes the calculation for the daily production. The number of sheets per hour was first calculated through dividing 60 minutes by the time that was needed to complete the cutting for one sheet of material (i.e. one cycle), which was 2.5 minutes, resulting in **24 sheets per hour**. This was followed by multiplying with an eight-hour shift totaling in 192 sheets per day. Downtime such as tooling replacement, maintenance and operator breaks (about 15% of manufacturing time) was also taken into consideration, and was equivalent to the production of about 29 sheets. Thus, the daily production was determined by deducting 29 sheets from the initial calculation of 192 of sheets per day, giving approximately a total daily production of **163 sheets**.

Table 4.9.2 Nesting process and calculation of machining time and number of sheets  
(Adapted from Vollmers, 2011).

<table>
<thead>
<tr>
<th>Process of nesting (repeated for every sheet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Prepare and position a new panel on the spoil board</td>
</tr>
<tr>
<td>2. Select and start the program</td>
</tr>
<tr>
<td>3. Run the program with routing operation</td>
</tr>
<tr>
<td>4. Clean the nested panel</td>
</tr>
<tr>
<td>5. Remove, sort, check and stack cut parts</td>
</tr>
<tr>
<td>6. Clean the spoil board</td>
</tr>
</tbody>
</table>
Table 4.9.2 Continued.

<table>
<thead>
<tr>
<th>Manufacturing time for a 4 × 8 ft. melamine chip board</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Placing the board onto the machine and loading of the machining program</td>
</tr>
<tr>
<td>2. Running the machining program for one sheet of 4 × 8 ft.</td>
</tr>
<tr>
<td>Sheet 1: Total perimeter for wall cabinets = 696 in. Machining time = 696 in. ÷ 500 ipm = 1.4 min</td>
</tr>
<tr>
<td>Sheet 2: Total perimeter for base cabinets = 732 in. Machining time = 732 in. ÷ 500 ipm = 1.5 min</td>
</tr>
<tr>
<td>Average machining time = 1.4 + 1.5/2 ≈ 1.5 min</td>
</tr>
<tr>
<td>3. Automatic offloading of the parts and cleaning the spoil board</td>
</tr>
<tr>
<td>Average total time for entire cycle</td>
</tr>
<tr>
<td>30 sec</td>
</tr>
<tr>
<td>2.5 min</td>
</tr>
</tbody>
</table>

Calculation for daily production

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Number of sheets per hour = 60 min. ÷ 2.5 min.</td>
</tr>
<tr>
<td>2. Number of sheets per day = 24 sheets/hr. × 8 hr./shift</td>
</tr>
<tr>
<td>3. Downtime for tooling replacement, re-surfacing, changing spoil board, preventative maintenance, and operator brakes = 15% of manufacturing time = 15% × 192 sheets</td>
</tr>
<tr>
<td>4. Total daily production = 192 sheets – 29 sheets</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>24 sheets per hour</td>
</tr>
<tr>
<td>192 sheets per day</td>
</tr>
<tr>
<td>29 sheets</td>
</tr>
<tr>
<td>163 sheets per day</td>
</tr>
</tbody>
</table>

The nesting process could be done using the program that comes with the CNC router system. Figures 4.9.7 and 4.9.8 simulate the nesting process for the wall cabinet doors using a nesting software called Cabinet Parts Pro. The parts were nested on a 4 × 8 ft. sheet. A similar operation was performed for the base cabinet doors as illustrated in Figures 4.9.9 and 4.9.10. All the parts were labeled separately for easy reference.
Figure 4.9.7 Wall cabinet parts and dimensions.
Figure 4.9.8 Wall cabinet parts nested on a $4 \times 8$ ft. sheet.
Figure 4.9.9 Base cabinet parts and dimensions.
4.9.4. Cost Analysis for Kitchen Cabinet Doors

Table 4.9.3 shows the input parameters for calculating the total cost per shift of producing the kitchen cabinet doors using different cutting settings. The values for the machine cost (MC), labor cost (LC), tooling cost (TC), power cost (PW), and maintenance cost (MT) were typical for the manufacture of furniture components (adapted from Annamalai, 2003). The stated machine cost of $200,000 fell within the range for a typical high speed CNC router. Additional $5000 in machine cost for the feedback control system was for the data acquisition system that was needed to control the spindle speed during cutting.
As stated earlier, changing the spindle speed affects the amount of tool wear, which could be translated to the amount of savings on tooling cost. As shown in the table, lowering the spindle speed to 12,000 rpm had resulted in a small decrease in the total cost per shift to $778.92; however, stepping up the spindle speed at regular intervals contributed to a total cost of $779.22. The cost per shift for the feedback control technique was $781.67. Detailed calculations on MC, LC, and TC per shift are presented in Table 4.9.4.

Table 4.9.3 Input parameters for cost analysis of kitchen cabinet doors.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>18K Control</th>
<th>12K</th>
<th>Step Function</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle Speed</td>
<td>18,000 rpm</td>
<td>12,000 rpm</td>
<td>12,000 rpm step up to 18,000 rpm</td>
<td>Regulated spindle speed</td>
</tr>
<tr>
<td>Machine Cost</td>
<td>$200,000</td>
<td>$200,000</td>
<td>$200,000</td>
<td>$205,000</td>
</tr>
<tr>
<td>Machine Cost per Shift (MC)</td>
<td>$100</td>
<td>$100</td>
<td>$100</td>
<td>$102.50</td>
</tr>
<tr>
<td>Labor Cost per Shift (LC)</td>
<td>$560</td>
<td>$560</td>
<td>$560</td>
<td>$560</td>
</tr>
<tr>
<td>Tooling Cost per Shift (TC)</td>
<td>$40</td>
<td>$38.92</td>
<td>$39.22</td>
<td>$39.17</td>
</tr>
<tr>
<td>Power Consumption per Shift (PW)</td>
<td>$40</td>
<td>$40</td>
<td>$40</td>
<td>$40</td>
</tr>
<tr>
<td>Maintenance Cost per Shift (MT)</td>
<td>$40</td>
<td>$40</td>
<td>$40</td>
<td>$40</td>
</tr>
<tr>
<td>Total Cost per Shift</td>
<td>$780</td>
<td>$778.92</td>
<td>$779.22</td>
<td>$781.67</td>
</tr>
</tbody>
</table>

Table 4.9.4 shows the calculations for the MC, LC, and TC for one shift. The description for each cost and input that were used in the calculations are listed following the table.
<table>
<thead>
<tr>
<th>Calculation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine Cost per Shift</strong></td>
<td>Machine cost / (8 hrs per shift × number of shifts per year)</td>
</tr>
<tr>
<td>18K, 12K, and Step Function</td>
<td>$200,000 / (8 hrs × 250 shifts/year) = <strong>$100 per shift</strong></td>
</tr>
<tr>
<td>Feedback control</td>
<td>$205,000 / (8 hrs × 250 shifts/year) = <strong>$102.50 per shift</strong></td>
</tr>
<tr>
<td><strong>Labor Cost per Shift</strong></td>
<td>Number of operator × hourly rate × number of hours per shift</td>
</tr>
<tr>
<td></td>
<td>$2 × $35/hr × 8 hours/shift = <strong>$560 per shift</strong></td>
</tr>
<tr>
<td><strong>Tooling Cost per Shift</strong></td>
<td>Tooling expenses in a year / number of shifts per year</td>
</tr>
<tr>
<td>18K (Control)</td>
<td>$10,000 / 250 shifts = <strong>$40 per shift</strong></td>
</tr>
<tr>
<td>Constant Spindle Speed at 12,000 rpm</td>
<td>$10,000 / 250 shifts = <strong>$40</strong></td>
</tr>
<tr>
<td></td>
<td>$40 – cost saving on tool life = <strong>$38.92 per shift</strong></td>
</tr>
<tr>
<td></td>
<td>$40 - $1.08 = <strong>$38.92 per shift</strong></td>
</tr>
<tr>
<td>Step Function</td>
<td>$10,000 / 250 shifts</td>
</tr>
<tr>
<td></td>
<td>= $40 - $0.78 = <strong>$39.22 per shift</strong></td>
</tr>
<tr>
<td>Feedback Control</td>
<td>$10,000 / 250 shifts</td>
</tr>
<tr>
<td></td>
<td>= $40 - $0.83 = <strong>$39.17/shift</strong></td>
</tr>
</tbody>
</table>
Table 4.9.4 Continued.

<table>
<thead>
<tr>
<th>Tooling Cost per Shift</th>
<th>Tooling expenses in a year / number of shifts per year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>18K (Control)</strong></td>
<td>=$10,000 / 250 shifts = <strong>$40 per shift</strong></td>
</tr>
<tr>
<td><strong>Constant Spindle Speed at 12,000 rpm</strong></td>
<td>=$10,000 / 250 shifts = $40</td>
</tr>
<tr>
<td></td>
<td>$40 – cost saving on tool life = <strong>$38.92 per shift</strong></td>
</tr>
<tr>
<td></td>
<td>$40 - $1.08 = <strong>$38.92 per shift</strong></td>
</tr>
<tr>
<td><strong>Step Function</strong></td>
<td>=$10,000 / 250 shifts</td>
</tr>
<tr>
<td></td>
<td>=$40 - $0.78 = <strong>$39.22 per shift</strong></td>
</tr>
<tr>
<td><strong>Feedback Control</strong></td>
<td>=$10,000 / 250 shifts</td>
</tr>
<tr>
<td></td>
<td>=$40 - $0.83 = <strong>$39.17/shift</strong></td>
</tr>
</tbody>
</table>

**Estimated increase in tool life**

<table>
<thead>
<tr>
<th>Cutting Setting</th>
<th>Tool Wear (µm)</th>
<th>Increase in Tool Life (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (18,000 rpm)</td>
<td>209</td>
<td>Control</td>
</tr>
<tr>
<td>Constant Feed Speed at 12,000 rpm</td>
<td>120</td>
<td>43</td>
</tr>
<tr>
<td>Step Function</td>
<td>144</td>
<td>31</td>
</tr>
<tr>
<td>Feedback Control</td>
<td>139</td>
<td>33</td>
</tr>
</tbody>
</table>

**Calculations:**

12K: $\frac{(209 \, \mu m - 120 \, \mu m)}{209 \, \mu m} \times 100 = 43\%$

Step Function: $\frac{(209 \, \mu m - 144 \, \mu m)}{209 \, \mu m} \times 100 = 31\%$

Feedback Control: $\frac{(209 \, \mu m - 139 \, \mu m)}{209 \, \mu m} \times 100 = 33\%$
Savings on tool cost based on tool wear amount

<table>
<thead>
<tr>
<th>Cutting Setting</th>
<th>Tool Cost Savings per Day</th>
<th>Tool Cost Savings per Week</th>
<th>Tool Cost Savings per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12K</td>
<td>1.08</td>
<td>5.40</td>
<td>270.00</td>
</tr>
<tr>
<td>Step Function</td>
<td>0.78</td>
<td>3.90</td>
<td>195.00</td>
</tr>
<tr>
<td>Feedback Control</td>
<td>0.83</td>
<td>4.15</td>
<td>207.50</td>
</tr>
</tbody>
</table>

Calculations:
*assuming one tool insert per day
12K: 43% × $2.50/insert / 100 = $1.08/day
Step Function: 31% × $2.50/insert / 100 = $0.78/day
Feedback Control: 33% × $2.50/insert / 100 = $0.83/day

12K: $1.08/insert × 5 working days = $5.40/week
Step Function: $0.78/insert × 5 working days = $3.90/week
Feedback Control: $0.83/insert × 5 working days = $4.15/week

*assuming 50 weeks in a year
12K: $5.40/week × 50 weeks = $270/year
Step Function: $3.90/week × 50 weeks = $195/year
Feedback Control: $4.15/week × 50 weeks = $207.5/year

- **Machine Cost**: This is the price of purchasing the CNC router machine in US dollars.
- **Number of Shifts per Year**: This is the number of eight-hour shifts the machine will be operated in a year. The default value is 250 shifts (1 shift/day, 5 days/week, 50 weeks/year).
- **Machine Cost per Shift**: This refers to the cost of operating the machine in a single shift. It is calculated by dividing the machine cost by the product of shift length times the total number of shifts in a year.
- **Number of Operators**: This is the number of operators needed to operate the machine in a single shift.

- **Number of Hours per Shift or Shift Length**: This is total number of hours in a single shift. Typical length is an 8-hour shift.

- **Labor Cost per Shift**: This is the product of number of operators times the hourly rate for each operator times the number of hours an operator works per shift.

- **Tooling Expenses**: This refers to the total cost of tooling for the machine incurred in one year.

- **Tool Cost per Shift**: This is the total cost of tooling for the machine incurred during a single eight-hour shift.

Table 4.9.5 presents the results for the cost of producing the kitchen cabinet doors. Detailed calculations can be found in Table 4.9.6. Results show that the constant spindle speed at 12,000 rpm, and step function tests produced the lowest cost per part of $9.61.

Table 4.9.5 Results for cost of producing kitchen cabinet doors.

<table>
<thead>
<tr>
<th></th>
<th>Setting 1 Control</th>
<th>Setting 2 Constant Spindle Speed</th>
<th>Setting 3 Step Function</th>
<th>Setting 4 Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts produced per Shift</td>
<td>1385.50</td>
<td>1385.50</td>
<td>1385.50</td>
<td>1385.50</td>
</tr>
<tr>
<td>Cost per Part</td>
<td>$0.566</td>
<td>$0.565</td>
<td>$0.565</td>
<td>$0.567</td>
</tr>
<tr>
<td>Cost per Product</td>
<td>$9.62</td>
<td>$9.61</td>
<td>$9.61</td>
<td>$9.64</td>
</tr>
</tbody>
</table>

The calculations for the cost per part, and the total cost for a complete set of the kitchen cabinet doors are presented in Table 4.9.6. The number of parts produced per shift was first calculated. Each input is described following the table.
### Table 4.9.6 Calculations for cost of producing kitchen cabinet doors.

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parts Produced per Shift</strong></td>
<td>Total number of parts per sheet × number of sheets in a shift</td>
</tr>
<tr>
<td><strong>Parts per sheet:</strong></td>
<td></td>
</tr>
<tr>
<td>Wall cabinet = 8 parts/sheet</td>
<td></td>
</tr>
<tr>
<td>Base cabinet = 9 parts/sheet</td>
<td></td>
</tr>
<tr>
<td>Average parts per sheet = ((8 + 9)/2) = <strong>8.5 parts per sheet</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Number of sheets in a shift:</strong></td>
<td>Shift length in minutes / total time per cutting cycle</td>
</tr>
<tr>
<td>= ((8 \text{ hrs/shift} \times 60 \text{ min}) / 2.5 \text{ min}) = 192 sheets per shift</td>
<td></td>
</tr>
<tr>
<td>Taking downtime into consideration (refer to Table 4.9.2)</td>
<td></td>
</tr>
<tr>
<td>= 15% of manufacturing time = 15% \times 192 sheets = 29 sheets</td>
<td></td>
</tr>
<tr>
<td>Number of sheets in a shift = 192 – 29 = <strong>163 sheets per shift</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Parts produced per shift</strong></td>
<td>Total number of parts per sheet × number of sheets in a shift</td>
</tr>
<tr>
<td>= 8.5 parts × 163 sheets = <strong>1385.50 parts per shift</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Cost per Part</strong></td>
<td>(Raw material cost per sheet / number of parts per sheet) + (Total cost per shift) / Parts produced per shift</td>
</tr>
<tr>
<td><strong>Raw material cost per sheet:</strong></td>
<td></td>
</tr>
<tr>
<td>4 × 8 ft. melamine-coated particleboard = $35.96/sheet</td>
<td></td>
</tr>
<tr>
<td><strong>Cost per part:</strong></td>
<td></td>
</tr>
<tr>
<td>18K (Control)</td>
<td></td>
</tr>
<tr>
<td>= ((35.96 / 8.5 \text{ parts}) + (780) / 1385.50) = <strong>$0.566 per part</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Constant Spindle Speed of 12,000 rpm</strong></td>
<td></td>
</tr>
<tr>
<td>= ((35.96 / 8.5 \text{ parts}) + (778.92) / 1385.50) = <strong>$0.565 per part</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Step Function</strong></td>
<td></td>
</tr>
<tr>
<td>= ((35.96 / 8.5 \text{ parts}) + (779.22) / 1385.50) = <strong>$0.565 per part</strong></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.9.6 Continued.

<table>
<thead>
<tr>
<th>Cost per Product</th>
<th>Feedback Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$35.96 / 8.5 parts + $781.67 / 1385.50 = $0.567 per part</td>
</tr>
</tbody>
</table>

Parts per product = 17 parts

Cost per product:
- **18K (Control)**
  
  $0.566 \times 17 = $9.62 per product

- **Constant Spindle Speed of 12,000 rpm**
  
  $0.565 \times 17 = $9.61 per product

- **Step Function**
  
  $0.565 \times 17 = $9.61 per product

- **Feedback Control**
  
  $0.567 \times 17 = $9.64 per product

- **Parts Produced per Shift**: This refers to the total number of parts produced in an 8-hour shift. A sheet of material that has several parts will produce a total, which is the number of sheets run in a shift times the total parts in a single sheet.

- **Cost per Part**: This is the cost of producing a single part in US dollars. If different parts are produced in a single cycle, the value will be the average cost of the parts produced.

- **Cost per Product**: This is the cost of producing the complete product, in this case, kitchen cabinet doors. The value is the cost per part times the total number of parts of the finish product.
Although the feedback control setting did not produce a significantly lower cost per product, it produced a good surface quality as demonstrated in previous tests, which may contribute to less rework cost. As in the case of the 12,000 rpm test, although it had a lower cost per product, the poor surface quality could further impact its cost per product. The cost analysis did not include the cost of rework; however, as an example to show the impact of it, a 40% less panel chipping in the feedback control technique could translate to that much less rework, which could be a $20.00 worth of improvement.

In order to further analyze the opportunities in the wood-based industry, a cost-benefit analysis was performed to identify and quantify the costs and benefits of feedback control system versus polycrystalline diamond (PCD) tooling as described in the next section.

4.9.5. Comparison of Costs and Benefits on the Application of Feedback Control Technique Using Tungsten Carbide Tools versus Polycrystalline Diamond Tooling

The application of the feedback control system in the CNC router operation resulted in longer tool life while maintaining good surface quality as demonstrated in the feedback control test. As the feedback control technique shows promise in an improved cutting performance, its opportunities in the wood-based industry need to be assessed.

A cost and benefit comparison on the application of feedback control system utilizing tungsten carbide tools versus polycrystalline diamond (PCD) tooling was performed in order to determine the worthiness of investing in such a system.

a) Costs and Benefits Comparison

In general, both applications have similar crucial benefits such as longer tool life, reduced downtime, and improved surface quality. These factors could lower the cost, which is predominantly related to the overall tooling costs. The difference, however, would be on the extent of the benefits by each of the application.
The first diamond tools were introduced by the Lach Diamant Company at the Ligna Fair in 1979. The PCD tooling is one of the main tool materials used in woodworking due to its superior properties in hardness, abrasive resistance, and thermal conductivity (Bai et al., 2002). The developments of man-made boards, which are highly abrasive such as MDF, particleboard, and reinforced laminated board, have created the need for special tooling.

The high initial cost of a PCD tool presents an obstacle in its application by the end users. However, its longer tool life of up to hundred times than that of carbide (Bai et al., 2002), reduces the downtime for tool changing that can be associated with cost savings (Philbin and Gordon, 2005).

Today’s demand for higher output requires speed and accuracy, and PCD tooling could meet the needs as it is suitable for high volume production. Besides producing higher quality and consistent surface finishes, which results in decreased finishing costs, PCD outperforms carbide tools when machining clean and consistent material without foreign objects. The downsides of PCD apart from the high price are such that it is fragile, and very hard to sharpen. Figure 4.9.11 shows an example of a compression PCD bit.

![Figure 4.9.11 Polycrystalline diamond router bit: (a) overall view; and (b) close-up view.](image)
Tungsten carbide on the other hand, is the main material for woodworking tools (Bai et al., 2002). Additionally, it is an extensively applied cutting tool material in most industrial cutting applications of various materials, due to its compromise between toughness and hardness properties (Heath, 2001). Incorporating a feedback control system with the carbide tooling could further improve the machining performance such as longer tool life, better surface quality, and increased productivity. The additional cost of having a data acquisition system that enables the feedback control to function will need to be considered. The combination of a feedback control system with tungsten carbide tooling provides a viable option for a better and improved solution in the wood-based machining operations on a CNC router.

In making a tooling choice, some of the factors that are needed to be considered including the type of material to be cut, ease of making tool changes, and the duration of the cutting operation. In addition, the costs and benefits for each of the tooling types vary greatly depending on the type of application, and the materials being cut. Hence, information on the input (or cost) and output (or benefit) of tooling will determine which one is the most cost-effective.

In the previous feedback control test, it showed a 31% improvement in tool life compared to cutting at a constantly high spindle speed of 18,000 rpm (i.e. without controlling the speed of the tool spindle). While PCD tooling may be ten times more costly than tungsten carbide tools, but has a far greater tool life; one must be aware of the extreme maintenance and handling that the tools require due to its brittleness. Additionally, it should also be noted that the feedback control system could also improve tool wear on PCD tooling.
5. CONCLUSION AND FUTURE WORK

5.1. Introduction

The study was conducted with a goal to improve the performance of a CNC router in wood-based machining operations by means of prolonging tool life. Longer tool life contributes to increased productivity, which is a vital factor in production performance and product quality. As found in the literature, various methods to prolong tool life have been extensively explored such as new cutting tool materials, tool coatings, and tool cooling to name a few. Thus, the study was set out to achieve two main objectives: (1) to determine the relationship between tool wear, panel chipping, and tool spindle vibration; and (2) to demonstrate the use of a process monitoring and control technique for extending tool life when machining wood-based products.

Extensive background work was conducted prior to conducting the feedback control technique. It was done in order to establish a solid foundation that supported the use of tool spindle vibration of the CNC router to control the spindle speed.

Process control such as the feedback control technique as used in the study is an innovative way to extend tool life. The feedback control technique regulates the spindle speed of a CNC router. Previous research had successfully shown that by increasing the spindle speed, tool wear was greatly reduced, thereby extending tool life. Thus, the study delved further into the idea of increasing the spindle speed during machining of melamine-coated particleboard on a CNC router through applying different spindle speed scenarios to increase tool life of tungsten carbide inserts. These scenarios included cutting at spindle speeds of 12,000 rpm, 18,000 rpm, increased at regular intervals (i.e. step function), and increased at a specified percentage when a certain tool spindle vibration level was reached (i.e. feedback control technique).

Some of the tests were also performed to investigate several issues that were encountered while conducting the study such as the drop in panel chipping at the 120th cutting pass, and also the introduction of an image analysis method to more accurately measure the panel chipping.
The following section presents the research main findings, followed by a conclusion, and suggested future work.

5.2. Research Main Findings

An extensive background work was done to provide an in-depth knowledge and understanding on the use of tool spindle vibration that was eventually applied in the feedback control technique. This particular section presents the main findings in order to give a complete perspective that represents the gist of the study.

5.2.1. Tool Wear, Panel Chipping, Spindle Speed, and Tool Spindle Vibration Relationship

The early stage of the study investigated the relationship of tool wear, panel chipping, and tool spindle vibration that would provide answers and explanations to these three important questions:

1. Does tool wear affect panel chipping?
2. Does increasing the spindle speed reduce panel chipping?
3. Could tool spindle vibration be used as a parameter to control the spindle speed?

These questions were of the utmost interest as they provide crucial information that supports and justifies the use of the feedback control technique, which could potentially extend tool life. Several tests were conducted in order to address these issues. In terms of the effect of tool wear on panel chipping, results showed that higher tool wear caused higher panel chipping, and lower tool wear reduced panel chipping as demonstrated in tests of the effect of different spindle speeds, tool grades, and feed speeds.

As for whether or not increasing the spindle speed could reduce panel chipping, comparisons were made on machining tests that were done using spindle speeds of 12,000 rpm, 18,000 rpm, and a step function, in which the spindle speed that started at 12,000 rpm was ramped up at regular intervals. While tool life was increased due to a constantly low spindle speed of 12,000 rpm, panel chipping was adversely affected due to a larger chip load.
In addition, a constantly high spindle speed of 18,000 rpm resulted in decreased tool life due to a higher rate of tool wear; however, it produced lower panel chipping due to a smaller chip load. It was evident in the step function test that panel chipping was consistently being reduced whenever the spindle speed was increased.

A previous study found that tool spindle vibration could be used to control the spindle speed of a CNC router. The current study investigated this with a different CNC router model and configuration. It was demonstrated that the vibration level of the CNC router tool spindle tracked well with the amount of tool wear, and panel chipping. Preliminary tests were conducted to understand the vibration pattern, and behavior as well as to identify the frequency band from which the tool spindle vibration was analyzed, and applied in the process control test. A frequency band of 5,500 Hz – 6,750 Hz was selected based on the fact that its upward trend correlated well with the panel chipping behavior.

5.2.2. Additional Studies on Drop in Panel Chipping Issue, Measuring Panel Chipping Area Using Image Analysis, Order Analysis Method, and Application of Tool Cooling in Extending Tool Life

A great amount of time and effort was put into solving issues and improving procedures. As an example, the issue of the drop in panel chipping was extensively investigated; and in terms of improving procedure, a more accurate panel chipping method was introduced through image analysis. The following paragraphs provide a comprehensive discussion on the results of the investigation on the drop in panel chipping, measuring panel chipping with image analysis, the application of order analysis, and the effect of tool cooling in extending tool life.

At the early stage of the study, the drop in panel chipping at the 120th cutting pass was observed during the test on cutting at different spindle speeds. It indicated that there could be something going on as the drop occurrence was found in other tests. A test usually had 200 cutting passes, which were cut in a pattern of ten sets of 20 passes on two 0.6 × 1.22 m (2 × 4 ft.) (refer to the Methodology section). Each panel had a total of five 20-pass sets, and the 120th cutting pass was located on the first set of the second board.
Three assumptions were made including: (1) the time in between changing the panel for the second set of 100 passes allowed tool temperature to decrease, which could result in a drop in panel chipping; (2) there could be a specific position on the CNC router table that could produce different vibration levels, which eventually causes the drop in panel chipping; and (3) amount of chip load could cause the drop. Tests on cutting configuration where both panels were placed side by side so that the 200 cutting passes were done at once were carried out to address the first assumption. Result of the panel chipping showed that the drop at the 120\textsuperscript{th} pass still existed. The second assumption was investigated through conducting a test where the machining test was started at three different starting positions on the CNC router table. As it turned out, there was no indication of differences in the levels of vibration across the CNC router. Finally, for the third assumption, chip load amount was varied through cutting tests at a constant spindle speed of 18,000 rpm, and three different feed speeds (i.e. 300 ipm, 400 ipm, and 500 ipm). A similar drop in panel chipping was still observed.

Board mass factor was also considered, and in the test where five 0.3 × 1.2 m (1 × 4 ft.) panels had two sets of 20 passes machined on it, it was shown that panel chipping was lower on the first set for all panels. Thus, this should be taken as a ‘normal’ occurrence, where it is actually not a ‘drop’, but rather a low panel chipping at the beginning of cutting as the board mass is continually decreasing.

At a later stage of the study, steps to improve the accuracy of measuring panel chipping were also done. Initially, chip count method was used, and chip length was also briefly explored. However, both methods could potentially introduce a less accurate panel chipping amount. A method to measure chip area was formulated, and it produced a better representation of the panel chipping level. This was done using a digital camera, and an image analysis software.

Order analysis technique was also explored, and it was shown that it has the potential to be used over the traditional way of analyzing vibration such as FFT. Further study showed that the more computational simple vibrational monitoring was sufficient.

Another method to extend tool life was done where cold air was directed to the tool during cutting. The cooling effect was expected to lower the tool wear on the tungsten
carbide insert as previous studies have shown; however, the test produced contradictory results for the panel material, and carbide grade that was used in this study.

5.2.3. Feedback Control Technique as a Method to Extend Tool Life and Cost-Benefit Analysis

Demonstrating the use of a process monitoring and control technique was one of the main objectives that the study was set out to achieve. A feedback control technique had shown an improvement in the cutting operation through a longer tool life, and increased surface quality, compared to when constant high spindle speed was used. Excessive tool wear causes severe damage to the materials being machined, and eventually degrades the product quality. Thus, the feedback control technique could be a viable option for industry application.

The feedback control technique could revolutionize the way a machining process on a CNC router is done. An example of a process that could utilize the feedback control technique such as the production of kitchen cabinets was conducted. Additionally, as the study had demonstrated that tool wear was reduced when machining melamine-coated particleboard; the technique could be expanded to other materials in order to determine if similar results are observed. Other materials including medium-density fiberboard; or other types of composite panels such as bamboo and oil palm fiberboards.

In terms of the cost-benefits analysis, the feedback control technique had a comparable cost with the other spindle speed settings. When comparing with the PCD tooling, the feedback control technique has the potential to be used in improving the wood-based machining operations due to its proven longer tool life, increased surface quality, and lower tooling cost when using tungsten carbide tools.

5.3. Conclusion of Study

Improvements in wood-based machining operations, specifically on CNC routers, could provide significant economic benefits to the wood-based industry as a whole. Companies could become more competitive due to high product quality and affordable
prices, which would also benefit the end consumers. The study has demonstrated that a process monitoring and control technique could be used to meet such endeavor.

5.4. Suggestions for Future Work

Some recommendations for future research are outlined below:

1. Optimize the feedback control technique by using different levels of vibration change that will cause different spindle speed changes in order to determine which one is the best.
2. Explore other control algorithms such as fuzzy logic control system.
3. Perform similar cutting tests on different materials such as medium density fiberboard or other laminated boards.
4. Utilize different types of tungsten carbide grades.
5. Investigate the technique with other CNC routers with different configurations.
6. Further explore the potential of the order analysis technique as a method to analyze tool spindle vibration in a process control system on a CNC router.
REFERENCES


115. Peeters, G. 2004. A *large set of audio features for sound description (similarity and classification) in the CUIDADO project*. IRCAM.


APPENDICES
Appendix A

Section 3.8  Effect of Cutting at Different Positions on CNC Router Table on Tool Wear, Panel Chipping, and Tool Spindle Vibration

Appendix A shows the vibration signal of the tool spindle at different frequency bands and panel chipping produced by 10% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm at three different table positions (one replicate for each table position).

Table positions: (1) **Position 1: X11.7, Y60**; (2) **Position 2: X11.7, Y48**; and (3) **Position 3: X11.7, Y36**. The rows represent the three frequency bands, i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The two graphs in each row are similar accept that the first graph has a common y-axis.
Figure 7.A.1 RMS of three frequency bands and panel chipping of 10% cobalt grade tungsten carbide insert that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at Position 1.
Figure 7.A.2 RMS of three frequency bands and panel chipping of 10% cobalt grade tungsten carbide insert that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at Position 2.
Figure 7.A.3 RMS of three frequency bands and panel chipping of 10% cobalt grade tungsten carbide insert that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 18,000 rpm of spindle speed at Position 3.
Appendix B

Section 3.11  Effect of Cutting at Different Feed Speeds on Tool Wear, Panel Chipping, and Tool Spindle Vibration

Appendix B shows the vibration signal of the tool spindle at different frequency bands and panel chipping produced by 10% cobalt grade carbide inserts cutting in conventional direction at 15,000 rpm of spindle speed and three different feed speeds of 7.6 m/min (300 ipm), 10.2 m/min (400 ipm), and 12.7 m/min (500 ipm) (one replicate for each feed speed).

The rows represent the three frequency bands, i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The two graphs in each row are similar accept that the first graph has a common y-axis.
Figure 7.B.1 RMS of three frequency bands and panel chipping of 10% cobalt grade tool that cut in conventional direction at 7.6 m/min (300 ipm) of feed speed and 15,000 rpm of spindle speed.
Figure 7.B.2 RMS of three frequency bands and panel chipping of 10% cobalt grade tool that cut in conventional direction at 10.2 m/min (400 ipm) of feed speed and 15,000 rpm of spindle speed.
Figure 7.B.3 RMS of three frequency bands and panel chipping for 10% cobalt grade tool that cut in conventional direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed.
Appendix C

Section 3.12  Effect of Cutting at Different Spindle Speeds on Tool Wear, Chipping, and Tool Spindle Vibration

Appendix C shows the vibration signal of the tool spindle at different frequency bands and panel chipping produced by 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and three different spindle speeds of 12,000 rpm, 15,000 rpm, and 18,000 rpm (three replicates for each spindle speed).

The rows represent the three frequency bands, i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The two graphs in each row are similar accept that the first graph has a common y-axis.
Figure 7.C.1 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 12,000 rpm (Rep 1).
Figure 7.C.2 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 12,000 rpm (Rep 2).
Figure 7.C.3 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 12,000 rpm (Rep 3).
Figure 7.C.4 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 15,000 rpm (Rep 1).
Figure 7.C.5 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 15,000 rpm (Rep 2).
Figure 7.C.6 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 15,000 rpm (Rep 3).
Figure 7.C.7 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 18,000 rpm (Rep 1).
Figure 7.C.8 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 18,000 rpm (Rep 2).
Figure 7.C.9 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 18,000 rpm (Rep 3).
Section 3.12 Effect of Cutting at Different Spindle Speeds on Tool Wear, Chipping, and Tool Spindle Vibration

Appendix D shows the average vibration signal of the tool spindle at different frequency bands and panel chipping produced by 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and different spindle speeds of 12,000 rpm, 15,000 rpm, and 18,000 rpm (three replicates for each spindle speed).

The rows represent the three frequency bands, i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The two graphs in each row are similar accept that the first graph has a common y-axis.
Figure 7.D.1 Averaged RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 12,000 rpm (three replicates).
Figure 7.D.2 Averaged RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 15,000 rpm (three replicates).
Figure 7.D.3 Averaged RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in conventional direction at 12.7 m/min (500 ipm) of feed speed and spindle speed of 18,000 rpm (three replicates).
Appendix E

Section 3.13  Effect of Cutting with Different Carbide Grades on Tool Wear, Chipping, and Tool Spindle Vibration

Appendix E shows the average vibration signal of the tool spindle at different frequency bands and panel chipping produced by different grades of tungsten carbide inserts (Grade and percentage of cobalt binder: T02SMG - 2.5%, H6N - 6%, and T10MG - 10%) that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (three replications for each tungsten carbide grade).

The rows represent the three frequency bands, i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The two graphs in each row are similar accept that the first graph has a common y-axis.
Figure 7.E.1 RMS of three frequency bands and panel chipping of 2.5% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 1).
Figure 7.E.2 RMS of three frequency bands and panel chipping of 2.5% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 2).
Figure 7.E.3 RMS of three frequency bands and panel chipping of 2.5% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 3).
Figure 7.E.4 RMS of three frequency bands and panel chipping of 6% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 1).
Figure 7.E.5 RMS of three frequency bands and panel chipping for 6% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 2).
Figure 7.E.6 RMS of three frequency bands and panel chipping of 6% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 3).
Figure 7.E.7 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 1).
Figure 7.E.8 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 2).
Figure 7.E.9 RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (Rep 3).
Appendix F

Section 3.13 Effect of Cutting with Different Carbide Grades on Tool Wear, Chipping, and Tool Spindle Vibration

Appendix F shows the average vibration signal of the tool spindle at different frequency bands and panel chipping produced by different grades of tungsten carbide inserts (Grade and percentage of cobalt binder: T02SMG - 2.5%, H6N - 6%, and T10MG - 10%) that cut in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (three replications for each tungsten carbide grade).

The rows represent the three frequency bands, i.e. 3,750 Hz – 5,250 Hz, 5,500 Hz – 6,750 Hz, and 6,750 Hz – 8,000 Hz. The two graphs in each row are similar except that the first graph has a common y-axis.
Figure 7.F.1 Average RMS of three frequency bands and panel chipping of 2.5% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (three replicates).
Figure 7.F.2 Average RMS of three frequency bands and panel chipping of 6% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (three replicates).
Figure 7.F.3 Average RMS of three frequency bands and panel chipping of 10% cobalt grade carbide inserts cutting in climb direction at 12.7 m/min (500 ipm) of feed speed and 15,000 rpm of spindle speed (three replicates).