ABSTRACT


Wood processing industries have continuously developed and improved technologies and processes to transform wood to obtain better final product quality and thus increase profits. Abrasive machining is one of the most important of these processes and therefore merits special attention and study.

The objective of this work was to design, develop, evaluate, and demonstrate a process monitoring and control system for use in the abrasive machining of wood and wood based products. The system developed increases the life of the belt by detecting (using process monitoring sensors) and removing (by cleaning) the abrasive loading during the machining process. This study focused on belt abrasive machining processes and included substantial background work, which provided a solid base understanding of the behavior of the abrasive, and the different ways that the abrasive machining process can be monitored. In addition, the background research showed that the abrasive belts can effectively be cleaned by the appropriate cleaning technique.

The process monitoring and control system developed included data acquisition (information from the sensors), signal analysis, and belt cleaning actions as required which were integrated and continuously monitored during the abrasive machining process.

A control system was created on LabView® version 8.2 from National Instruments (www.ni.com) that integrates the monitoring process and the actions required depending on the abrasive machining process conditions. Thus, the system is able to acquire information from the optical sensor to detect loading and activate the cleaning system. The system
designed continuously monitors the condition of the abrasive belt by using an acoustic emission sensor and alerts the operator of the status of the belt (green, yellow and red lights indicate optimal, medium and poor belt condition). The system also incorporates an additional safety device, which helps prevent permanent damage to the belt, equipment or workpiece by alerting the operator when an excessive temperature has been reached. As a final step, the system design was adapted to an industrial machine manufactured by a prominent woodworking machinery manufacturer. This adaptation included the design of a mounting and traversing system for the sensors and cleaning apparatus and the integration of the system with the current machine PLC in order to take action based on information from the sensors relating to belt loading, acoustic emission and temperature and take action based on the status of the process.
PROCESS MONITORING AND CONTROL SYSTEM
DESIGN, EVALUATION AND IMPLEMENTATION OF
ABRASIVE MACHINING PROCESSES

By

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BIOGRAPHY

Daniel Enrique Saloni Flores was born on July 15, 1971 in Caracas, Venezuela. After finishing his high school education at “Unidad Escolar Gran Colombia”, he joined “Universidad Catolica Andres Bello” (UCAB) to pursue the Industrial Engineering Bachelor. Immediately after he completed his undergraduate in 1995, he began working as research/instructor at UCAB. In 2000, Daniel is invited to participate on a research project at Wood Machining and Tooling Research Program (WMTRP) and supported by both universities NCSU and UCAB. In 2001, he started his master degree in Integrated Manufacturing System Engineering Program at NCSU and still working as a research assistant at WMTRP. After he finishes his master degree in manufacturing in 2003, Daniel finished in 2007 his doctorate degree at Wood and Paper Science Department sponsored by WMTRP.
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1. INTRODUCTION

Wood is a renewable resource that can be transformed into a variety of useful products, which are beautiful as well as durable. There are many steps in the manufacture of wood products. The main processes performed before a final product is obtained are: tree harvesting, log breakdown, lumber drying, part machining (cutting, milling, machining, etc.), assembly, finishing, and packaging. A critical process in this value chain is abrasive machining. This can include conventional belt machining, abrasive planing, shaping or white sanding, among others. Abrasive machining is one of the most expensive processes in wood processing industries and therefore merits special attention and study. Abrasive machining processes are complicated to typify and analyze because of the random nature and distribution of the grains on the abrasive belts. In the case of abrasive machining of a highly variable no homogeneous material such as wood, the complexity of the process increases and many variables have to be considered. The abrasive machining process represents an important investment in the machining process because machining belt price per unit is high and the belt life is short.

Two of the most important factors that affect abrasive belt life are the loading of the belt and the belt temperature. These factors have been identified by many authors in the past and efforts have been directed toward developing feasible and effective solutions. High temperatures have a considerable impact because increased temperature causes degradation of the machining belt and also cause problem in the workpiece (wood). The heat from the machining operation at the belt/wood interface can be so high that the heat melts resins in the wood. The liquefied resin then flows onto the belt, where the resin cools and become hard again, which result in loading. In order to reduce high temperatures, it might be useful to use
cooling systems to control/reduce the temperature and help to prevent loading in machining belts.

Abrasives can either become worn or also become loaded with wood fiber. A loaded belt has wood fibers, and melted wood resins compacted into the spaces between and around the abrasive grains. A loaded condition will cause the belt to be unable to cut additional material, as the grains cannot fully come into contact with the wood piece. The result is a situation where rubbing and friction generate excessive heat and the wood becomes burnished. In addition, because the abrasive becomes loaded with wood fiber material, the material removal rates in abrasive machining, as reported by Grivna (2004), can be reduced substantially. This correlates to a reduction in machining efficiency as well as an increase in energy consumption. This cost is in addition to the high cost of abrasive belts (according to industry experts, many companies spend more than twice the cost of their machining machine in purchasing abrasives annually).

There has been a great deal of research done to increase the life of abrasives. This ranges from developing new or different minerals, backing materials, and adhesives to methods of cleaning the abrasives. Many systems of cleaning are in existence in the woodworking industry today. One system manufactured by Nu-Life (http://www.abrasiveservice.com/Bars.html) uses a “Gum Eraser” block, which can be applied to a moving belt by manual or automated means (U.S. Patent 81/0081), or fed through the machining machine in sheet form. Other systems include pressure washing or chemical baths, including a cleaning system (Abrasive Belt Master at www.modernwoodworkingbluebook.com) that utilizes a 1200 lb/in² (8273 kN/m²) and 140 °F (60 °C) water/cleaning solution. This system requires that the belt be removed from the
machine and then placed in the bath for cleaning, which increases down time and labor costs. Other systems on the market have been developed to clean abrasives by blasting with either glass beads (Zintexx® at www.modernwoodworking.com) or dry-ice crystals (Cryokinetics® at www.cryokinetics.com). For purposes of this discussion, blasting is defined as the process by which high-pressure air is used to force particles to impact a surface for, in this situation, the purpose of cleaning. These systems have traditionally been expensive to install and maintain, and also can damage the abrasive material.

High-pressure washing with or without detergent is the most common method, even though this technique is time consuming and requires the operator to stop the process to remove the machining belt from the machine.

Some research has been done in the past to determine the effect of cleaning on the belt life. According to Grivna (2004) the usable life of the belt when cleaned can be increased by two to five times when belt cleaning is used for hardwood machining and considerably more when machining softwoods.

In order to increase abrasive life, improve material removal rate, reduce down time and labor costs associated with the changing of the abrasive, and to reduce the overall number of abrasives that need to be purchased by a manufacturer, a multi-level research effort is needed.

1.1. Statement of Objectives

The objective of this study is to design, develop, evaluate, and demonstrate a process monitoring and control system for use in the abrasive machining of wood and wood based products. The system proposed in the present research includes several major
steps, including (1) development of a process monitoring system to detect loading and predict/determine the life of the machining belts, (2) development of a system to effectively remove the loading by cleaning the machining belts, and (3) development of an integrated process monitoring and control system incorporating (1) and (2) above to improve the machining process.

This system increases the life of the belt by detecting (using process monitoring sensors) and removing (by cleaning) the loading on the belts during the machining process without the need of removing the abrasive belts or stopping the abrasive machining process. In addition, the system indicates when the abrasive belt needs to be removed by the use of acoustic emission sensors and also when a critical condition has arisen due to elevated temperatures by using a temperature sensor for prima (primarily for safety purposes).

1.2. Methodology

This study was broken down into several chapters, each of which is summarized below:

**Chapter 2. Literature Review.** This chapter contains a review of previous work in abrasive machining. Papers, technical literature and publications in the field of wood science, machining, power consumption, abrasive processes, process monitoring, belt cleaning, temperature control, belt cooling and other fields of interest were reviewed to determine and document the main needs of the industry in this area. This facilitated the establishment of the main objectives of this research.

**Chapter 3. Conventional Machining of Wood and Wood Materials.** This chapter contains an overview of the conventional machining of wood and wood-based materials. The
Chapter 4. Background Research. Experimentation was conducted to evaluate the applicability of different sensors to monitor and control the abrasive machining process for wood. Optical sensors and a temperature thermographic camera were used to evaluate the ability of these sensors to detect and analyze loading. Additionally, different cleaning methods were evaluated to determine the most appropriate method to remove loading without affecting the integrity of the abrasive belts. Hybrid methods (cooling and cleaning simultaneously) were also analyzed to verify the reduction in belt loading when cooling is applied.

Chapter 5. Prototype System Design. This chapter covers the steps in the design of the system such as sensor evaluation, control system design, prototype fabrication, and validation. Once the sensors were selected, implemented and validated, and the control system was designed according to the established criteria, the prototype system was fabricated. The fabrication process included the integration of the sensors with the control system and the determination of the required thresholds for activation of the required actions (cleaning, worn out belt alert, or a warning due to elevated temperature). The refinement of
the system included conducting preliminary experiments and performing the necessary analyses. Adjustments to the prototype system were performed in order to improve the functionality and accuracy of the system.

Chapter 6. Evaluation and Refinement of the Prototype System. This chapter describes the process of validation of the prototype system design. An experimental design was developed containing the main variables that affect the abrasive machining process. Loading, temperature, and belt life were measured based on the combination of the different factors and their respective levels. The data collected from the experiments was analyzed and the prototype control design was refined and improved by making adjustments to the sensors, the control design, the process, etc..

Chapter 7. Application of the System to an Industrial Machine. The implementation of the prototype system to an industrial machine provides information related to the technical feasibility of the implementation of the process monitoring and control system design for industrial applications. Discussions with a well-recognized manufacturer of abrasive machines have been very positive with respect to technical feasibility and ease of implementation. This chapter also describes the machine and controller issues relating to installation of the system on a typical belt machining machine.

Chapter 8. Conclusions and Future Work. The conclusions of the work are presented in this chapter. Additional, future work showing new avenues of research is also included.

Chapter 9. References and Literature Cited. A directory of references, books, journals, presentations, interviews and other sources of information are included in this chapter.
Chapter 10. Appendices. Relevant technical information relating to the equipments and apparatus used for this research is included in this chapter in order to facilitate future system improvement and optimization.
2. LITERATURE REVIEW

Abrasive machining is a widely used technique across the entire range of manufacturing. There are some similarities in all abrasive processes; however, it is generally accepted that abrasive machining processes are highly dependent on the workpiece material characteristics. In the present study, the abrasive machining of wood is addressed. As a background for this study, an extensive literature review was performed. A brief summary of this review, which addressed both published literature, as well as a study of current applications of abrasive machining of wood in industry is included in this section, including some of the definitions, terminology, etc., specific to the sanding of wood.

2.1 Previous Work on Abrasive Machining

There have been substantial improvements and modifications to coated abrasives since the bulk of the abrasive machining research for wood was conducted. Further work needs to be conducted to improve the life of the sanding belts by integrating abrasive machining monitoring and control via belt cleaning and cooling.

In 1954, Franz and Hinken presented the effects of pressure, belt speed, contact area, moisture content, and dressing on material removal rate, belt life and power consumption.

Work done by Mckenzie (1962) established that there is a theoretical relationship between tool geometry and cutting forces, surface characteristics, and wood mechanical properties. However, the final quality of the surface was not considered in this work. Moreover, the study had a limited range of grit sizes and did not included softwoods.

Nakamura (1966) found that feed speed was inversely correlated to wood removal rates for a belt sanding operation. On the other hand, Pahlitzsch (1970) detected that belt
speed had little effect on surface quality and that it was almost independent of belt pressure.

According to Stewart (1972, 1974) the power required by a belt sander was positively correlated to the material removal rate, and with both depth of cut and feed rate of the wood being sanded. Stewart (1974) also found that the power requirements were positively correlated to the moisture content and the specific gravity of the wood.

In 1982, Story (1982) formulated equations that described the behavior of the magnitude and variation of forces in the two basic categories of belt grinding. Fixed force grinding that covers those applications where the applied force is directly applied to the workpiece) and fixed cut rate grinding which covers the applications where the feed rate of the work piece is controlled).

Smith (1996) investigated the power requirements for high-speed CNC routers. He concluded that width of cut, depth of cut, spindle rotational speed (rpm), number of cutter knives, workpiece feed speed, and the milling process (conventional or climb cutting) were the primary factors influencing the power consumption. Additionally, he found grain orientation and wood species were important factors, while only minimal power consumption differences were found for different moisture content over the range of 5 to 30 percent.

Carrano (1997) found no significant interaction effects in the wood sanding operation. In addition, the type of abrasive utilized proved to be a significant parameter affecting the surface roughness but not for material removal at the coarsest grit size.

Work done by Carrano (2000) showed that grit size, tooling resilience and wood grain orientation were significant for material removal rate and final surface quality for all the species studied (hard maple, white oak, black cherry and white pine).

Other studies done by Saloni et al. (2002) showed that material removal rate was
always higher when an aluminum oxide abrasive belt was used, in fact, sometimes nearly twice as high as the others were. These studies also confirmed, like many others experiments developed by several researchers, that material removal rate is positively affected by pressure, which means that it increases when pressure increases. Additionally, it was observed that final surface quality did not have a predictable behavior and/or specific trend to conclude any significant tendency for both species and abrasive used.

Saloni (2003) found a correlation between the most critically controllable variables in abrasive machining and the three main outputs: material removal rate, surface quality and power consumption. Multiple linear regressions described the general process and the effect of the variables on the outputs; however, large variability in surface quality and material removal rate were observed which demonstrated the complexity of the characterization.

Shibata et. al. (1979) found that the heights of the majority of the grain cutting edges on abrasive belts gradually reduce to produce a worn flat area on the tips of the mineral.

Ratnasingam et. at. (1999) described that, despite coated abrasives being widely used in the furniture industry, the abrasive machining process has not received the consideration it deserves. Moreover, they found that an appropriate selection of coated abrasives, machine and workpiece could help to improve productivity. Additionally, they explained that the abrasive application is more economical for low material removal with moderate production rates in order to obtain acceptable final surface quality. In addition, Ratnasingam et. at. (1999) discussed that it is possible to augment the production throughput by increasing the material removal rate; however, this will considerably increase the power consumption and reduces the life of the sanding belts. Moreover, this material removal rate increase will inevitably increase the temperature that could result in an increase of the loading, which has
been proved to reduce the life of the belt (by prematurely discharging the abrasive belts).

Phadke et. al. (1975) developed a model to evaluate the coated abrasive grain geometry and wear. They found an increase in apex angle when comparing new to worn abrasives profiles. In addition, they determined that the apex angle decreased from 105.7” to 76.0” when grit size increased from 40 to 150.

Burney and Wu (1976) demonstrated that coated abrasive surface profile show consistent and physically meaningful change in their values as the surface wears.

Date and Malkin (1976) found that a reduction in the performance of the abrasive mineral accompanied clogging from material chips and adhesive particles within the grains for finer grit size. In addition, for coarser grit, they found extensive grain fracture occurred resulting in considerable deterioration in the performance of the abrasive but without clogging.

Richter et. al. (1995) proved that sanding is an advantageous processing step before applying paint. In addition, they found that the amount of paint needed for sanded surfaces was relatively small. Moreover, they showed that sanded surfaces have the best paint performances even on low-grade wood.

Wettschurack et. al. (1999) determined that loose mineral particles embedded in the workpiece affected the subsequent abrasive belt, creating a damage called “ridge” that is a major defect in kitchen cabinet doors.

Ockajová and Siklienka (2000) confirmed that material removal decreased in the dependence of decreasing grit size and belt speed.

Ratnasingam et. al. (1999) discussed that the furniture industry has to recognize the importance of wood machining in order to be competitive and to continuously improve. They
stated that wood machining is an integral part of manufacturing of furniture and has to be considered with deeper details.

Ratnasingam et. al. (2002) found that silicon carbide belts had a better performance than aluminum oxide when sanding Rubberwood. In addition, they found that increasing material removal rates tended to negatively affect the surface quality. Moreover, high stock removal rates accelerated belt loading that can considerably shorten the belt life.

Billingham and Lauridsen (1974) found that dulling was the most common type of wear in coated abrasives. Additionally, they discussed that the irregular and random nature of the abrasive mineral on the belt produces variations in the distance from the backing cloth to the cutting points, this phenomena causes discharged of the sanding belts when a considerably number of grits do not have contact with the workpiece during the machining process.

Ohtani et. al. (2004) showed that the surface roughness on smooth sanding profiles were almost as homogeneous as aluminum, however, sassafras had a higher heterogeneity than aluminum.

2.2 Previous Work on Process Monitoring

Process monitoring is a continuous real time activity of determining the status of a process at any given time.

Process monitoring should not be confused with process control. In process monitoring, a signal is generated to inform that a specific condition has been achieved. Process control, on the other hand, considers actions that need to be taken. Examples of monitoring parameters are power consumption, spindle vibration, spindle temperature, etc.
Examples of control parameters are spindle vibration, cutting forces, acoustic emission, cutting sound, belt life, surface quality, etc. It is important to note that some monitoring parameters can be simultaneously control parameters.

According to Byrne et al. (1995), the focus of monitoring is on the machine, the tools or tooling, the workpiece, or the process itself. They established that research and development activities promise a continuous improvement in process monitoring systems. In addition, Byrne et al. (1995) stated that process monitoring is required to insure an optimum performance of manufacturing systems. However, the monitoring systems have to consider improvement in the stability of the process, tool breakage detection, reduction of non-productive time, optimize tool usage, etc. Moreover, they established that the main user’s requirements for tool condition monitoring systems are reduced response time, maximum operational reliability, wide ranging integration capability, high robustness, low installation costs, simplicity for retro-fitting, user friendly operation with minimal calibration, small space requirements, minimum modification to install in manufacturing system, and low maintenance.

Motavalli and Barh (1993) found that automated tool monitoring and part recognition could be integrated into a system for a better and more automated control of the process.

Process monitoring has become more successful since the technology has advanced throughout the years. Pusey (2000) ascertained that there are a number of good reasons to use tool condition monitoring such as safety, economics, environmental and legal among others. Moreover, quality assurance can be considerably improved by the use of monitoring and control techniques. Schaffer (1999) established that monitoring the tool condition is fundamental for maintaining the quality control of the process. Moreover, Richter (2003)
established that tool monitoring saves money by preventing tool breakage and reducing defects. He explained how companies such as Caron Engineering, Inc., J. C. Gibbons Mfg. Inc., and Smith & Wesson as well as others have successfully implemented process monitoring for tools.

Lemaster et. al. (2000) established that process-monitoring techniques can be used to measure spindle vibration on a CNC router and ultimately evaluate the tool wear. Moreover, they found that tool wear was correlated to surface quality, thus, process-monitoring techniques can also be used to evaluate final product quality.

Lemaster and Dornfeld (1993) demonstrated the feasibility of using acoustic emission (AE) to monitor the abrasive machining process. They showed that the AE technique was able to determine when the surface was smooth. The technique was also sensitive to belt wear and grit size as well as machining parameters such as feed speed and depth of cut. Additionally, Lemaster and Dornfeld (1993) found that AE was not significantly sensitive to loading and cleaning.

Matsumoto and Murase (1997) also found that AE can be used to monitor the abrasive machining process. Moreover, they established that AE was able to detect changes in material removal rates but not necessarily capable to monitor abrasive loading or cleaning. They concluded that this phenomenon was due to the removal of wood particle loading causing an increase in the penetration of the abrasive grains, which increase the generation of the AE. However, it also causes a decrease of the AE generation due to the friction between the wood specimen and the fact that loading is reduced.

Continuous technological advancements in automated manufacturing have created a large need of implementation of better process monitoring and controls techniques. In the
past, manufacturing processes were controlled by humans that introduced errors that affect the quality of the products and the equipment condition. With higher speed machines and newer technologies, the probability of introducing human errors in the process is becoming higher everyday. According to Motavalli and Barh (1993), human tool monitoring is expensive and sometimes erroneous. Moreover, they established that human monitoring errors could cause significant damage to the material or the machine. Furthermore, advances in microprocessors, sensors, vision systems, among others, have offered a wide variety of tools that can be used in process monitoring and control.

Matsumoto and Murase (1995) planted the importance of the use of monitoring techniques for wood machining processes. They suggested the use of acoustic emission (AE) to monitor the wood machining processes for the automation of wood machining operations. Based on the premised that, in wood machining, processes generate acoustic emissions, they developed an experiment to investigate the main parameters in acoustic emissions in sanding. Matsumoto and Murase (1995) found that the AE signal in wood sanding has a high frequency component in the range of 0.1 – 0.3 Mhz. In addition, they found that the AE count rate increase when grain size increases, and decrease with increasing sanding time. The variations in the AE count rate and the material removal rate with sanding time also show similar tendencies.

Lemaster et. al. (1985) showed that acoustic emission can be used to monitor tool wear. They found that there was a linear relationship in the initial stages of the blade wear and then, AE levels dropped considerably when the blade became worn.

Work by Matsumoto and Murase in 1997 showed that acoustic emission (AE) count rate decreased rapidly in the early stage of the abrasive machining process for sanding
parallel to the grain, and then gradually approaches constant values for each grain size and each sanding pressure. They also found that an increase in the sanding pressure increased the AE count rates due to increases in both the number of cutting points and the amount that the abrasive minerals penetrated into the workpiece.

Matsumoto and Murase (1998) evaluated the acoustic emission characteristics for the wood sanding process. They found that both the AE event count rates and the amplitude distribution of AE in sanding parallel to the grain were smaller and narrower than these values when sanding perpendicular to the grain. In addition, they determined that the AEs with low amplitude were greater for finer grit size and the AEs with high amplitude were greater for coarser grit size.

Bejhem and Nicolescu (1999) demonstrated the importance of ensuring a reliable process cycle with high machining quality by using monitoring systems to continuously identify machining conditions and to respond when unexpected conditions arise with remedial actions in good time. Moreover, they stated that the development of robust sensors and effective monitoring techniques is a critical problem that process monitoring faces.

Work done by Dornfeld (1984), showed that the requirements for process monitoring techniques include reliability, ease of application, and a close correlation between the output of the technique and the characteristics of the operation. In addition, he found that acoustic emission generated during manufacturing processes provides information regarding the state of the processes.

Beggan et. al. (1999) showed that acoustic emission proved to be a feasible technique to monitor surface quality. They demonstrated that AE signals, predominantly used to monitor tool wear and breakage, can be correlated with the surfaces roughness (Ra).
Sabin et. al. (not dated) stated that the number of instruments used to acquire data and the number of operators who need to utilize it define the configuration complexity of a monitoring system. They also explained that the real value of a monitoring system is in automatic downloading from the measuring instruments.

Liang et.al. (2004) explained that research in automating the process level of machining operations provide increased productivity, improved part quality, reduced costs, and relaxed machine design constraints. They explained that process monitoring and control systems are the key in the effectiveness of the manufacturing process automation. In addition, they summarized the sensors’ signals and their features used to monitor machining outcomes such as vision for surface roughness and tool wear, acoustic emission for tool wear, chipping and tool breakage, vibration for chatter, surfaces roughness and tool wear, and temperature for tool wear as well as others. However, Liang et.al. (2004) confirmed that commercial availability of these systems are fairly limited mainly due to lack of robust sensor hardware and monitoring algorithms, lack of concerted effort in the research community, lack of standardization in automation, lack of consistent success, embedded sensors and actuators, miniaturization of system components and telecommunication-based and wireless process monitoring and control systems.

Lee et.al. (2006) discussed the unique requirements of monitoring of precision manufacturing processes, and the suitability of acoustic emission (AE) as a monitoring technique at the precision scale. They explained that, with the current manufacturing trends aim for smaller and finer forms and features, the necessity for reliable process monitoring with the appropriate set of sensors and technology is critical to characterize and monitor the machining operations. Finally, Lee et.al. (2006) showed that AE can be used to closely link
the manufacturing and quality control stages together.

Work by Landers et. al. (not dated) showed that complex processes can be monitored by sophisticated signal processing sensor measurements. They also explained how controls could be used to take actions to prevent defects such as adjusting feeds and speeds to suppress chatter and initiating an emergency stop in response to a tool breakage. In addition, they discussed the use of process monitoring and control as an innovative and revolutionary technique to support the industry trends to produce products with the greatest quality possible, cheaper and faster. However, as many other authors agree, Landers et. al. (not dated) explained that the biggest obstacles facing the implementation of process monitoring technology are low reliability, limited applicability, and the need for experimentation to determine threshold values, characteristic patterns, etc.

Tönshoff et. al. (not dated) discussed that, due to the complexity of grinding operations, the need for using process monitoring approaches may be imminent. Moreover, they argued that demands to increase productivity and quality of grinding require the process to be closely monitored and controlled. That means that sensors, signal processing, and evaluation procedures have to be implemented. Work done by Tönshoff et. al. (not dated), found that the size of the sensors is directly associated with the positioning, therefore, miniaturization of sensors is an important criteria to locate a sensor close to the source that propagates the signal. In addition, they highlight the necessity to integrate different sensors to collect the maximum amount of information regarding the status of the process and the actions that need to be taken when an undesired condition arise. Finally, they established that the future demands on monitoring systems must focus on the performance, sensitivity, and reliability at an acceptable cost.
Bhateja and Bielak (1990) discussed the lack of focus on the grinding process in production industries. They explained how, by monitoring the main process parameters of grinding, can significantly improve the grinding process and considerably improve productivity.

Leem and Dornfeld (1996) proposed a methodology to effectively deal with critical issues such as expense information on correct tool condition, troublesome off-line pre-selection of features from original sensor signals, impartial fresh/worn dichotomy, and fallible signal-interpretation with stationary sensor information. Furthermore, their suggested methodology was implemented and proved to be able to reduce the gap between academic research and industrial needs for a practical and reliable sensor-based tool wear monitoring system.

Dornfeld et. al. (2003) explained the use of different sensors commercially available for monitoring and controlling machining processes in order to improve productivity. Moreover, they presented the feasibility of using an acoustic emission sensor and its applications to monitor ultra precision machining.

Wang et. al. (2001) presented a new approach for monitoring tool wear in machining processes. They found, from experimentation, that the average detection rate for a sharp and a worn tool reached 97%, indicating that this technique could be successfully used to monitor tool condition.

Du et. al. (1992) argued about the imperative need for tool condition monitoring as one of the most important monitoring requirements of untended machining operations. They discussed the main research issues in tool condition monitoring such as the development of accurate and reliable on-line measurement of machining parameters, the choice of correct
analysis strategies (data reduction, improvement of signal-to-noise-ratio, etc), the detection of a specific tool failure mode by developing/selecting signature features which are sensitive to that particular mode, and the development of signal classification routines for automatic identification of several defect classes.

Fu et. al. (2003) discussed how filtering of surface profiles is essential for process monitoring.

Finn and Highes (1995) showed that machining parameters can be selected for new materials by using sensors to monitor machining processes.

Liu et. at. (2002) showed that a fiber optic sensor can be used as a process monitoring method to evaluate machined surface roughness. In addition, they explained the prototype sensor probe has high resolution and sensitivity for ground and milled surfaces.

Despite many advances in process equipment and sensor technology, limited research has been conducted on process monitoring of an abrasive machining process but those projects have typically relied on acoustic emission monitoring or power consumption monitoring. Work presented here is an attempt by the WMTRP to integrate acoustic emission, vibration, and image analysis to monitor and control the abrasive machining process.

2.3 Previous Work on Abrasive Belt Cleaning

As stated above, sanding represents an important investment in the machining process because sanding belt price per unit is high and the abrasive belt life is short.

It is not unusual to spend more then twice the cost of a machine for a year’s worth of abrasives. Norton Abrasives specialists estimates (2006) that common wide belt sanding
abrasive machine costs $75 per hour of processing (labor and overhead). This is substantial more than knife machining. Any technique that could extend the life of the abrasives would be of great benefit to the woodworking industry and would result in energy savings by reducing the number of abrasive belts required in addition to savings in labor and downtime due to belt replacement and setup.

Two of the most important factors that affect the belt life are the belt loading and belt temperature. These factors have been identified by many authors in the past and efforts have been focused on reducing them with feasible and effective solutions.

High temperatures have a considerable impact because increases in temperature can cause negative effects not only in the wood but also in the performance of the sanding belt. The heat from the sanding operation where the belt meets the wood can be so high that the heat melts resin in the wood. The heated resin then flows onto the belt, where the resin cools and become hard again, which result in loading. In order to reduce high temperatures and therefore overheating, it can be useful to use cooling systems to control/reduce the temperature and help to prevent loading in sanding belts. However, stops in the process to let the belt to cool down can be inconvenient and costly.

Abrasives can either become worn or become loaded with wood fiber. A loaded belt is one which has wood fibers compacted into the spaces between and around the abrasive grits. A loaded condition will cause the belt to be unable to cut additional material, as the grits cannot fully come into contact with the wood piece. The result is a situation where rubbing and friction generate heat and the wood becomes burnished.

Abrasives machining continues to be a more expensive process than comparable blade technologies due to the cost of the abrasives. Much research has been conducted to extend
the life of the abrasives. This has included different backing materials, abrasives, and adhesives. In addition, work has been conducted on developing cleaning systems to remove wood fiber from the abrasives. This has included a cleaning system (Abrasive Belt Master) that utilizes a 1,200 psi and 140 °F water and cleaning solution where the belt is removed from the machine and then placed in the bath for cleaning. Another system (Nu-life) uses a “gum eraser” stick or block which is sanded to remove the wood fibers from the abrasives. Other more exotic systems include blasting the abrasive with an abrasive media to remove the wood fiber. This includes sand (glass bead) blasting (Zintexx) and blasting with dry ice pellets (Cryokinetics). According to Lemaster et. al. (2005), blasting is a technique that uses high-pressure air to carry hard particles to impinge on a workpiece for material removal and surface integrity modification. Erosion wear is the material removal mechanism in blasting.

The disadvantage of these methods is the expense of application and the susceptibility of damage to the abrasive. High-pressure washers with or without detergent is the most common method, though this technique is time consuming and requires the process to be stopped and the belt to be removed from the sander, which as stated before, can be inconvenient and costly. Thus, any technique that could extend the life of the abrasives would be of great benefit to the woodworking industry and would result in indirect energy savings by reducing the number of abrasive belts required.

Some research in abrasive machining has been done in order to determine the effect of cleaning on the belt life. According to Grivna (2004), cleaning of abrasive belts can considerably increase belt life in the case where the belts have been prematurely replaced due to loading instead of mineral wear. In fact, he showed that the life of the belt (cleaned with dry ice blasting) could increase two to five times, when hardwoods were sanded and
considerable more when sanding softwoods. Grivna’s (2004) work consisted of evaluating different belt cleaning methods such as air nozzle blow off system, dry ice blasting, eraser-type removal, high pressure water or steam blasting, caustic soaking with brushes, glass bead blasting, and wire brushing. His results showed that some methods (especially dry ice) were more efficient than others were. In fact, he found that only three of the methods were viable (air jet blast, water blast, and dry ice) to remove loading and extend, to some level, the life of the sanding belts.

Spur et al. (1999) established that the use of chemicals and solvents for cleaning involve reconditioning and disposal cost. On the other hand, jet process with sand, steel and glass particles tend to damage the surface of the parts. Thus, they showed that dry ice blasting is an effective technique that can be used to clean surfaces simultaneously reducing cleaning costs and ecological damage.

2.4 Previous Work on Process Control

Control systems have been used and integrated into many applications for years. It has been discussed that planning without controlling makes no sense since the main idea of planning is to take actions based on the continuous monitoring of the plan. There are many ways to control a process however, in this research; the process will be controlled by a control system. A control system is a collection of components connected together in a specific way that is able to modify itself or another system.

Franklin et al. (1994) pinpointed the importance of control and defined it as the process of causing a system variable to conform to some desired value. Moreover, they discussed that both manual and automated control systems have significantly evolved in the past years into the discipline of control system design. Franklin et al. (1994) explained that
one of the most important control system designs is the feedback, which is the process of measuring the controlled variable and using the information to affect or modify the value of the controlled variable.

According to Galip and Koren (1993), process control has been successfully implemented with the requirement of realistic process modeling based on an understanding of the process that is being controlled. They explained that some models developed by many researchers have focused on the estimation of wear from indirect measurement such as cutting forces, temperature, and acoustic emission. In addition, Galip and Koren (1993) concluded that sensing and control technologies not only have a great impact on the development and precision of the machines but also have a significant economic impact.

Ramsden (2006) argued that a very important application of sensors is in real time monitoring in which the information from the sensor is used to determine the steering direction of the external process. Thus, he defined that one of the basic characteristics of process control is to collect information from a sensor and use this information to direct an actuator that has control over the process.

Dornfeld and Tomizuka (1987) discussed that there are two fundamental problems in control, the regulation under the presence of disturbances and the tracking of the desired output.

Koren (1997) reviewed the evolution in machine tool controls. He discussed three main types of controls: servo-control loops, interpolators, and adaptive controls. Koren (1997) defined that, in servo control for machine tools, PID controllers, fuzzy logic controllers, feedfoward controllers and cross-coupling controllers are the most used. He defined that in a PID controller, the correction of the signal is a combination of three major
components, a proportional, an integral and a derivative of the position error.

Franklin et. al. (1994) gave a brief overview of the history of feedback controls. They discussed that after feedback amplifier and feedback control of industrial processes became standard, the development of proportional-integral-derivative (PID) control was necessary in order to deal with processes that were not only highly complex but also were non linear and subject to relatively long time delays between the actuator and the sensor.

Auslander et. al (1974) explained that PI action is better than I action alone for many system. Moreover, they explained that the D action added to the P or PI action improves the recovery since the D action detects changes in trends anticipating the future. Finally, Auslander et. al (1974) summarized that there are three main components of the linear control laws, the P actions respond to the present situation, the integrated actions represents the past history, and the D actions that attempt to speculate about the future.

DiStefano et. al. (1990) defined a PID controller as a combination of a proportional (P) controller which has an output proportional to its input; an integral (I) controller in which the output is proportional to the integral of its input; and a derivative (D) controller that has an output proportional to the derivative of its input.

Ramsden (2006) explained that the main difference between an ON-OFF control system and a proportional (P) control system is the controller provides a continuously variable output. Thus, he established that the proportional (P) control system can change the output by a certain percentage based on the conditions desired.

Auslander et. al (1974) stated that the human function in an extremely man-machine operation is a PID system with a dead time of a fraction of a second.

Franklin et. al. (1994) discussed that the combination of proportional, integral, and
derivative control strategies is sometimes able to provide an acceptable degree of error reduction with satisfactory stability and damping. Moreover, they affirmed that PID controllers are so effective that they are commonly used in processing industries such as petroleum, papermaking, and metalworking.

Franklin et. al. (1994) concluded that proportional feedback reduces error while integral control improves the steady-state error and provides robustness with respect to parameter variations. It also reduces stability while derivative control increases damping and improves stability. Thus, the combination of these three control strategies can significantly improve the performance of the control systems.

Another type of control system that has been widely used in industries and other applications is a Fuzzy Logic Control System. Lewis and Liu (1996) confirmed that the fuzzy logic concepts in control applications have expanded at an increasing rate. Moreover, they explained the extraordinary success of fuzzy logic controllers in recent years.

Pfeiffer and Isermann (1994) discussed that fuzzy control has had a great development in the past years and an extraordinary number of applications from different areas due to the approach incorporating empirical process knowledge and linguistically formulated strategies into automation systems. Furthermore, they explained that fuzzy logic is a method able to synthesize, from empirical knowledge, a multidimensional control characteristic that can be divided into regions having certain logical meanings defined by rules. Moreover, Pfeiffer and Isermann (1994) established that one of the main advantages of fuzzy systems is that they allow reasonable treatment of inputs due to their interpolative characteristics. Finally, they concluded that fuzzy systems facilitate online implementations in real time.
Moratori et. al. (not dated) analyzed the reliability of fuzzy logic based systems by studying three different configurations and measuring two main parameters; processing time and the amount of steps necessary to reach the goal. They found that simplicity and easiness of the design of fuzzy controllers did not compromise their efficiency, in fact, they concluded that fuzzy logic based systems can properly perform under adverse conditions. Moratori et. al. also discussed that fuzzy logic reduces the difficulties of implementation because even when the designer does not have a complete knowledge of the problem, it is possible to develop a simple and efficient controller.

Work done by Coleman and Godbole (1994) compared fuzzy logic control and classical control design methodologies. They concluded that fuzzy logic control could be a useful tool for the control designer due to it being relatively simple to implement and providing satisfactory results. However, they remarked that only time, experience, and further analysis would determine whether fuzzy logic control becomes a prominent tool in the control toolbox used by devotees of classical control techniques.

Yen (1999) explained that fuzzy logic explores an effective trade-off between precision and the cost in developing an approximate model of a complex system or function. He discussed that in recent years cost has become an important issue in artificial intelligence. Indeed, he concluded that fuzzy logic provides a cost effective solution to a wide range of real problems which is why fuzzy logic has found several successful applications in industry.

Liu and Lewis (1993) argued that despite the fact that fuzzy logic deals with a wide variety of ambiguous events and situations, these events and situations do not necessarily need to be totally “fuzzy” and disorderly. This means that fuzzy logic should not be fuzzy. In addition, they discussed that conventional PD or PI or PID controllers are just special cases
of fuzzy logic controllers if the filtered tracking error is used as the feedback signals.

Lee (1990) discussed the increasing use of fuzzy controllers in industrial processes. He explained that fuzzy control is based on fuzzy logic, which is a system closer in spirit to human thinking and natural language than traditional logic systems. Thus, fuzzy logic controllers provide a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy.

Ahn et. al. (1996) proposed a loop controller that deals with two of the main limitations in implementing fuzzy logic in loop controllers such as the speed of the fuzzy logic controller and the number of parameters to define the fuzzy logic controller. Thus, they showed that a fixed control table increases the inference speed and reduces the number of defining parameters, while the mapping parameters provides flexibility of the designed fuzzy logic controller.

An anonymous paper (1995) presented fuzzy sets and fuzzy logic as powerful tools for managing complexity and controlling computational cost. Moreover, fuzzy set theory and the associated fuzzy logic can effectively deal with a broader class of problems. It is explained in the paper that an important feature of fuzzy set theory is its capability to capture the vagueness of linguistic terms in statements of natural language providing a great capability to model human common sense reasoning, decision making, and other human cognition. The document concluded that the most visible application of fuzzy sets is in the area of control, however, it has been equally successfully implemented in database, expert systems, pattern recognition and clustering, image processing and computer vision, speech recognition, and decision-making.

Lee (1990) discussed that fuzzy logic control has numerous applications as a means
of replacing a skilled human operator. He discussed a new direction in the design of fuzzy system that have the capability to learn from experience, thus, a combination of techniques from both fuzzy logic and neural network provide a powerful tool for the design of systems that can emulate the human ability to learn and adapt to changes in the environment.

Work done by Harber et. al. (2002) provided important information about a proposed control scheme based on fuzzy logic to fulfill the current needs and design requirements of the machine tools such as new servo systems, strategies for thermal compensation, cutting fluid supply controls, and material removal optimization. Moreover, they concluded that these control schemes based on fuzzy logic can increase the machine tool performance and productivity. Furthermore, they discussed that the characteristics of the hierarchical controllers are remarkable.

Research by Smith (1994) showed that fuzzy logic inference and fuzzy-based sensors have had a significant effect on manufacturers, suppliers and consumers in the Japanese market due to them being able to solve control problems that have resisted the best efforts of conventional methodologies. The main reason he explained is the ability of fuzzy logic to interact so well with people. Smith (1994) proposed a few rules of thumb for when fuzzy logic should be used such as when the parameters can be expected to change, when the existing traditional controllers must be augmented, when it is easier to design and implement a fuzzy rule base that will control a complex system as opposed to developing a classical control system to do the same, when sensor inaccuracy is a problem, to decrease data communications costs in multiprocessor applications, and when systems require adaptive signal processing to overcome changing environmental or process conditions.

Reinfrank (1991) discussed how fuzzy logic integrates the concepts use in daily life
(tall, big, small) with machines’ precise definitions. He argued that fuzzy logic makes controls more robust, cheaper and require less energy to operate. In fact, he agreed that in some cases, fuzzy logic is the only option to answer to a number of challenging control problems.

Research by Ashbaugh and Boitano (not dated) showed that fuzzy logic seems to have some advantages over other methods. A fuzzy controller is highly recommended when speed is crucial. Moreover, they concluded that fuzzy logic controllers appear to be slightly more flexible that other controllers such as naïve. But, they also argued that a non-fuzzy logic controller could be designed much more quickly, require much less hardware, and will have speed on the same order of magnitude as a fuzzy logic controller.

Roy and Miranda (1997) discussed that, due to the fact fuzzy logic is fundamentally based on the learning mechanism of humans and are learned from real data and facts and that the fundamental learning mechanism of humans is some type of neural network, it is possible to define fuzzy rules data from training one of the standard neural networks from the same data. Thus, the fuzzy rules can indeed be found in the net.

Work by Du et. al. (1992) showed the use of fuzzy sets to create a linear equation to describe the relationship between the tool condition and the monitoring indices. Findings from their research showed that an overall 90 percent reliability can be obtained by using fuzzy set linear equation for detecting tool conditions regardless of the variation in cutting conditions.

Langari (1999) stated that the semantic style used by fuzzy logic enable control designers to efficiently develop control strategies in application areas marked by low order dynamics with weak non linearities. Thus, he proposed that the broader impact of fuzzy logic
should be in hierarchically structured systems, perhaps in combination with conventional control techniques.

Koren (1997) stated that the two main problems with PID controllers in contouring applications are the poor tracking of corners and nonlinear contours and the significant overshoots. However, he defined that these problems can be reduced by preprogramming of acceleration and deceleration.

Brubaker (1995) explained that the linear PID controller is a workhorse because it is well-understood, easy to design, and performs well in most linear control applications with unchanging parameters.

Åström and Hängglund (2001) affirmed that the PID controller is the most utilized feedback controller in use today. In fact, they said that more than 90 percent of all control loops are PID.

Ramsden (2006) discussed that it can be difficult to design an effective controller. He also established that PID control algorithms are on the low end of the complexity scale.

Ashbaugh and Boitano (not dated) concluded that fuzzy logic controllers may have slightly better performance over other control methods but must be carefully tuned to achieve maximum performance.

Otsubo et. al. (1998) discussed that one of the special features of fuzzy control is that improvement of the transient characteristic of control performance and control with excellent robustness can be easily realized. They also stated that PID controls have a great advantage due to stability which is guaranteed theoretically and high-accuracy control which is possible especially in the steady-state characteristic region.
Pease (1995) compared proportional-integral-derivative and fuzzy logic controllers. He said that most fuzzy logic controllers do not have the integral response since they only respond to the proportional and derivative response. Thus, Pease (1995) affirmed that a PID controller can achieve better accuracy and dynamic response than a simple fuzzy logic controller. Based on his research, Pease (1995) argued that the number of fuzzy logic rules can dramatically increase when increase from two to three parameters with seven fuzzy rules (from 49 to 343).

Yan et. al. (2001) implemented PID control system to control temperature and moisture for wood drying kiln. They also proved that the system can be improved an integrated intelligent together with conventional PID controller.

Åström and Hängglund (2001) discussed that PID controllers are widely used in many industries to solve a large variety of problems such as process control, motor drives, magnetic and optic memories, light control, instrumentation as well as others. Moreover, they explained that the controllers can come in different forms from single loops to distributed control systems as the ones found in robots and CD players.

Hindmon (1998) explained that one of the main advantages of PID control is that it can detect and react to the rate and direction of the input change. Thus, if the input rapidly approaches the setpoint, the system will not make any correction, on the other hand, the system will react swiftly if the input rapidly moves away from the setpoint. He also discussed that one of the major disadvantages of PID control is that in order to be effective it needs a high quality and complicate mathematical model for the system to be controlled. Additionally, Hindmon (1998) established that PID control tends to overshoot when the system tries to return to changes in load as fast as possible.
Virvalo (not dated) demonstrated by both simulations and experiments that linear PI and PID controllers can be used in hydraulic position servos. However, overshoots were observed when fast responses with relatively short settling times were required.

Silveira et. al. (2002) compared PID and fuzzy control strategies for speed velocity control. They found that there were no significant differences when comparing both control strategies. However, they determined that the implementation of the two control strategies presented a meaningful difference of work time; the fuzzy control implementation was much faster and simpler in relation to the development and implementation of these strategies.

Zhao (not dated) used PID control due to its simple structure, ease of design and robustness under certain model and parameter uncertainties.

Morris (2005) discussed that one of the main advantages of feedback control is that the action occurs as soon as the controlled variable deviates from the setpoint regardless of the source of trouble. Additionally, he agreed that PID control requires minimal knowledge about the process in which a complex mathematical model is not required although they are very useful in control system design. Moreover, he affirmed that PID is versatile, robust and that retuning of the controller settings produces satisfactory control when the process conditions change. On the other hand, Morris (2005) discussed that one of the major disadvantages of feedback control is that if large and frequent changes occur, the system might operate continually and never achieve the desired steady state.

Thahn and Ahn (2006) explained that PID control is one of the most popular control strategies in industry due to the fact that this type of control have an easy structure, are easy tuning, cheap and have an excellent performance. They also agreed that one of the main
drawbacks is the determination of the appropriate gains which is difficult for nonlinear and unknown controlled plants.

Panagopoulos and Åström (2000) described that the design objectives of a typical process control problem are expressed as requirements on: load disturbance response, measurement noise response, robustness with respect to model uncertainties, and set point response.

Wong and Rad (1994) demonstrated that a fuzzy logic controller provided good noise rejection and low overshoot for a heating process; however, it showed a lack of a closed loop stability.

Åström and Hångglund (2001) compared fuzzy controls and PID controls. They discussed that, despite authors claim that fuzzy controls are easy to use and nonlinear, their justification has been very weak. They also explained that if nonlinear behavior is desired gain schedule can be added to the PID controller. Moreover, Åström and Hångglund (2001) agreed that one advantage of fuzzy control is that very good software is available.

Tao and Taur (2005) showed that the stability robustness of classical PID controllers can be improved by using piecewise linear PID-like fuzzy controllers.

In general, proportional-integral-derivative control main advantages are: able to reject disturbances; good performance even under uncertainties where the model does not imitate the real process perfectly; processes can be stabilized and reduced sensitivity.

Åström and Hångglund (2001) discussed the main aspects when designing a PID controller such as it should yield a controller that meets the design specifications, it should be based on the available/obtainable process knowledge, and it should meet limitations on computational power and resources available for the design.
Franklin et. al. (1994) designed a simple but complete methodology to design control systems:

1. Understand the process and its performance requirements. It is important to define in this step what the system is supposed to do.

2. Select the most appropriate sensor(s) considering location, technology, noise, performance, accuracy, size and weight, quality, lifetime, robustness, and cost as well as others.

3. Select the appropriate actuator considering technology, location and power. The actuator must be capable of driving the system to meet the specified required performance.

4. Make a linear model of the process, actuator and sensor.

5. Make a simple trial design of a PID control. A simple PID control may succeed and be accurate and robust enough for the system.

6. Try an optimal design. Make a trial pole-placement design based on optimal control or other criteria.

7. Simulate the design and evaluate its performance including the effects of nonlinearities, noise, and parameter variations.

8. Build a prototype and measure its performance with a typical input signal. No system can be acceptable and defendable without testing and validation.
Figure 2.1 shows a flowchart of the control system design methodology based on Franklin et. al. (1994) methodology.

![Control system methodology flowchart based on Franklin et. al. (1994).](image)

**Figure 2.1. Control system methodology flowchart based on Franklin et. al. (1994).**
3. CONVENTIONAL SANDING OF WOOD AND WOOD BASED MATERIALS

The sanding process involves the modification of the surface topography of the wood by the action of abrasive materials. This process separates fine particles and dust from the wood surface causing a systematic failure on the surface of the wood. Therefore, the anisotropic nature of wood is a significant characteristic of the wood that considerably affects the formation of wood particles and dust. Thus, an understanding of wood anatomy is essential to understanding the performance of the sanding process.

Wood is composed of cellulose, lignin, hemicelluloses, and minor amounts (5 to 10 percent) of extraneous materials contained in a cellular structure. Variations in the characteristics and volume of these components and differences in cellular structure make woods heavy or light, stiff or flexible, hard or soft. The properties of a single species are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate. However, to use wood to its best advantage and most effectively in engineering applications, specific characteristics or physical properties must be considered (from USDA Handbook, 1999).

The inherent factors that keep wood as a preferred material are many and varied, but a chief attribute is its availability in many species, sizes, and configurations to suit almost every demand. Wood has a high ratio of strength to weight and a remarkable record for durability and performance as a structural material. Dry wood has good insulating properties against heat, sound, and electricity. It tends to absorb and dissipate vibrations under some conditions of use, and yet it is an incomparable material for such musical instruments as the violin. The grain patterns and colors of wood make it an aesthetically pleasing material, and
its appearance may be easily enhanced by stains, varnishes, lacquers, and other finishes. It is
easily shaped with tools and fastened with adhesives, nails, screws, bolts, and dowels.
Damaged wood is easily repaired, and wood structures are easily remodeled or altered. In
addition, wood resists oxidation, acid, saltwater, and other corrosive agents, has high salvage
value, has good shock resistance, can be treated with preservatives and fire retardants, and
can be combined with almost any other material for both functional and aesthetic uses (from

Trees are divided into two broad classes, usually referred to as hardwoods and
softwoods. These names can be confusing since some softwoods are actually harder than
some hardwoods, and conversely some hardwoods are softer than some softwoods. For
example, softwoods such as longleaf pine and Douglas-fir are typically harder than the
hardwoods basswood and aspen. Botanically, hardwoods are Angiosperms; the seeds are
enclosed in the ovary of the flower. Anatomically, hardwoods are porous; that is, they
contain vessel elements. A vessel element is a wood cell with open ends; when vessel
elements are set one above another, they form a continuous tube (vessel), which serves as a
conduit for transporting water or sap in the tree. Typically, hardwoods are plants with broad
leaves that, with few exceptions in the temperate region, lose their leaves in autumn or
winter. Most imported tropical woods are hardwoods. Botanically, softwoods are
Gymnosperms or conifers; the seeds are naked (not enclosed in the ovary of the flower).
Anatomically, softwoods are nonporous and do not contain vessels. Softwoods are usually
cone-bearing plants with needle- or scale-like evergreen leaves. Some softwoods, such as
larches and bald cypress, lose their needles during autumn or winter (from USDA Handbook,
1999).
Major resources of softwood species are spread across the United States, except for
the Great Plains where only small areas are forested. Softwood species are often loosely
grouped in three general regions. Hardwoods also occur in all parts of the United States,

As a result of the nature of wood, the sanding characteristics of different types of
wood and wood based products are significantly different and unique.

There is a significant effect of the anatomical features of the wood on the sanding
process. Growth rings, abnormal wood, sapwood and heartwood ratio, texture and extractives
in wood are some of the anatomical features to be considered (Ratnasingam and Scholz,
2004). Growth rings and the sapwood heartwood ratio impart variability to the stock, to the
extent that it affects the sanding forces and the resulting surface quality. (Ratnasingam and
Scholz, 2004). A fine textured wood would appear to produce a lower quality sanded surface
as opposed to a coarse texture wood, because they can hide the sanding marks and scratches
on the surface. Additionally, extractives in the wood such as silica and resin considerably
affect the performance of the sanding process by increasing wear and clogging (Ratnasingam
and Scholz, 2004).

In general, due to its anatomical complexity, hardwoods are more complex to
characterize with respect to sanding performance than softwoods.

The physical properties of the wood must be also studied and considered when
evaluating the performance of sanding. As stated before, the sanding process involves the
failure of the wood fibers producing small particles and dust. This failure depends on the
strength of the fibers of the wood, which are significantly affected by the physical properties
of the wood. Moisture content has been shown to have a pronounced effect on wood behavior
and must be considered. Wood weakens as its moisture content increases up to its fiber saturation point (FSP). Therefore, wood with high moisture content is easier to sand; however, it has been shown that high moisture content wood tends to clog up the belt considerably more. Additionally, high moisture content wood tends to generate more surface defects such as raised grains after the sanding process is performed.

Another physical characteristic of the wood that considerably affects the sanding is the temperature. Excessive temperature reduces the strength of the wood and in some cases can result in burning the surface of the wood which creates discoloration and reduces the capacity of the wood to adsorb the finishing material. It is important to note that this effect is offset by the reduction of moisture due to high temperature.

In general, higher density leads to higher strength, which obviously affects the sanding process. Thus, species with higher density (higher degree of hardness) are more difficult to sand than those with lower density. Therefore, hardwoods and softwoods with higher density have a higher resistance to being cut by the abrasive minerals, causing difficulty in removing the scratches and the machining marks. Hence, higher density woods should be sanded with the finest and sharpest grit abrasives possible.

Ratnasingam and Scholz (2004) stated that wood grain size or texture has a great effect on sanding. They said that coarse-grained woods, such as red oak (Quercus sp.) and ash (fraxinus sp.) have large cells and open pores that tend to hide scratches, while fine-grained woods that lack visible pores, such as maple (Acer sp.) and ebony (Diospyros sp.) more easily show scratches.

Wood that has high resin content such as hemlock (Tsuga sp.) and spruce (Picea sp.), pitch or latex pockets such as pine (Pinus sp.) and jelutong (Dyera sp.), or extractives and
oils such as rosewood (Dalbergia sp.) and teak (Tectona sp.), may be difficult to sand with fine grit abrasives because of their natural tackiness which tends to clog up the abrasive belt (Ratnasingam and Scholz, 2004).

3.1 Abrasive Materials

Abrasive materials have been used for thousands of years as means of shaping materials to obtain products. In traditional sanding, abrasive materials are used for two main purposes, heavy material removal to obtain a final desired shape and size, and light material removal to prepare the surface for finishing by generating a very smooth surface.

There are two main traditional abrasive tools, bonded abrasive and coated abrasive. Bonded abrasive are mainly for resharpening cutting tools and are not the subject of this study.

Coated abrasives consist of small, sharp particles or grains of an abrasive material bonded onto a flexible backing (Clark et al., 1987). According to Ratnasingam and Scholz (2004) the mineral grains are attached and held in position to the backing by two layers of adhesive.

Figure 3.1 shows the traditional configuration of coated abrasives.

![Figure 3.1. Traditional coated abrasive configuration.](image)

As can be seen in Figure 3.1 there are several elements that constitute the structure
and contribute to the performance of the coated abrasives. The mineral used such as aluminum oxide, the backing material such as paper, the distribution and orientation of the mineral such as closed coat, and flexure pattern for flexibility depending on the shape of the surface to be sanded.

There are five main abrasive minerals used to sand wood, two of them occur in nature (flint and garnet), and three are man-made (aluminum oxide, silicon carbide, and zirconium-based). **Flint**\(^1\) is a grayish white to faint pink silicon dioxide quartz found in large natural deposits in many areas. It is the abrasive on common sheet sandpaper for hand sanding. Although flint breaks up into sharp fragments and is low cost, it is seldom used for industrial applications because it is not as hard or durable as other available abrasives. Hardness of flint is seven in the Moh scale, less in cryptocrystalline forms. Specific gravity is 2.65 or less if cryptocrystalline. **Garnet**\(^2\) is mixed orthosilicate of iron, aluminum, calcium, and magnesium. It is red in color. Almandite \((\text{Al}_2\text{O}_3\text{FeO}.3\text{SiO}_2)\) is the principal mineral used for coated abrasives. Garnet crystals, when crushed, provide light wedge-shaped grits that are harder and sharper than flint. Having a hardness of approximately 7.5 on the Moh hardness scale\(^3\), garnet is harder than glass and is a widely used natural abrasive. The specific gravity of garnet ranges from 3.4 to 4.3. Hardness: \(6^{1/2} - 7^{1/2}\). Garnet is used in polishing and grinding. **Aluminum Oxide**\(^4\), first created synthetically about 1900, is a reddish brown smelted derivative of bauxite ore. This ore, heated in an electric furnace to approximately 3500 °F, together with a small amount of coke and iron filings, produces a "pig" that may contain as much as 50 percent aluminum oxide. When crushed, aluminum oxide forms a grit

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\(^1\)http://mineral.galleries.com/minerals/silicate/quartz/quartz.htm.

\(^2\)http://www.geocities.com/EnchantedForest/Cottage/3292/rocks/garnet.htm

\(^3\)http://www.24carat.co.uk/hardnessmohsscale.html

\(^4\)http://mineral.galleries.com/.
having heavy wedge-shape particles with a hardness of 9.5 on the Moh hardness scale and a specific gravity of 3.96. In combination with a resin bond, aluminum oxide is very resistant to breakdown, and is widely accepted for sanding applications requiring high pressures. When dull, cutting points become rounded, and heat induced burnishing of surfaces may result. Silicon Carbide\(^5\), blue black in color, was first experimentally produced in the early 1890’s. It is manufactured commercially by combining a mixture of sand (silicon dioxide), powdered coke (carbon), and a small quantity of sawdust and salt in an electric resistance furnace at about 4000 °F. The sawdust makes the mass porous and aids in the escape of carbon monoxide. The salt helps remove iron impurities by forming a volatile chloride. The crystals of silicon carbide that form around the electrode have a hardness of about 9.6 on the Moh scale and a specific gravity of 3.2. When these crystals are cooled and crushed, the resulting grit is chiefly sharp, wedge-shaped particles. Although silicon carbide is the hardest and sharpest of the minerals used in the manufacture of coated abrasives, it is the most readily fractured because of its brittleness. It is excellent for light sanding operations, such as removing raised fibers from previously sanded wood. It is also an efficient abrasive for sanding hardboard and particleboard, which have resin binders. Zirconium-based (Koch, 1985) is an alloy of aluminum oxide and zirconium oxide which became commercially available about 1972. The grit has a specific gravity of about 4.56. Its hardness cannot be easily measured on the Moh scale because fractures develop that make the Moh test invalid. The zirconium-based grit, i.e., alumina zirconia, is used for heavy stick removal and high-pressure grinding.

The sizes of particles used on coated abrasives are established by sifting the grit through screens of standard mesh. The number of screen apertures per square inch

\(^5\) http://www.accuratus.com/404redirect.html
determines the size of the grain to be used in making a particular type of sandpaper. For example, 100-grit sandpaper has a grain size that was sifted through a screen having 100 apertures per square inch. As many as 20 different grain sizes are used in the woodworking and furniture industries (Clark et al., 1987). The coarser grains are used for the heavy cutting needed to remove knife marks and torn grain. Very coarse grains are used in abrasive planing where lumber is being cut to a precise thickness. The coarse grains leave relatively deep scratches that must be removed by sanding with successively finer-grit sizes.

Table 1 shows some examples of typical grain sizes that are used for different sanding operations (Clark et al., 1987).

Table 3.1. Typical grain sizes for different applications (Clark et al., 1987).

<table>
<thead>
<tr>
<th>Grade #</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 24</td>
<td>Rough planing; removes up to 1/4&quot; of stock</td>
</tr>
<tr>
<td>36 to 40</td>
<td>Finish planing; removes up to 1/16&quot; of stock</td>
</tr>
<tr>
<td>60 to 80</td>
<td>Primary sanding; planing of wood, edge banded panels</td>
</tr>
<tr>
<td>100 to 120</td>
<td>Secondary sanding; veneer tape removal</td>
</tr>
<tr>
<td>120 to 220</td>
<td>Finish or polish sanding</td>
</tr>
<tr>
<td>360 to 500</td>
<td>Topcoat rubbing and polishing</td>
</tr>
</tbody>
</table>

Table 3.1 shows that there are different sizes of grains depending on the different applications and finished desired. Thus, the proper selection of grain size will assure the results required based on material removed and required surface quality.

The selection of the abrasive grade is more or less discretionary and depends on many
variables. Some factors include species of wood, quality specifications, product styling, and the color and sheen of the finished product (Clark et al., 1987). If the objective of the abrasive machining operation is to remove material and produce a high quality surface (fine finish), it is necessary to use several grades. On the other hand, if material removal is of importance regardless of the surface, the use of one grade that gives the best cutting rate and maximum removal is recommended. In contrast, if a fine finish is required, the grade must be as fine as possible, which will produce smaller material removal and the final surface, desired (Clark et al., 1987).

The sanding process must be executed in steps depending on the quality of the surface required and the amount of material to be removed. Different work levels require several steps of sanding. The selection of intermediate grades is important from both quality and cost standpoints. If too few intermediate grades are used, some of the coarser scratches may not be removed and optimum abrasive life is not attained.

Generally, a greater number of grades may be skipped in the coarse end of the range than in the finer end.

Figure 3.2 shows the effect of skipping steps on the resulting surfaces.

Figure 3.2. Grain size skipping effect on resulting surfaces.

Figure 3.2 shows how skipping steps on the sanding process can considerably affect
the surface and generate the need for rework. In cases where the final quality of the surface is a significant factor and an important requirement for the subsequent processes, skipping sanding steps can produce low quality surfaces that will be accentuated after the layers of finished are applied.

Backing is the foundation of coated abrasives. Backings are made of different materials, the most commonly used in the manufacturing of coated abrasives are cloth, resin fiber, paper and a combination of these materials. The flexible backing to which the abrasive grains are bonded is either paper or cloth. Paper backing comes in a wide range of thicknesses or weights. The thicker papers are naturally stronger but less flexible than the thinner ones and cost more per square foot (Clark et al., 1987).

Cloth backing is available in various weights depending on the use and specific properties required. “J” weight (jeans) cloth is normally used for polishing and finishing operations or sometimes where a flexible product is necessary. “X” weight (drills) is a heavier, stronger, and less flexible material that is used in heavy and medium duty operations. “Y” weight (sateen) is a super heavy backing for heavy duty grinding. Resin backings are multiple bonded layers of impregnated paper. They are normally tough and strong.

Paper is also available in several weights. “A” weight is light and flexible but less resistant to wear and higher demanding conditions. “C” and “D” weights are stronger and less flexible. “E” and “F” weights are stronger but lesser flexible and are normally used for high resistance to tearing. Combination backing, as its name indicates, is a combination of laminating “E” weight paper and light cloth. It is normally used for floor sanding discs and drum sanding. If paper backing is not strong enough or flexible enough, cloth backing is
available. Its cost is considerably higher than paper. In general, there are two types of cloth backing "jeans" and "drills" (Clark et al., 1987).

Users often struggle with the choice of paper-backed abrasives versus cloth-backed abrasives. Paper products usually cost less but have poor tear resistance. If the severity of the operation is such that cuts, tears, nicks, etc. may be encountered, cloth should be chosen since such damage to a paper product would cause almost immediate breakage because of the tension on the belt. Flexibility with strength is an important attribute of the backing materials (Clark et al., 1987).

In coating, the glue is applied to a backing and the abrasive grains are dropped onto the backing. If the grains completely cover the surface of the backing, the abrasive is called closed-coat. The grains can be distributed on the wet glue so that there is a predetermined distance between grains that leaves some spaces of the backing bare and free from abrasive grains. This is called open-coat. In open coating, approximately one-half to three quarters of the backing surface is covered with abrasive grains (Clark et al., 1987). Open coat configuration is more resistant to loading and has more flexibility for sanding curves and intricate shapes however; in general, it removes less material and wears out faster than closed coat configuration.
Figure 3.3 shows a loaded (clogged) abrasive belt after performing the sanding operation.

![Figure 3.3. Loaded (left) and new (right) sandpaper.](image)

As can be seen from figure 3.3, during sanding, the dust tends to clog up the face of the sandpaper. When the sandpaper clogs up, it does not cut freely and sanding efficiency is greatly reduced. Open-coated is less likely to clog than closed-coated. This tendency is worse in some species of wood than in others. It is also aggravated by species, such as pine, that have sticky resin content (Clark et al., 1987). This clogging phenomenon significantly affects the sanding process.

Abrasives belts are fabricated from roll material, which is made endless when joined by a splice. Belts vary in width from 1/4 to 100 inches and can be almost any length.

There are four basic steps followed in bonding the abrasive grains to a large roll of paper or cloth. They are as follows (Clark et al., 1987):

1. A printer prints the trademark, brand name, mineral, grade number, backing designation, etc. on the backside of the backing.

2. A carefully regulated coating of adhesive is applied that will vary in concentration and quantity according to the particle size of the mineral to be bonded.
3. The selected abrasive grains are applied by either a mechanical or an electrostatic method. The product is then carried through drying ovens.

4. A second application of adhesive, called the sizing coat, is made. After drying, the coated goods are wound into large rolls to await subsequent conversion into marketable forms of coated abrasives.

The common adhesives used in bonding are principally hide glues, urea resins, and phenolic resins. The first coating of adhesive is called the "make" coat and usually consists of a high-grade animal hide glue. The second adhesive coating is called the "sizing" coat and is usually one of the resins. The use of resin in the size coat results in a more heat-resistant bonding system. Where the abrasive grain is subjected to a high level of mechanical shock, the resins are used for both the make and size coats. Phenolic resins are used to make waterproof papers that are used with rubbing lubricants. Hide glue is used for both make and size coats only when extreme flexibility is desired (Clark et al., 1987).

3.2 Abrasive Machining Processes

Abrasive machining involves material removal by the action of hard abrasive particles (Groover, 1999).

In general, abrasive machining is the process of removing material by the cutting action of abrasive mineral in order to obtain a final surface or a desired shape. Abrasive machining is important not only due to its complexity, but also it is normally the last step before finishing. Defects from the sanding process will be accentuated on the final finish causing higher costs in material, labor, and equipment for the required rework.

Abrasive machining processes are difficult to characterize. The randomness in the
distribution of the mineral on the abrasive belt and the shape of the mineral, the large amount of variables to be considered that affect the process, and the wide variety of minerals, backing and coats combinations make the process difficult to model and predict mathematically. Additionally, the complexity of the characterization of the abrasive machining processes increases when the material to be processed is wood. Density variations, moisture changes, defects, resins, and other substances in the wood can significantly affect the performance of the abrasive and introduce large variations in experimental work.

Thus, the combination of controllable and non-controllable variables of both the wood and the abrasive machining process per se make the characterization a complex task that needs special attention and careful study and analysis. In the woodworking industry, outward appearance and surface quality of the final product is often the first and last thing that a potential customer notices. Sanding is, therefore, an essential process in the woodworking industry. It is also one of the most costly.

According to Stewart (1970), the abrasive machining of wood requires six times the amount of energy that is required to machine with a knife in a comparable operation. This correlates to a reduction in machining efficiency, and an increase in energy consumption. The expense of the abrasive is also extremely costly. According to industry experts, many companies spend more than twice the cost of a sanding machine in purchasing abrasives annually.

### 3.3 Abrasive Machining Equipment

The selection of the equipment to perform the sanding process depends mainly on the geometry and size of the workpiece, the final surface quality and the processing rate required.
Abrasive machining equipment can be classified into two large groups depending on the geometry of the workpiece.

According to Ratnasingam and Scholz (2003) the most common abrasive machining equipment for sanding flat surfaces are the wide belt sander, stroke sander, edge sander and disk sander. On the other hand, the most used equipment for contoured surfaces are the drum sander, brush sander, mould sander, carving sander, and turning sander.

Belt sanders are the most common abrasive machining equipment used in the wood industry. They use a continuous belt of abrasive material. Belts run over a drive pulley at one end and an idler pulley at the other. Most small shop belt sanders\(^3\) have an adjustment feature that keeps the belt tracking properly. Some sanders offer a design feature that automatically maintains the belt in the center of the pulleys during operation to eliminate belts that wander off the pulleys and require regular readjustment.

Typical setups of a belt sander are showed in figure 3.4. It is also important to note that belt sanders can be fed manually or fully automated, and can have different belt sizes depending on the final applications and the capacity required.

Figure 3.4 shows the common forms in which a workpiece can be sanded depending on the configuration of the machine and the orientation of the sanding process.

Belt sanders have been used for heavy material removal rate and for light sanding applications in which the workpiece is pressed against the belt to remove small quantities of material and to produce an improved final surface.
Industry uses, in general, combinations of small sanders along with wide belt sanders depending upon the type of work that needs to be performed.

Wide belt sanders are manufactured in a large variety of models based on the needs of the market and the technology available. According to Ratnasingam and Scholz (2003), wide belt sanders are considered the most important machine on the factory shop floor. There are several configurations of wide belt sanders depending on the operations to be performed. In general, wide belt sanders have a series of sanding heads (solid rolls and platen) to thickness and smooth flat parts. Koch (1985) summarized them into Multi-head, double deck, abrasive machining for thicknessing and smoothing both sides of the workpiece, and single deck machines designed for cutting down and polishing.

Stroke sanders are used to remove scratches left by previous sanding operations and to prepare the surface for the next process such as finishing. The machine consists of a horizontal flat bed with one or more narrow belts. The belt is brought into contact with the workpiece by a pressure pad that reciprocates along the belt while the operator pushes the
worktable under the belt to perform the abrasive action (Koch 1985 for more details).

Edge sanders are mainly used to machine a flat surface on the edge of the workpiece (Koch, 1985). It consists of an abrasive belt that runs around a pulley on the top end of a vertically mounted drive motor and then to an idler pulley on the opposite end of the machine (Clark et. al. 1987). Most edge sanders are manually fed but can also be equipped with power feed and a tilting belt to permit sanding of edge bevels (Koch, 1985).

Disk sanders consist of a worktable set across the face of a revolving plate to which coated abrasive disks are attached by adhesive or sometimes by mechanical clamps. The machine is adapted for bevel and angle sanding, end grain sanding, and sanding drawers and square portions of turned legs and posts (Koch, 1985).

Drum sanders are a cantilever pulley or drum, with a coated abrasive that rotates around a horizontal axis (Koch, 1985). A version of the drum sander is the pneumatic drum sander that is a simple but effective machine for sanding irregular shapes and contours. An inflatable rubber drum is mounted on a motor spindle and held in place by two metal collars. An air valve through one-collar permits inflating the drum to any desired pressure. The inflated drum results in a pliable, cushioned surface that conforms to the shape and surface of the parts to be sanded. The degree of inflation controls the hardness or softness of the drum (Clark et. al. 1987).

Brush sanders are designed to sand contoured, carved, or turned parts. It is suitable for light sanding and polishing, but is not too effective in removing knife marks. The sander consists of a number of brushes in holders spaced around the periphery of the wheel. Centrifugal action and the stiffening effect of the brushes causes the shredded tips of the abrasive to reach into grooves and depressions in the workpiece (Koch, 1985).
Mould sanders are designed to accommodate moulded edges machined by a shaper or moulder head. The abrasive belt must be brought into contact with the profiled area to be sanded. This is normally done with a pressure block that has been shaped to the reverse contour of the profile (Clark et. al. 1987). The most common mould sanders are a formed-block sander (a formed hand block is held against the belt and moved along the workpiece), a formed-wheel sander (a belt is made to rotate around a formed, idle contact wheel) and an abrasive impregnated wheel (a wheel is formed from nylon fiber coated with abrasive grain).

Carving sanders are used to sand carvings, which by nature are very difficult and time consuming. The abrasives are fastened to spindles that can be horizontal or mounted on air or electric powered hand drills. The abrasives are usually in disk form and made of flexible cloth in which the sanding is done by the outer points that present a soft, resilient sanding surface that can get into the intricate recesses of the carving without damaging the detail (Clark et. al. 1987).

Turning sanders are used to sand turnings. Sanding machines for turnings can be classified into two classes, workpiece-centered and centerless. The centerless spindle sander is designed for centerless sanding of straight, tapered, round or oval turnings. A first belt is used to cut down and smooth the turning and the second performs a polishing (Koch, 1985). In the workpiece-centered, the sanding is accomplished by spinning the turning at high RPM’s against stationary abrasives (Clark et. al. 1987).

Abrasive planers are designed for heavy material removal while smoothing oversized material such as lumber, particleboard, plywood as well as others. The need to machine rough lumber to thickness calls for a very aggressive cutting action and substantial cutting power and feed-works adaptable to warped lumber (Koch, 1985). Abrasive planers must not
be confused with wide belt sanders; the objective of the abrasive planer is to remove material to make a uniform thickness ( thicknesser) in contrast to the objective of the wide belt sander, which is to make the surface flat and smooth prior to the finishing processes (Clark et. al. 1987). The abrasive planer is a heavily built and powerful machine that uses coarse sanding belts instead of knives to accomplish the planing operation to obtain a uniform thickness (Clark, 1987). Abrasive planers are often double deck, simultaneously machining both top and bottom of the wood in one pass (Koch, 1985). Through the years, abrasive planers have experienced some operational difficulties due to the large cuts, which result in high power consumption, high belt consumption (resulting in increased total set up time, high cost of the belts, etc.), slower feed rates than the knife planer, and the large amount of dust as compared to knife planers, which increases the danger of fire.
4. BACKGROUND RESEARCH

The current research required a comprehensive understanding of the abrasive machining process for wood. Years of work were devoted to becoming familiar with the abrasive machining process, process material removal characteristics, surface quality evaluation, and the influence of factors that affect the machining process. A full factorial experimental design was developed by Saloni 2003 in order to (1) gain a better understanding of the variables that most significantly affect the material removal rate, surface quality, and power consumption and (2) determine the combined effect of parameters such as interface pressure, wood species, abrasive type and size, and belt speed. The relationships and interactions of these parameters on material removal rate, final surface roughness, and power consumption for three different grain sizes were determined via these experiments. The data analysis (Saloni 2003) established the statistical significance of the variables and their interactions.

The research results were based primarily on monitoring of the abrasive condition via the monitoring of loading and belt life. Results indicate that material removal rate can be changed by modifying the belt workpiece interface pressure level, the abrasives material, and the machining feeds and speeds. Power consumption increased linearly when pressure was increased, however, power consumption remains fairly steady for the same pressure and belt speed levels regardless of the type of abrasive or wood species (for the levels tested). Surface roughness values were higher (rougher) for aluminum oxide abrasive as opposed to the silicon carbide abrasive for both hard maple (Acer saccharum) and eastern white pine (Pinus strobus). In most cases, a high belt speed produced a better final surface quality than a low belt speed. Statistical analysis showed that most of the variables were statistically significant
(Saloni 2003) at the levels studied, however, only a few interactions between variables were significant.

The experiments led to the identification of the major problems associated with the abrasive machining process and the main variables, which must be focused on in order to improve the machining process. As a result of this process improvement phase, the need for monitoring and control of the machining process became evident and is an integral part of this research.

In this work, two related issues were analyzed in detail; belt loading represents the amount of wood dust and wood resin melted accumulation on top of the abrasive belt and belt life is defined as the status of the abrasive belt when is not able to adequate remove material due to worn out of the abrasive mineral.

4.1 Belt Loading Monitoring Using Optical Sensors

Belt loading was analyzed and monitored using various optical measurement techniques. These included three sensor types including: a CCD camera, an intensity detector (Wenglor® @ www.wenglor.com), and an optical contrast detector (R55 Expert™ by Banner® @ www.bannerengineering.com). The contrast detector is similar to a camera except that on-board electronics determine the average gray scale intensity of the surface. This type of detector is inexpensive and eliminates the need for image analysis software (which is needed by the camera system). The disadvantage of the contrast detector is that it has to be placed very close (within 0.4 in - 10 mm) to the surface being evaluated. The intensity detector can have an offset distance up to 7.8 in (200 mm). This would make the implementation of the intensity detector much easier in an industrial environment.
Figure 4.1 shows a photograph of the three types of sensors; including two types of CCD cameras (a standard consumer Camcorder and an industrial black and white machine vision camera), an intensity detector, and a contrast detector. These are the main optical sensors used in the experimental work to monitor the abrasive machining process and evaluate the extent of loading.

![Figure 4.1. Sensors for determination of wood loading resulting from abrasive machining (clockwise: consumer camcorder, Banner® contrast detector, Wenglor® intensity detector, industrial CCD camera).](image)

In the initial testing, the surface of the abrasive was observed with each sensor while the belt was in motion but not in contact with the workpiece. This experiment was designed to determine if it is possible to continuously monitor the abrasive belt with the belt moving. The experiment consisted of placing a 3 x 4 inch (76 x 102 mm) piece of southern yellow pine on a standard 6 x 48 inch (152 x 1219 mm) belt abrasive machine. A weight was placed on top of the specimen to provide the desired machining pressure.

Figure 4.2 shows a comparison of the results for the three sensor types at various stages of the abrasive machining process. In this experiment, 0.75 lb/in² (5.17 kN/m²) of

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pressure was used and a P100 aluminum oxide belt was used. The specimen and weight were placed on the machine for 3 minutes and then removed.

![Figure 4.2. Comparison of normalized outputs from three detector types.](image)

As can be seen from figure 4.2, the output of the intensity detector (Wenglor®) did not change in magnitude as much as the other detectors due to abrasive loading. The Wenglor® intensity detector, while not offering the greatest change in signal output for a change in abrasive belt loading, offered the lowest experimental variation. Another advantage of the Wenglor® sensor is that post processing of the sensor output (such as image analysis) is not required. Though the image intensity from the CCD camera can be obtained in real time, in this experiment it was obtained off-line using SigmaScan™ image analysis software (www.sigmascan.com).
The Banner contrast detector showed the highest sensitivity with changes in the loading; with the signal strength increasing 39.81 percent from new to semi-used and 43.52 percent from semi-used to used, resulting in a total range of 83.33 percent, and also provided the largest loading range between new and used.

This research also showed that optical sensors can be used effectively to evaluate the loading on abrasive belts; however, they are not a good predictor of the belt wear. Despite the finding, that belt wear (discussed in the next section) is not directly detectable by optical sensors, the life of the belt can be improved by detecting the loading and then cleaning the belt at preset (known) loading levels. The main disadvantage of the optical sensors in general is the low accuracy and high variability in the measurements.

The Wenglor® intensity detector appeared to be the best option among the sensors evaluated; providing the lowest experimental variation, an adequate sensitivity in signal output for a change in abrasive loading, and requiring no post processing of the output signal.

Further investigation revealed new developments and technologies in optical color detectors. According to Letterle (2001), this new generation of color sensors is able to generate an output indicating intensity and the “intensity” of each color. The ColorMax 1000 color sensor from EMX Industries, Inc. was also tested to evaluate its capability in detecting loading of the abrasive machining belts.

Figure 4.3 shows the output of the ColorMax1000 sensor during abrasive machining using an aluminum oxide P150 belt.
Figure 4.3. ColorMax 1000 sensor output levels as a function of time.

Figure 4.3 shows that the red color showed the highest change in signal and was the most sensitive to changes in the loading during machining.

Figure 4.3 illustrates that the red color output decreased considerably (from 50% to 41%) when the abrasive machining first started and then after about sixteen minutes, decreased more slowly and became nearly constant at about 40%. This result demonstrates that the sensor measurement is repeatable since it did not significantly change during the experiment when its location was kept constant relative to the belt. However, the sensor was not sensitive to changes in the loading after the initial contact with the workpiece.

Based on figure 4.3 it can be concluded that the red color was the most significant color to use as a predictor of the presence of loading.
Figure 4.4 shows the red color output comparison for aluminum oxide P220 and P150 for abrasive machining (2600 ft/min – 217 m/min and 1.25 ft/in² – 8.62 kN/m²).

Figure 4.4. ColorMax 1000 sensor red color output comparison for P150 and P220 aluminum oxide belts.

Figure 4.4 shows that the red color output (loading indicator) was not appreciably affected by the grain size. In addition, figure 4.4 verified the repeatability of the sensor detecting the presence of loading (represents the moment in which wood dust started building up on top of the abrasive belt) but it was not sensitive to degree of loading (defined as the accumulation of wood dust and wood melted resin on top of the abrasive machining belt that covers the abrasive mineral).

Figure 4.5 shows a comparison between different types of abrasive minerals; aluminum oxide and silicon carbide for abrasive machining with P220 belts.
Figure 4.5 shows that there was not a considerable difference in the red color output (which is correlated to the amount of wood embedded in the belt when different types of minerals were used. It is seen that the red color percentage for silicon carbide was lower than aluminum oxide during the beginning of the machining process and then stabilized. This can be explained by the fact that silicon carbide (black color) has a lower amount of red that aluminum oxide (dark red color). After the initial machining when the loading first occurs, the belt is covered with wood dust and the sensor starts detecting more of the wood particles (loading) and less of the background color (color of the belt).

Further investigation of the effect of machining variables for the ColorMax 1000 sensor output led to figure 4.6, which compares the red color percentage for abrasive machining particleboard and pine using an aluminum oxide P150 belt.
Figure 4.6 shows that the ColorMax 1000 sensor was slightly more sensitive in
detecting the changes in the loading level when machining pine than particleboard. However,
the signal did not appear to be sensitive to different overall loading levels during the
machining.

One of the objectives of detecting loading is to determine the appropriate time to
perform belt cleaning. Thus, additional experimentation was performed to determine the
capability and sensitivity of various sensors in evaluating belt cleaning.

Figure 4.7 shows the red color percentage average when different cleaning materials
(media) were used for abrasive machining (2600 ft/min – 217 m/min and 1.25 ft/in² – 8.62
kN/m²).
Figure 4.7. ColorMax 1000 sensor red color output comparison when applying different cleaning media.

Figure 4.7 shows that there was a change in the red color percentage average when a cleaning process was applied. Walnut shell cleaning media (consisting of granulated 150 microns walnut shell) showed the best performance in reducing the loading, which correlated well with the material removal rate average data and the life of the belt. It is also observed from figure 4.7 that the change between media type was not significant and confirmed that the ColorMax 1000 sensor was not sensitive to loading changes during the machining process for the set up in this experiment. Additional investigations of the output of the ColorMax 1000 sensor involved the effect of different levels of loading on belts.

Figure 4.8 shows the colors output from the ColorMax 1000 sensor based on the condition of the abrasive machining belt for four loading levels at four different locations on the belt when machining pine with aluminum oxide P150 for abrasive machining (2600 ft/min – 217 m/min and 1.25 ft/in² – 8.62 kN/m²).
Figure 4.8 shows that different loading levels generated different color output percentages. The red color percentage varied from 49% when the belt was new to 39% when a heavy loading was present on the belt. This result shows that the color sensor has potential in detecting loading level. As with any sensor, in order to be effective, the sensor must traverse the belt continuously in order to correctly monitor the status of the belt loading during abrasive machining since localized loading occurs more often than a uniform loading, as shown in figure 4.9.
Figure 4.9. Photograph of localized loading on an abrasive belt.

4.2 Belt Life Monitoring Using Acoustic Emission and Vibration Sensors

As discussed in the literature review, Acoustic Emission (AE) and vibration sensors have been used extensively to monitor tool wear and tool life for cutting tools. Abrasive belt life was monitored by Lemaster et. al. (1993) and Matsumoto and Murase (1995, 1997 and 1998) using acoustic emission sensors. In the current research, three AE sensors were utilized, including a contact wide band AE sensor (see appendices), a contact narrowband resonant AE sensor (see appendices), and an air coupled narrowband resonant AE sensor (see appendices). These AE sensors were evaluated for effectiveness based on monitoring of the machining parameters. Broadband AE sensor and vibration sensors with a wide frequency range were used to determine the typical frequency range of the process as well as provide insight into the most effective combination of band pass filters.
Figure 4.10 shows a power spectrum analysis of the AE signals for a contact wide band AE sensor attached to the workpiece holder.

Figure 4.10 clearly shows the highest peak of the signals to be between frequencies of 30 kHz and 40 kHz.

The results from the vibration sensor measurements (see appendices) are shown in figure 4.11. As for the case of the AE signals, the highest peak of the vibration signals was between frequencies of 30 kHz and 40 kHz.
Once the optimum configuration of the contact wide band AE sensor and the accelerometer sensor were determined, a preliminary experiment was conducted in order to determine the most appropriate sensor to continuously monitor the machining process. This determination was based on technical feasibility, performance and sensitivity in detecting changes in the signal as the abrasive belts wear. Based on research developed by Carrano (1997) and Saloni (2003), the initial sets of operating conditions were belt speed 2600 ft/min (217 m/min), interface pressure 1.25 lb/in² (8.62 kN/m²), silicon carbide and aluminum oxide abrasive materials with grain sizes of P100, P150 and P220. Particleboard was used to
accelerate the belt wear since this type of material has been shown to be cause extreme wear. These same machining conditions were used in figure 4.12 through figure 4.37.

Figure 4.12 shows the root mean square (RMS) values of the acoustic emission signal for abrasive machining for the contact wide band AE sensor with an operating frequency range of 20 kHz- 1000 kHz. The contact wideband AE sensor was used to determine the predominant frequency band of the AE signal of the process in order to select a suitable contact or non-contact resonant AE sensor to reduce cost and optimize the measurement.

Figure 4.12. Acoustic emission RMS signal for contact wideband AE sensor for abrasive machining (sensor was located on the workpiece holder).

Figure 4.12 shows that the change in the acoustic emission signal for the wideband sensor was relatively small for the period of time studied. In spite of the continuous increase in the signal, which could be an indicator of the belt wear, changes in signal were relatively small. This could affect the accuracy of the sensor in predicting the condition of the belt (the drop in signal observed at minute 24 was due to the process of changing to a new workpiece,
which adversely affects the machining related signal). This investigation led to the testing of a 30 kHz to 40 kHz band pass sensor to evaluate the feasibility of using acoustic emission sensors to monitor the belt life.

Figure 4.13 shows the RMS acoustic emission signal for the abrasive machining for the air coupled resonant AE sensor. These experiments were aimed at determining if the sensor’s frequency range was appropriate and sensitive enough to measure small changes in abrasive belt wear.

Figure 4.13 shows that the signal decreased continuously (the abrupt increase in the signal at minute 13 was due to replacing the workpiece sample.) during the execution of the abrasive machining experiment. This sensor was different from the wideband sensor in that
it was designed for air coupling with a resonant frequency of 40 kHz. This acoustic emission sensor was able to detect smaller changes in the signal throughout the abrasive machining process. Based on the experiment it was concluded that the air coupled resonant AE sensor would be well suited for use in evaluating the life of the abrasive belt.

As discussed in the literature review, despite the great potential of acoustic emission sensors to monitor belt life, one of the biggest disadvantages of the acoustic emission sensors involves location and attachment of the sensor. This disadvantage is very apparent for the abrasive machining process due to the abrasive belt rotating at relatively high speeds. Based on the preliminary result that acoustic emission sensors can be used effectively to monitor the condition of the abrasive belt and the fact that location is an issue, an air coupled resonant AE sensor was tested based since its location requirements are less stringent.

The accelerometer sensor discussed earlier was also included in these evaluations. Figure 4.14 shows the RMS value of the signal output for the vibration sensor located under the belt platen (surface supporting the abrasive belt) to continuously monitor the abrasive belt condition. This sensor was held in place with a magnetic base attached to the faceplate of the sensor.
It can be seen from figure 4.14 that the accelerometer signal decreased during the experiment until a new part was machined while caused an abrupt increase in the signal. The signal also showed a small amount of variability, which could cause sensitivity and accuracy problems if used in a process control scheme. Thus, while monitoring machine vibration did show some sensitivity to changes in the wear of the abrasives, the variability of the signal and low sensitivity to these changes would limit the implementation of this type of sensor for monitoring the status of the abrasive belt condition.

Figure 4.15 shows a comparison in the RMS signal between a contact wide band AE sensor, an air coupled resonant AE sensor, and an accelerometer.
Figure 4.15 shows that the signals from both the contact wide band AE sensor and the accelerometer showed decreasing trend during the abrasive machining process (abrasive belt wear), however, the change in the signal with time was very small. As stated previously, the air coupled resonant AE sensor showed the greatest change with time. The contact wide band AE sensor and the vibration sensor signal decreased as well as the signal from the AE air coupled sensor.

As a result of this research, it can be concluded that both acoustic emission and vibration sensors could be used to monitor the status of the abrasive belt life with the proper selection and location of the sensor. Based on this research, the air-coupled resonant AE sensor proved to be the most sensitive for monitoring the life of the abrasive belt.
Figures 4.16 and 4.17 show the RMS values of the contact resonant AE sensor signal when machining particleboard with silicon carbide P100 with the machining parameters the same as defined in the previous explanation of the experimental design.

Figure 4.16 shows that the contact resonant AE sensor had a higher sensitivity than the contact wide band AE sensor. Figure 4.16 shows large peaks in the signal each time the workpiece was replaced. (the sensor was attached to the workpiece part holder which caused considerable changes in the AE signal level each time the workpiece was changed). However, the signal between workpiece changes showed specific trends that can be used to predict the status of the abrasive belt.
Figure 4.17 shows the RMS AE signal from an air coupled resonant AE sensor. This sensor has been shown to be sensitive to the status of the abrasive belt life as discussed previously.

![Figure 4.17. RMS of the signal from the air coupled resonant AE sensor when abrasive machining.](image)

Figure 4.17 shows that the air coupled resonant AE sensor was also sensitive to workpiece changes showing large peaks every time a workpiece was replaced. Nevertheless, similar to the contact resonant AE sensor, a specific trend of the acoustic emission signal could be observed between workpiece changes, which can be correlated to the abrasive belt wear.

Figures 4.16 and 4.17 verified that acoustic emission sensors can be used to monitor the status of the abrasive belts at the levels studied. However, additional research needs to be
performed to verify whether the sensing technique is able to be consistent and can continuously monitor the status of the belt regardless the type of abrasive or the grain size.

Figure 4.18 shows the acoustic emission RMS signal from a contact resonant AE sensor when machining particleboard with silicon carbide P150 belt. In this case, the sensor was placed on the back of the belt platen. This was done in order to try to reduce the effect of changing the workpiece exhibited in the previous figures.

![Figure 4.18. RMS voltage of the AE signal for a contact resonant AE sensor when abrasive machining with silicon carbide P150 belt (sensor was located on the workpiece holder).](image)

Figure 4.18 shows that the acoustic emission signal decreases and fluctuates during the beginning of the machining. This behavior is attributed to the high signal generated from the grains breaking during the first minutes of the machining process. After this initial “break-in” period, the signal exhibited a stable period where the signal did not change until
after approximately 26 minutes after which the signal began increasing for the remainder of the experiment. This is a clear indication that the AE signal increases as the belt wears.

Figure 4.19 shows the acoustic emission RMS signal from an air coupled resonant AE sensor when machining particleboard with silicon carbide P150 belt.

Figure 4.19. RMS signal for an air coupled resonant sensor for abrasive machining with silicon carbide P150 belt.

Figure 4.19 shows that the acoustic emission signal for the air coupled resonant sensor dropped drastically during the first 10 minutes of machining and then stabilized until around minute 26. After the stabilization occurred, the signal continuously increased for the rest of the abrasive machining time. Similar to the contact resonant AE sensor, this signal could be used as an indication of the abrasive belt life.
Figure 4.20 shows the acoustic emission RMS signal comparison between both the contact resonant and the air coupled resonant AE sensors when machining particleboard with silicon carbide P150 belt.

![Graph showing RMS signal comparison between contact resonant and air coupled resonant AE sensors.](image)

**Figure 4.20. Comparison of RMS signal using contact resonant and air coupled resonant AE sensors for abrasive machining with silicon carbide P150 belt (sensor was located on the workpiece holder).**

Figure 4.20 shows that both sensors exhibited a similar trend of the AE signal in which, there was an initial drop during the beginning of the abrasive machining process, a stabilization period and then a continuous increase of the signal after the stabilization period. Figure 4.20 also shows that the air coupled resonant AE sensor had a more variable but stronger signal than the contact resonant AE sensor at the beginning of the abrasive machining process, however, the AE signal for the contact resonant AE sensor continuously
increases and becomes higher than the air coupled resonant AE sensor as the abrasive belt wear progresses.

Figure 4.21 shows the acoustic emission RMS signal air coupled resonant AE sensor when machining particleboard with aluminum oxide P150 belt.

![Graph showing the acoustic emission RMS signal of a contact resonant AE sensor during abrasive machining with aluminum oxide P150.](image)

**Figure 4.21. RMS signal of contact resonant AE sensor when abrasive machining with aluminum oxide P150 (sensor was located on the workpiece holder).**

Figure 4.21 shows that the AE signal continuously increased as the machining process continues. Figure 4.21 also shows that the AE signal is sensitive to workpiece changes, which can be observed at minute 15 and 43. It is important to note the erratic behavior of the acoustic emission signal during the first 10 minutes of the experiment again demonstrated that the AE technique is sensitive to the breaking of the grains during the beginning of the abrasive machining process regardless of the type of mineral that is being used. In addition, as observed when the silicon carbide mineral was used, a period of
stabilization was observed until minute 27, after which, the acoustic emission signal increased providing a clear indication of the condition of the belt during the abrasive machining process. It is believed that the stabilization period before 27 minutes for the silicon carbide mineral was due to the silicon carbide being harder than aluminum oxide and wood not being hard enough for the grains to break apart and sharpen itself. The grains can still get dull and the abrasive load up when machining.

Figure 4.22 shows the RMS value of the AE signal from an air coupled resonant AE sensor when machining particleboard with silicon carbide P150 belt.

![Figure 4.22](image)

**Figure 4.22. RMS signal for air coupled resonant AE sensor for abrasive machining with aluminum oxide P150 belt.**

Figure 4.22 shows that the acoustic emission signal from the air coupled resonant AE sensor is again sensitive to the changing of the workpiece as discussed previously, however, in this case, the signal decreased during the abrasive machining process, which is contrary to
the trend observed when machining particleboard with silicon carbide P150. This continuous decreasing trend could be used to determine the status of the abrasive belt, however, further investigation of the signal behavior is necessary to clarify this opposite trend between mineral types which was not observed with the contact resonant AE sensor.

Figure 4.23 shows the comparison between the RMS values of the AE signal for both contact resonant and air coupled resonant AE sensors when machining particleboard with aluminum oxide P150 belt.

Figure 4.23 shows that the AE signal from the contact resonant AE sensor increased continuously while the AE signal from the air coupled resonant AE sensor signal decreased.
Both sensors showed sensitivity to workpiece changes. In addition, the AE signal from the air coupled resonant AE sensor exhibited a higher variability, as observed in previous experiments.

Figure 4.24 shows the acoustic emission RMS signal from contact resonant AE sensor when machining particleboard with aluminum oxide P220 belt. For this experiment, the sensor was placed on the backside of the belt platen.

The AE signal from the friction of the belt across the platen did not appear to be significant; the AE signal from the actual abrasive machining process was much more significant.

![Figure 4.24. RMS signal for contact resonant AE sensor mounted on the backside of belt platen while abrasive machining with aluminum oxide P220 belt.](image)

Figure 4.24 shows that the RMS value of the signal of the contact resonant AE sensor exhibited an erratic behavior during the first 10 minutes of machining. Then, a stabilization
period was observed until minute 18. After this period, the signal continuously increased during the remainder of the machining process. This behavior was consistently observed with different mineral type and grain sizes.

Figure 4.25 shows the RMS value of the AE signal for an air coupled resonant AE sensor when machining particleboard with aluminum oxide P220 belt.

![Graph showing RMS values of the air coupled AE sensor](image-url)

**Figure 4.25. RMS values of the air coupled AE sensor when abrasive machining with aluminum oxide P220 belt.**

Figure 4.25 shows a behavior observed in previous experiments in which there is an erratic signal behavior during the beginning of the machining process followed by a stabilization zone and then a continuous increase of the acoustic emission signal during the abrasive machining process. In this case, the acoustic emission signal increased which is in contrast with the signal obtained when machining particleboard with aluminum oxide P150.
Figure 4.26 shows a comparison of the RMS value of the AE signal between the contact resonant AE sensor and the air coupled resonant AE sensor when machining particleboard with aluminum oxide P220 belt.

Figure 4.26. Comparison of the RMS AE signals for a contact resonant AE sensor and an air coupled resonant AE sensor for abrasive machining with aluminum oxide P220 belt.

Figure 4.26 shows that both sensors (contact resonant AE sensor and air coupled resonant AE sensor) produced a similar trend of the acoustic emission signal but at different levels. Thus, three well-defined trends can be observed, with the grains breaking at the beginning of the machining process, a stabilization zone, and after stabilization a continuous increase of the signal during the abrasive machining process. As observed before, the acoustic emission signal from the air coupled resonant AE sensor exhibited higher variability than the contact resonant AE sensor. However, in this case, the signal for the AE air coupled
resonant AE sensor was weaker than the contact resonant AE sensor as was observed previously.

In order to have a better understanding of the most appropriate sensor and facilitate the sensor selection, further comparison of mineral type and grain size on the sensor signal levels was performed.

Figure 4.27 shows a comparison of the RMS signal level for the contact resonant AE sensor when machining with both silicon carbide and aluminum oxide belt.

![Figure 4.27](image_url)

**Figure 4.27.** Comparison of the RMS signal level for the contact resonant AE sensor when machining with both silicon carbide and aluminum oxide P150 belts.

Figure 4.27 shows that the AE RMS signals, for machining with both aluminum oxide and silicon carbide belts, are similar and exhibit the three main stages described previously. The signal showed an erratic behavior due to grains breaking during the first minutes of the machining, then a stabilization zone, followed by a continuous increased
signal, which clearly shows the status of the condition of the belt life. However, these stages occurred at different times and for different durations. In addition, figure 4.27 also shows that the AE signal for the contact resonant AE sensor was always higher when machining with aluminum oxide, and was affected by workpiece changes. This effect of workpiece changes can be observed by the changes in the signal when an aluminum oxide belt was used. The silicon carbide belt did not require as many workpiece changes as aluminum oxide. This is explained by the fact that aluminum oxide mineral, in general, removed more material than silicon carbide under the same machining conditions (see Saloni 2003).

Figure 4.28 shows a comparison of the RMS value of the AE signal when using an air coupled resonant AE sensor when machining with silicon carbide and aluminum oxide belts.

![Graph](image)

**Figure 4.28.** Comparison of the RMS value of the AE signal when using an air coupled resonant AE sensor and machining with aluminum oxide and silicon carbide P150 belts.
Contrary to the behavior observed for the contact resonant AE sensor, the AE signal for the air coupled resonant AE sensor exhibited different trends when machining with silicon carbide and aluminum oxide as seen in figure 4.28. Thus, the signal decreased during machining with aluminum oxide but increased when machining with silicon carbide (similar to the trend when using the contact resonant AE sensor). This is an indication that the air coupled resonant AE sensor might produce unpredictable behavior that might cause problems when defining belt status parameters and thresholds.

In addition, observation of figures 4.27 and 4.28 clearly shows that the AE signal from the contact resonant AE sensor had a lower variability than the air coupled resonant AE sensor.

Figure 4.29 shows the comparison of the RMS signal values for the acoustic emission signal for two grain sizes (P150 and P220) for aluminum oxide belts.

![Figure 4.29. Comparison of the RMS signal for the contact resonant AE sensor for two grain sizes (P150 and P220) of aluminum oxide belts.](image)
Figure 4.29 shows that the acoustic emission signal produced by the contact resonant AE sensor exhibited the behavior discussed before with the three well-defined stages, grains breaking, stabilization, and continuous increase. In addition, the AE signal was shown to be sensitive to workpiece changes that can be observed in figure 4.29 when machining with grain size P150 on minutes 15 and 43. Figure 4.29 also shows that the acoustic emission signal for the grain size P220 was higher than for the grain size P150 (after the erratic and stabilization zones). The slope, however, of the trend of the AE signal for P150 was steeper than the AE signal for P220 throughout the experiment, however, the changing of the workpiece for P150 caused a discontinuity in the trend of the AE signal that makes the interpretation of the slope difficult.

Figure 4.30 shows the comparison of the RMS value of the AE signal for machining with aluminum oxide with P150 and P220 using an air coupled resonant AE sensor.

![Graph showing comparison of RMS signals for P150 and P220](image)

Figure 4.30. Comparison of the RMS signals for the air coupled resonant AE sensor for machining with aluminum oxide with two grain sizes (P150 and P220) for aluminum oxide belts.
Figure 4.30 shows that the trends for the AE signals were opposite for the two grain sizes (P150 and P220) in the final stage (the signal during stage three increased when using the P220 grain size and decreased when using P150 grain size. This contradictory behavior was observed regardless of which of the two mineral types were used and is viewed as a major disadvantage of using the air coupled resonant AE sensor.

As it was previously explained, for the experiments discussed above contact resonant AE sensor was attached directly to the workpiece holder, which resulted in considerable variation in the AE signal from workpiece to workpiece. The effect of location of the sensor was investigated in an attempt to minimize the adverse effect on the AE signal of changing the workpiece. The additional experiments utilized a location, which was directly underneath the platen that supports the abrasive machining belt and in line with the contact area between the belt and the workpiece.

For this additional experiment, both acoustic emission sensors (contact resonant AE sensor and air coupled resonant AE sensor) were used in order to compare the signals and their capacity to monitor the belt condition during the abrasive machining process.

Figure 4.31 shows the RMS value of the acoustic emission signal from contact resonant AE sensor located under the belt platen for silicon carbide P150 belt.
Figure 4.31. RMS signal for the contact resonant AE sensor located under the belt platen for silicon carbide P150 belt.

Figure 4.31 shows that the AE signal from the contact resonant AE sensor increased continuously during the abrasive machining process and did not show a drastic change in the level of the signal when the workpiece was changed at minute 14 and 38. It is important to note that the sensor output can be also used as an indicator of problems during the machining process (note the impacts between the workpiece and the abrasive belt for minutes 38, 39, 40, 41, 42 and 43 which are possibly due to a new workpiece not being perfectly flat causing the workpiece to bounce and generate impacts between the workpiece and the belt. The impacts can be clearly seen in figure 4.31.

Figure 4.31 also illustrates that the signal was more consistent at the platen sensor location and was not as sensitive to the workpiece changes. The increase and decrease of the signal when a new part is processed was eliminated by positioning the sensor at this location. For purposes of this research, the first two stages of the belt wear process are not of critical
importance, so that the platen location for the sensor should be adequate to monitor the life of the abrasive belt.

Another important observation was that the acoustic emission signal was stronger for the platen location as compared to the workpiece holder location.

Figure 4.32 shows the comparison of the RMS signal for the contact resonant AE sensor and the air coupled resonant AE sensor when machining particleboard with silicon carbide P150 belt.

![Figure 4.32. Comparison of the RMS signal for the contact resonant AE sensor and the air coupled resonant AE sensor when machining particleboard with silicon carbide P150 belt (contact sensor placed beneath the platen).](image)

Figure 4.32 shows that the AE signal for the contact resonant AE sensor was stronger and more consistent than for the air coupled resonant AE sensor. Thus, it can be concluded that the locating the sensor beneath the platen provides better monitoring of the status of the
abrasive belt during machining due to a stronger and more consistent signal. The necessity of performing the detailed investigation of the location and coupling of the AE sensor is supported by many authors from literature review who indicate that the location of the acoustic emission sensor is extremely critical.

4.3 Belt Life Monitoring Using Temperature Sensors

Further investigations of process monitoring opportunities for abrasive machining indicated that continuously measuring the temperature of the process can give an indication of the loading of the belt. Temperature is one of the main factors that control the formation of belt loading, thus, monitoring and controlling the belt temperature could help improve the process.

During the abrasive machining process, some of the wood residue is embedded between the grains of the belt. Wood dust combined with wood resin create the loading condition. Loading reduces the amount of grains exposed to cut the wood thereby reducing the effectiveness of the belt to remove material which presumably would increase the belt temperature as a consequence of the higher friction.

According to Ratnasingan and Scholz (2004), the wood machining process can generate high temperatures (up to 356 °F - 180 °C in this work). Excessive heat during abrasive machining can negatively affect the process, weakening the wood significantly, and in some cases burnishing and/or burning the wood surface if the heat is not quickly dissipated (Ratnasingan and Scholz, 2004). High temperatures during the machining process can also promote the melting of the wood resin which can then cover the abrasive grains of the belt; and become part of the loading (The Wood Doctor’s Rx, 2001).
A preliminary experiment was designed to measure the interface contact temperature between the workpiece and the abrasive belt. To perform this experiment, a ThermoVision® A20V infrared camera by Flir™ (www.flir.com) was utilized. This camera measures thermal energy emitted from an object (in this case, the energy emitted from the belt). The camera measures temperature ranges of -20°C to +250°C (-4°F to +482°F), and +120°C to +900°C (+248°F to +1652°F). The accuracy (% of reading) is ± 2°C or ± 2%. The camera provides precise non-contact temperature measuring capabilities.

Figure 4.33 shows the results of the interface temperature between the workpiece and the abrasive belt during an abrasive machining process.

Figure 4.33. Interface temperature what method of measurement between workpiece and abrasive belt as measured by a thermographic A20V camera.
Figure 33 shows that the interface temperature between the workpiece and the abrasive belt increases quickly after the machining process begins and thereafter remains in the temperature range of 210 °F (99 °C) to 230 °F (110 °C).

It can be also seen in figure 34 that there is very little change in the interface temperature throughout the process, which is a clear indication of the lack of sensitivity of the camera for the detection of loading or abrasive belt life condition. It is noted that some temperatures were under the expected temperature range, due to delays in the replacement of the specimen, which allowed the belt temperature to decrease.

These investigations indicate that temperature measurements are not suitable for monitoring abrasive life or loading formation, however, they would be useful in setting and monitoring temperature limits in order to avoid wood surface burnishing/burning.

4.4 Evaluation of Abrasive Belt Cleaning Methods

As stated before, loading and high temperatures are two of the most important factors that affect the belt life. These factors have been identified by many authors in the past and efforts have focused on developing feasible and effective solutions. As explained previously, high temperatures during abrasive machining can not only burn the surface of the wood, but also can result in melting of the resins contained in the wood, which flows into the abrasive belt mixes with the wood dust produced in the process creating the abrasive loading. Loading causes premature failure, frequent changing of belts, and poor quality products.

Research in this focus area was designed to evaluate the performance of different cleaning methods.
4.4.1 Belt cleaning with abrasive media

Based on preliminary experimentation and manufacturers information the experimental design for these experiments involved six primary variables.

1. Six levels of cleaning media: Armex® (75-micron sodium bicarbonate crystal with water resistant flow additives), Contam-Away® (150-micron crystal of sodium bicarbonate blasting medium that contains no additives), pecan shell, compressed air, Nu-Life® gum “eraser”, and no cleaning),

2. One wood species: southern pine

3. Two abrasives: aluminum oxide P100 and P220,

4. One blasting angle: perpendicular to belt

5. One blasting distance: 4.0 inches (101.6 mm) from the nozzle to the belt,

6. One blasting pressure: 70 lb/in² (483 kN/m²) (based on previous results a lower pressure was selected)

Table 4.1 shows the effect of cleaning media on belt life and material removal rate.

**Table 4.1. Cleaning (blasting) media effect on belt life and material removal rate.**

<table>
<thead>
<tr>
<th>Media</th>
<th>Grain size (P220)</th>
<th>Grain size (P100)</th>
<th>Media Effect on belt life (% increase in belt life)</th>
<th>Material Removal Rate Average (in³/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Cleaning</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.2630</td>
</tr>
<tr>
<td>Contam-Away</td>
<td>38</td>
<td>128</td>
<td>38</td>
<td>0.3310</td>
</tr>
<tr>
<td>Pecan Shell</td>
<td>Lower than no cleaning</td>
<td>23</td>
<td>0.2700</td>
<td>0.7420</td>
</tr>
<tr>
<td>Air</td>
<td>Lower than no cleaning</td>
<td>No Significant</td>
<td>0.3230</td>
<td>0.5105</td>
</tr>
<tr>
<td>Nu-Life</td>
<td>15</td>
<td>50</td>
<td>0.1999</td>
<td>0.3529</td>
</tr>
<tr>
<td>Armex</td>
<td>23</td>
<td>Lower than no cleaning</td>
<td>0.3279</td>
<td>0.4490</td>
</tr>
</tbody>
</table>
As can be seen in table 4.1, the abrasive belt with the longest usable life was the belt cleaned with Contam-away™, which lasted 1.38 times longer for P220 and 2.28 times longer for P100 than the control belt, which was not cleaned. The material removal rate when the belts were cleaned was consistently higher than the control belt except for Nu-Life (for both P220 and P100) and Armex for P100. The belt cleaned with the Nu-life “Gum Eraser:” lasted 1.15 times longer for P220 and 1.50 times longer than the control belt for P100, but resulted in a lower material removal rate (MMR) than the control belt for both grain sizes. It was also observed during the machining process that residue from the cleaning material (gum) remained embedded in the grain after cleaning.

Table 4.1 also showed no significant differences in the overall belt life between the control belt, and the belt that was cleaned with compressed air. However, an increase in the MRR average was observed for both grain sizes. The belt cleaned with Armex®, lasted 1.23 times longer than the control belt for P220 but the belt life for P100 was lower than the control belt. Similar behavior was observed on the MRR in which the average MRR was higher for P220 but lower for P100.

Pecan shell results shown in Table 4.1 point out that, despite the belt life being less than the control belt for P220, it was higher for P100 by 23 percent and the MRR was higher for both grain sizes, resulting in the highest MRR of all medias for P100 (0.7420 in³/min). An interesting result was that unlike the P220 belt, the P100 belt cleaned with Armex® seemed to have been damaged by the cleaning media, lasting only 0.70 times as long as the control belt, resulting in a lower average MRR. This could be due to the fact that the P100 has larger grains that are more exposed to the blasting media, which could cause more damage to the abrasive.
Figures 4.34 and 4.35 show microscopic pictures of the structure of the belt. Discuss material belt and machining conditions

Figure 4.34. Microscopic picture with catastrophic failure of the “size coat” and damage on the “make coat” allowing the mineral to separate from the belt (magnification 40X).

Figure 4.35. Example of a failure of the “size coat” using a scanning electron microscope (magnification 100X).

Figure 4.34 shows a microscopic examination of a belt which revealed catastrophic failure of the “size coat” and damage on the “make coat”. This allowed the abrasive grains to loosen and dislodge from the belt (no mineral is visible on the belt as shown in figure 4.34). Figure 4.35 shows a high magnification scanning electron microscope image of the “size coat” leaving the abrasive grains exposed.

4.4.2 Blasting with Dry-Ice

Previous research (Saloni et. al., 2005 and Saloni et. al., 2006) has demonstrated the potential for using dry ice blasting as a method to remove loading and reduce belt temperature during abrasive machining processes. These experiments focused primarily on
material removal rate average, belt life, and belt temperature. Table 4.2 shows the experimental design for each of the factor level combinations (FLC) considered. Material removal rate and belt life were used as indicators to determine the effectiveness of the belt cleaning using blasting techniques.

Table 4.2. Dry ice blasting experimental design.

<table>
<thead>
<tr>
<th>Dry Ice Blasting Experimental Design</th>
<th>Blasting Interval (min)</th>
<th>Blasting Time (sec)</th>
<th>Blasting Pressure (lb/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC 1</td>
<td></td>
<td>No Cleaning</td>
<td></td>
</tr>
<tr>
<td>FLC 2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>FLC 3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>FLC 4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>FLC 5</td>
<td>3</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>FLC 6</td>
<td>3</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>FLC 7</td>
<td>6</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>FLC 8</td>
<td>6</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>

<sup>a</sup> Second best combination among FLC 5, 6, 7 & 8
<sup>b</sup>& <sup>c</sup> best combination among FLC 5, 6, 7 & 8 at different pressure levels

Figure 4.36 shows the results for the average material removal rate for each combination of the variables studied.
Figure 4.36. Average material removal rate after belt cleaning using dry ice blasting.

Figure 4.36 shows that the interactions between blasting pressure, interval and time have a strong influence on the material removal rate (MRR) performance during abrasive machining.

The highest amount of material removed was 27 grams in 3 minutes of machining with 6 minutes blasting interval, 3 seconds blasting time and 20 lb/in² (138 kN/m²) blasting pressure. Figure 4.36 also shows that some variable combinations did not exhibit good performance. Factor Level Combinations (FLC) 2, 3, 4 & 8 had MRRs the same or similar to the belt with no cleaning. This could be due to the blasting time being too long (5 seconds), the pressure being excessively high (FLC 3), or too low (FLC 4).

The experiment also showed that the variability in MRR increased when blasting was performed. The process of cleaning during the machining process creates sudden increments in MRR as the loading is suddenly removed exposing the abrasive grains. This permits the grains to penetrate the wood more effectively thereby increasing the material removal rate.
Figure 4.36 also shows that a lower cleaning time (three seconds) providing the best MMR performance (FLC 5 & 7). The best pressure level was 20 lb/in² (138 kN/m²) (FLC 7) when compared to 18 lb/in² (124 kN/m²) (FLC 4) and 25 psi (FLC 3) under the same experimental conditions.

Figure 4.37 shows the results of the average belt life for each combination of the variables studied.

Figure 4.37. Belt life for the various treatment based on the experimental design.

Figure 4.37 shows that the highest belt life was 199 minutes when using a three minute blasting interval, three second blasting time and 20 lb/in² (138 kN/m²) blasting pressure. This means a 14% increase in belt life.

Figure 4.37 also shows that in three of the variable combinations (FLC 4, 6 & 8), the life of the belt was shorter when blasted than for the (uncleaned) control belt. This clearly shows that excessive blasting times (5 seconds) or excessive pressure can negatively affect
the abrasive belts and therefore the overall performance of the belt. It is important to note that due to the high variability of the data when cleaning, the prediction of the belt life is subject to considerable error. Additional replications of the experiment could reduce the variability and generate better prediction of the belt life if necessary.

4.5 Belt temperature analysis for dry ice cleaning

The experimental design for evaluating the effect of dry ice cleaning on belt temperature shown in Table 4.3 (Saloni et. at., 2006) shows the variables studied and the FLC combinations of variables used to determine the effect of temperature on the abrasive machining process.

Table 4.3. Experimental design for determining the effect of dry ice cleaning on belt temperature.

<table>
<thead>
<tr>
<th>Dry Ice Blasting Experimental Design / Temperature</th>
<th>Blasting Interval (min)</th>
<th>Blasting Time (sec)</th>
<th>Blasting Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLC 1</td>
<td>No Cleaning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FLC 5</td>
<td>3</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>FLC 7</td>
<td>6</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>FLC 8</td>
<td>6</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 4.38 shows a thermographic photograph of the belt/workpiece interface during the abrasive machining process.
Figure 4.38. Thermographic photograph of the temperature change during abrasive machining process (left image shows the beginning of the machining process, right image shows the process after 30 seconds of machining).

Figure 4.38 shows the results for typical specimen. The left image is at the beginning of the machining cycle where the right edge of the specimen got hot quicker due to the belt/specimen alignment not being perfect; whereas the right image is after 30 seconds of machining when the belt pressure has equalized across the specimen resulting in a uniform temperature profile.

Figure 4.39 shows the average temperature for each combination of the experimental design.
Figure 4.39. Average temperatures for the various dry ice blasting.

Figure 4.39 shows the temperature changes for the various test cases described in the experimental design (Table 4.3). The lowest average temperature was 162.5 °F (72.5 °C) which resulted from a six minute blasting interval, three second blasting time, and 20 lb/in² (138 kN/m²) blasting pressure. The highest average temperature was with a six minute blasting interval, five second blasting time, and 20 lb/in² (138 kN/m²) of pressure. The probable explanation for this behavior is that a higher blasting time (five seconds) could cause damage to the belt, reducing the capacity of the abrasive to cut and remove material, thereby increasing the friction during the machining and therefore the temperature.

The best overall combination was six minutes blasting interval, three seconds blasting time and 20 lb/in² (138 kN/m²) blasting pressure. This corresponds to the highest material removal rate obtained but not to the longest belt life. Thus, FLC 7 had the best performance on material removal rate, the second best effect on belt life, and the lowest belt temperature.
(which would reduce the formation of loading due to melting the wood resin, and in turn reduce burning of the wood surface).

Additional work done by Cardenas (2006) showed the effectiveness of different cleaning techniques in extending the belt life using the material removal rate as an indicator of the condition of the belt. In these experiments, sodium bicarbonate blasting, walnut shell blasting, dry ice blasting and CO$_2$ flakes blasting were evaluated to determine relative performance in removing loading and the negative effect of cleaning on the abrasive belts using MRR as an indicator. This study concluded that walnut shell blasting and CO$_2$ flakes blasting were the cleaning techniques with the best performance in extending the life of the belt of the techniques studied.

Figure 4.40 shows a comparison between the different cleaning techniques studied.

![Material removal rate averages for the various cleaning techniques (from Cardenas, 2006).](image-url)
Figure 4.40 shows that the MRR was notably higher for the CO$_2$ flakes than for the rest of the cleaning techniques tested. Even though the initial MRR was higher when CO$_2$ flakes was used (as compared to the control case).

This technique also confirmed that cleaning the belts can substantially improve the MRR. This research also included the determination of the average belt life for each cleaning technique as shown in figure 4.41.

It was concluded that the CO$_2$ flakes and walnut shell media resulted in a considerably longer belt life when compared to the control belt. However, the CO$_2$ flakes resulted in a slightly higher variability in the results than the walnut shell media.

![Figure 4.41. Belt life average for the various belt cleaning techniques.](image)

A summary of the performance of different abrasive belt cleaning techniques based on the media characteristics, the effect of the cleaning on the abrasive belt and possible explanations of the results of each cleaning technique tested is shown in Table 4.4.
Table 4.4. Cleaning process media characteristics, effects of cleaning on belt performance and possible explanation of the cleaning processes results (Cardenas, 2006).

<table>
<thead>
<tr>
<th>Cleaning Technique</th>
<th>Characteristics of media</th>
<th>Effect of cleaning</th>
<th>Possible explanation of process observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walnut Shell</td>
<td>This media was blasted using an opened sandblaster. The nozzle size was bigger (larger diameter and length) than the CO2 flakes but smaller than the dry ice. In addition, the media was combined with compressed air to blast the media. The walnut shell was the finest media and had low aggressiveness.</td>
<td>The combination of media size, pressure, nozzle and aggressiveness seemed to be appropriate to clean the belts because of the media was able to increase the belt life in 23 % and the MRR in 18 %. When cleaning with the walnut shell, the effect was barely visible by the human eye.</td>
<td>The media was not only removing partially the loading but also part of the walnut media can get trapped between the grains spaces. In addition, the media may not been changing the shape of the grains.</td>
</tr>
<tr>
<td>Dry ice</td>
<td>The dry ice was one of the most abrasive media. For this study, it was used a relatively large diameter and a medium flow nozzle. Additionally, it is important to mention that this media has a very low temperature. The loading removed can be detected by the human eye.</td>
<td>The combination of media size, pressure and flow was not the optimal because of even though increased the Average MRR in 6 percent, it reduced the belt life in 7 percent.</td>
<td>The media was not only removing almost all loading but also might be removing the grains from the belt, and thus, reducing the effectiveness of the belt. In addition, the media could be rounding the sharp shape of the grains reducing the ability to cut the wood.</td>
</tr>
<tr>
<td>CO2 flakes</td>
<td>The CO2 flakes was one of the softest medias used. The nozzle was relatively small and conical shape. This specification provided medium flow. This is a cold media but lesser than dry ice</td>
<td>The combination of, pressure and nozzle shape created a positively effect on the belt life (46%) and MRR (35%). When cleaning with the CO2 flakes the effect was barely visible by the human eye.</td>
<td>The CO2 flakes removed partially the loading and might not damage the grains. In addition, it was possible that the shape of the grains was not affected by the blasting process.</td>
</tr>
</tbody>
</table>
These experiments indicated that CO₂ flakes was the best of the methods tested for cleaning the abrasive belts based on improved belt life (46.4 % improvement) and average MRR (35.4 %).

### 4.6 Conclusions from the background research

The background research provided a better understanding of the behavior of the abrasive machining process and the techniques for monitoring the abrasive machining
process. The evaluations included the use of accelerometers, acoustic emission sensors, optical sensors (light intensity and color) and temperature sensors. The following conclusions were reached:

1. The contact resonant acoustic emission sensor was the most sensitive of the sensors evaluated for monitoring the life of the abrasive belt. This sensor was not effective in detecting the formation of loading or determining when cleaning techniques were needed or applied.

2. Temperature sensors are not good indicators of belt loading or belt life. The utility of temperature sensors is restricted to indicating excessive temperature to avoid belt damage or burning of the wood.

3. Optical sensors are suitable for monitoring loading but are not able to effectively monitor belt life. The Wenglor® light intensity sensor was the most effective sensor for monitoring loading since it was able to detect not only the loading level but also the effect of the cleaning process on the belt.

4. The best sensor combination for monitoring condition of the abrasive machining belt is a Wenglor® optical sensor to monitor the loading status and a contact resonant acoustic emission sensor to determine when the belt needs to be replaced. Therefore, the integration of these two sensors is the most effective means of continuously monitoring the status of the abrasive machining process and determining the action required (such as no action, cleaning or belt replacement.

5. Related research by Cardenas (2006) showed that the abrasive belts can effectively cleaned by using an appropriate cleaning technique. It was shown that CO₂ flakes blasting is the best overall technique for cleaning the abrasive belt since it has the best combination of
advantages (extended the life of the belt, low equipment and material cost, no residues after blasting, easy to use and implement, and small equipment size.)
5. PROTOTYPE SYSTEM DESIGN

This chapter addresses the various steps in the design of the abrasive belt monitoring and cleaning system. The discussion will be divided into five sections; sensor analysis and selection to monitor abrasive belt loading, sensor analysis and selection to monitor abrasive belt life, sensors analysis and selection to activate the belt cleaning process, sensor analysis and selection to detect belt temperature, and process control system design.

5.1 Sensor Analysis and Selection to Monitor Abrasive Belt Loading

Chapter 4 discussed the feasibility of using different sensors to monitor the loading during abrasive machining. Four different types of sensors were studied and analyzed in order to identify the best combination of sensors for monitoring loading; including temperature, vibration, acoustic emission (contact and air coupled) and optical (color and gray scale) sensors.

5.1.1 Temperature Sensor

Temperature sensors have been used in a wide variety of industries to monitor different processes. As discussed in Chapter 4, the heat from the abrasive machining operation at the belt/wood interface can be so high that the heat melts resins in the wood, which cools, and become hard again, which results in belt loading. A loaded condition will cause the belt to be unable to cut properly, as the grains cannot fully come into contact with the workpiece, causing rubbing and friction, which generates excessive heat, belt wear and workpiece surface problems. Thus, monitoring and controlling the temperature is an important step in the abrasive machining process improvement.
The experimental work showed that there was no significant change in temperature during increases in loading. It was observed that after the first 20 seconds of machining, the temperature rapidly stabilized and slowly increased showing no clear indication of correlation between increased loading and belt temperature. This is a clear indication of the lack of sensitivity that the temperature sensors tested had for the detection of loading or abrasive belt life.

Thus, temperature sensors are not viewed as effective indicators of abrasive life and loading formation, however, they were found to be effective in helping establish high temperature limits in order to avoid burned wood surface and or belt damage.

5.1.2 Accelerometer Sensor

The experimental work discussed in Chapter 4 showed that accelerometers, which measure vibration over a wide frequency range, can be used to monitor belt life but do not show a clear indication of belt loading.

The accelerometer sensor results discussed in Chapter 4 clearly showed that the sensor signal was able to detect changes in belt wear by showing a reduction in the signal strength during the abrasive machining process. Results from the accelerometer did not show changes or variation in the signals due to increases in loading despite clear evidence of abrasive loading being present.

These results indicated that the accelerometers tested were not effective in detecting loading formation and accumulation during the abrasive machining process and therefore were not considered for use in the monitoring system design.
5.1.3 Acoustic Emission Sensors

Two types of acoustic emission sensors were considered for the system design based on the experimental work reported in Chapter 4. The two sensors evaluated for use in monitoring belt loading were a contact resonant AE sensor and an air coupled resonant AE sensor. As was the case for the accelerometer and temperature sensors, neither of the acoustic emission sensors were shown to be effective in the detection of loading. The experimental work described in Chapter 4 clearly showed that similar to the accelerometer, the acoustic emission sensors (contact resonant and air coupled resonant) were able to detect workpiece changes and belt wear during the abrasive machining process but were not able to detect loading or changes in loading even though loading formation was observed throughout the abrasive machining process.

Chapter 4 also described the results from an evaluation changes in the location and mounting of the contact resonant AE sensor to the abrasive machine in order to improve the signal and avoid variations in the signal due to workpiece changes. None of the changes in sensor location indicated that loading formation could be monitored effectively by using acoustic emission sensors. This result agreed with previous authors that concluded that acoustic emission sensors were not able to detect the formation of loading or the degree of loading when belt cleaning was applied.

5.1.4 Optical Sensors

As previously discussed in Chapter 4, optical sensors are inexpensive and easy to use and can be utilized to detect the loading on abrasive belts, however, most of the optical sensors evaluated exhibited a lack accuracy and high variability in the measurements.
Based on the preliminary results, the Banner® sensor was eliminated due to its requirement of having to be significantly close to the object to be measured. CCD cameras were also analyzed but were rejected due to the requirement for post processing analysis of the signal. The Wenglor® intensity detector appeared to be the best option among the sensors investigated for detecting belt loading. This type of sensor offered the lowest experimental variation, an adequate sensitivity in signal output for a change in abrasive loading, and no need for post processing of the output.

A new generation of optical color sensors that are able to measure the intensity and the “intensity” of the individual colors were also discussed in Chapter 4. This type of sensor detects not only the presence of a particular color but also the degree of color present. An intensity detector from Wenglor® and a ColorMax-1000 color sensor from EMX Industries, Inc. (www.emx.com) were selected for additional analysis and testing to verify and confirm the results presented in Chapter 4. The ColorMax 100 sensor was able to detect the formation of loading by exhibiting a considerable increase in the red color (the red color was the most significant and sensitive to change). The ColorMax 1000 sensor was slightly more sensitive in detecting the changes in the loading level when machining pine than particleboard. However, the ColorMax 1000 sensor signal did not appear to be sensitive to different loading levels during the abrasive machining process. From the preliminary experiments, it could be concluded that the ColorMax 1000 sensor could be more sensitive to detect changes in color percentage when different types of material (wood or wood composites) were machined since the color percentage was stronger and more variable. Additional experiments were conducted using cleaning techniques in order to determine the sensitivity of the ColorMax 1000 sensor to drastic changes in loading. The change in the sensor signal was not significant and re-
confirmed that the ColorMax 1000 sensor is not sensitive to changes in loading for abrasive machining. Another shortcoming of the ColorMax 1000 sensor is that it requires the sensor to traverse the belt continuously in order to correctly monitor the status of the belt loading during abrasive machining (this is a result of the fact that localized loading occurs more often than uniform loading). It was concluded that the color sensor did not have enough sensitivity to the changes in loading to be of use in the evaluation of loading. Results from the experimentation also showed that the Wenglor® intensity detector appeared to be the best option among the optical sensors studied. It offered the lowest experimental variation, and no required post processing of the output (such as image analysis) was required.

Figure 5.1 shows the light intensity from a Wenglor® sensor when machining particleboard using aluminum oxide P100 belt at a 2600 ft/min (217 m/min). These same conditions are used in figure 5.1 through figure 5.12.

Figure 5.1. Wenglor® optical sensor signal as a function of machining time.
Figure 5.1 shows that a continuous increase of the light intensity signal during abrasive machining occurs with the progression of belt loading. As can be seen in figure 5.1, the loading formed rapidly and then continuously increased with time until a maximum level was reached.

Additional testing of the Wenglor® intensity sensor was performed in order to verify the measurement of belt loading during two different stages of the process; when machining and when the belt was rotating but the workpiece was not contacting the belt. This test was focused on verifying the effect of dust on the detection of loading.

Figure 5.2 shows the signal from the intensity sensor for the two conditions indicated above.

Figure 5.2. Wenglor® optical sensor signal when machining and idling.
Figure 5.2 shows that there is no significant difference in the signal when machining versus when the machine is idling (no machining). This was the expected result since the location of the sensor was such that the dust produced during the machining process did not affect the sensor signal.

Additional experiments were performed to evaluate the effect of belt cleaning on the detection of loading.

Figure 5.3 shows the signal of the Wenglor® intensity sensor when cleaning with CO₂ flakes for five seconds every six minutes when machining particleboard with aluminum oxide P100 belt.

![Figure 5.3. Wenglor® optical sensor signal when cleaning after machining (particleboard workpiece).](image)
Figure 5.3 shows that the intensity sensor was able to detect the cleaning action as indicated by the large drop in signal level at minute 6, 12, and 18.

However, the intensity signal when after cleaning did not present a predictable trend. This behavior is contradictory to that shown in Figure 5.1 in which the signal continuously increased when loading increased. Thus, further investigation of this phenomenon was required in order to identify the causes of this inconsistency in the behavior of the signal output.

Closer observation and monitoring of the Wenglor® optical sensor indicated that this behavior was mainly due to changes in the ambient light and shadows from the operator when approaching the sensor to operate the machine. A solution for this problem was to utilize a LED light array mounted directly on top of the sensor to concentrate the light over the belt and thereby avoid the effect of ambient light and other external sources of light variation. As a result of the implementation of this solution, a more consistent signal was obtained.

Figure 5.4 shows the intensity sensor signal when cleaning with CO₂ flakes for five seconds every six minutes after machining white pine with aluminum oxide P150 belt.
Figure 5.4. Wenglor® optical sensor signal after cleaning during machining.

Figure 5.4 shows that the light intensity signal continuously increased after the cleaning process was applied. In addition, it can be seen that the level of the light intensity signal was lower when the belt was new. Additionally, the cleaned light intensity level (level after cleaning was applied) tended to be similar regardless of the status of the belt or the level of the loading prior to cleaning. Thus, even though the loading level for minute 11 was higher than minute 17, the loading level after cleaning tended to be similar. The condition of the belt after each cleaning never did reach the initial level (new belt).

Finally, the “saw tooth” shape of the curve observed in figure 5.4 clearly indicates the ability of the sensor not only to detect loading during the machining process after cleaning but also, the sensors capacity to monitor the cleaning process. It is important to note that the
loading slope after cleaning tended to decrease, thus, the slope of the loading tendency from minutes six to eleven was larger than from minutes twelve to seventeen. It is speculated that this behavior is due to the abrasive grains becoming worn, which reduces the capacity of the grains to remove material causing a reduction in the amount of loading that can be accumulated. This would produce a larger difference in signal strength between cleaned and non-cleaned belt. This effect would facilitate not only the detection of loading but also the implementation of a system to control loading.

Further investigation of the behavior of the loading and the effectiveness of cleaning techniques was conducted as is discussed below.

Figure 5.5 shows the signal from the Wenglor® optical sensor when machining white pine and cleaning the belt with CO₂ flakes every 10 minutes instead of every 6 minutes as in previous experiments (measurements of the signal were done every minute). The abrasive belt used was aluminum oxide P150.
Figure 5.5. Wenglor® optical sensor signal after cleaning with CO₂ flakes (white pine workpiece).

Figure 5.5 shows trends similar to those observed in previous experiments in which the belt was cleaned every six minutes with the loading continuously increased during machining until it stabilized at a certain level (after ten minutes of machining). It is important to note that there was a small drop in the signal at minute 23, which was the result of the introduction of a new workpiece. This validates the ability of the sensor to detect changes in the loading during machining.

Figure 5.6 shows the results of additional investigations of the change in the light intensity and the effect of cleaning times and different cleaning techniques when machining white pine.
Figure 5.6 shows that the light intensity when measuring loading drastically increased at the beginning of the machining and then stabilized up to certain level. Thus, both curves regardless of the type of cleaning technique used showed that the highest loading level obtained correspond to a relative a light intensity of 3.5 volts. In addition, figure 5.6 shows that the Wenglor® optical sensor was able to differentiate between the types of cleaning technique used by exhibiting a difference in the light intensity output. In this case, the light intensity after cleaning with the gum eraser was around 2.50 volts while when cleaning with CO₂ flakes was around 3.00 volts.
Figure 5.7 presents an additional investigation of the effect of cleaning as detected by a contact resonant AE sensor and a Wenglor® optical sensor when machining white pine with aluminum oxide belts grain size (P150) and cleaning with CO₂ flakes.

![Graph](image)

**Figure 5.7. Wenglor® optical sensor and resonant acoustic emission sensor signals comparison when cleaning with CO₂ flakes.**

Figure 5.7 shows that the acoustic emission signal was not detected by the cleaning process; however, the cleaning was clearly detected by the Wenglor® optical sensor at minutes 10 and 20. As expected, the acoustic emission signal did not show a significant change with increased loading, however, the loading was clearly observed by the optical sensor as indicated by a continuous increase of the signal from minutes 1 to 10 and from 10 to 20.
In summary, the Wenglor® intensity sensor was shown to be effective in monitoring loading during the abrasive machining process. Thus, this sensor will be used as a tool to continuously monitor loading and initiate associated process control actions (belt cleaning).

5.2 Sensors Analysis and Selection to Monitor Abrasive Belt Life

Chapter 4 addressed the feasibility of using acoustic emission sensors to monitor abrasive belt life. The evaluation of AE sensors described in Figure 4 indicated that these sensors could be used effectively to monitor abrasive belt life (note that there was no indication that AE could effectively detect loading). The contact resonant AE sensor was found to be superior to the air coupled resonant AE sensor and consequently this sensor will be used in the system design. The selection of the appropriate frequency band of the AE signal for monitoring the abrasive machining process was an important consideration. A contact wideband acoustic emission sensor with a range of 20 kHz – 1000 kHz was used to determine that the predominant signal frequency range was between 30 kHz and 40 kHz. Additional analysis for purposes of system design was focused on the determination of the optimal location of the contact resonant AE sensor to obtain the most appropriate signal to monitor the wear of the abrasive belt. As a result of the evaluation described in Chapter 4, a sensor location underneath the belt platen was selected to avoid abrupt changes in the signal every time a new workpiece is machined.

Results from the preliminary research clearly showed that the contact resonant AE sensor was able to measure belt wear with the proper set up and the appropriate location even for the high belt speeds experienced during machining (2600 ft/min - 217 m/min).
5.3 Sensors Analysis and Selection to Activate the Belt Cleaning Process

The results from the experimentation discussed in Chapter 4 also aided in the establishment of the thresholds used to activate the cleaning control system and the indication that the abrasive belt needs to be replaced. Once the sensors were selected to meet the monitoring requirements of the abrasive machining process, the details of the belt cleaning system design were addressed. Based on the nature of the outputs from the sensors, a single signal can be used as a trigger for the belt cleaning control system. The belt cleaning control system was based on the integration the various sensor signals, which enable the system to initiate actions (such as no action, activate the cleaning system to remove the loading, or generate an alert signal when the process must be stopped to replace the belt). As discussed previously, a Wenglor® optical sensor was selected to measure the loading level and was used as a trigger to activate the cleaning system. The contact resonant acoustic emission sensor was used to continuously monitor the life of the belt and activate a signal to indicate when the abrasive belt needs to be replaced. In addition, the AE sensor also detects when an abnormal event occurs that produces a significantly large signal due primarily to machining problems.

5.4 Sensors Analysis and Selection to Detect Belt Temperature

Temperature analysis was selected for safety reason in order to avoid permanent damages of the belt, workpiece or machine. Thus, an infrared thermometer was selected to monitor continuously the temperature of the belt and indicates when an excessive temperature level has been reached that would required an immediate action. It is important to note that due to the nature of the abrasive machining process (rotating abrasive belt) a non-
contact thermometer had to be used. In the other hand, no high sensitivity was required to monitor the temperature of the belt since changes in belt temperature do not occur suddenly therefore a non-expensive commercial type infrared thermometer was selected (see appendices for technical details).

5.5 Process Control System Design

The design of the belt cleaning control system was based on the selection criteria and requirements of the output and input characteristics, signal characteristics, flexibility, and accuracy.

The number and characteristics of the input and output can significantly determine the type of control system to be selected. A detail analysis of the input or inputs signals and the subsequent output or outputs signal is critical for the sensor selection. Thus, based on the experimental work it was found that both sensors, optical and acoustic emission, have respective single outputs. As discussed previously, the optical sensor signal measures the belt loading level and sends the information to the control system in order to determine the action required.

Based on the two parameters to be controlled, loading and belt life, two different signals were obtained. The signal from the optical sensor was analyzed based on the experimental work. It was observed that the signal continuously increased until a stabilization area in which the slope of the trend tended to be zero (the trend of the data in this area tended not to change with time). Thus, it was possible to define the characteristics of the signal and the thresholds for the control system.
This is one of the most important characteristics to be considered when designing a control system. This characteristic becomes more critical when the process to be monitored and controlled is abrasive machining. Moreover, it become even more complex when wood is used due to it being a material with a large, uncontrollable variability such as density, resin content, as well as others.

The required accuracy of the control system must be determined before its implementation. Thus, analysis and validation of the control system must be pursued in order to validate the robustness of the control design.

Figure 5.8 shows the basic concepts involved in the control system design.
The schematic shown in figure 5.8 represents the proposed prototype system design. A control system receives the information on the status of the process from the sensors, a comparison level determines the actions needed to be taken based on the status of the process, and then when appropriate, the control system activates the cleaning or cooling process, or alert the operator to stop the process depending on the condition of the abrasive belt.

Figure 5.9 shows the components of the prototype system design.

The prototype system design, as shown in figure 5.9, integrated a dedicated experimental abrasive machining apparatus with sensors connected to a computer with a data
acquisition card to collect the information generated by the sensors. The data was analyzed by the computer based on the characteristics of the process and the acceptable levels of loading and belt wear. The system was designed to take the required actions such as cleaning as shown in figure 5.9. Labview™ by National Instruments® was used to collect and process the signals from the sensors.

Analysis of the data collected from the AE sensor facilitated prediction of the condition of the belt by monitoring the belt life. The Wenglor® optical sensor was used to continuously detect the belt loading. The use of independent sensors to collect belt loading and belt life data made it possible to design the control system based on three different independent actions, cleaning based on the optical sensor, stopping the machining process based on the acoustic emission signal, and emergency stoppage based on the belt temperature sensor.

The analysis of the output showed that a simple discrete control could be used to take the required actions since each action was basically a one time discrete action for a certain period of time every time a specific condition occurred.

The cleaning process was activated when the signal from the optical sensor reached a certain level based on the preliminary experiments.

Analysis of figures 5.4 and 5.5 revealed that the slope of the data points for the light intensity tended to continuously decrease while loading increased, thus, at certain levels, the slope of the curve tended to approach zero (horizontal). This mathematical characteristic permitted the establishment of the point in which cleaning was required such as when the slope tended to zero. Moreover, practical definition of the threshold was set when the slope between two consecutive points (light intensity output in volts) was less than 0.02. Extensive
experimentation by Saloni (2005 and 2006) and Cardenas (2006) showed that cleaning with CO2 flakes for five seconds was the optimal time to remove the loading without affecting the integrity of the abrasive grains or reducing the overall life of the belt. Therefore, the cleaning process was activated when the slope of the two consecutive data points was less than 0.02 for five seconds.

Belt life was defined by using the output from the contact resonant AE sensor. Analysis of the acoustic emission output showed that the signal tended to increase until the signal stabilized at a certain level. Thus, a cumulative representation of the data was used for better understanding and analysis of the acoustic emission signal. The threshold acoustic emission level was defined primarily by defining the life of the belt by using the material removal rate (MRR) which continuously decreases during the life of the belt until it tends to zero. For purposes of this research, the cumulative MRR was used and compared to the acoustic emission cumulative output in order to verify and validate the threshold for the belt life.

Figure 5.10 shows the cumulative contact resonant AE signal compared to the cumulative material removal rate for abrasive machining as a function of time.
Figure 5.10. Cumulative MRR and contact resonant AE signal after cleaning with CO₂ flakes.

Figure 5.10 shows that the slope of the cumulative material removal rate tended to decrease with time while the slope of the cumulative acoustic emission signal tended to increase with time. Thus, it was possible to define the threshold of the belt life based on the slope of two consecutive points when the cumulative acoustic emission data was greater than 3.5 for at least two consecutive measurements.

It is important to note that this threshold was established based on using aluminum oxide abrasive belt type with a grain size of P100 when machining particleboard. Thus, regardless of the type of mineral, grain size, and material used the threshold was automatic recalibrated based on the sensor signal.
Further investigation of the acoustic emission signal trend was conducted in order to determine the validity of the method of determining the threshold, which indicates that the abrasive belt should be replaced. Thus, a comparison of different types of mineral and grain size were performed and discussed.

Figure 5.11 shows a comparison of the cumulative contact resonant AE sensor signal for aluminum oxide and silicon carbide for P150 belt.

![Cumulative contact resonant AE sensor signal comparison of aluminum oxide and silicon carbide P150 belt.](image)

Figure 5.11. Cumulative contact resonant AE sensor signal comparison of aluminum oxide and silicon carbide P150 belt.

Figure 5.11 shows a comparison of the cumulative contact resonant AE sensor signal between two different mineral types, aluminum oxide and silicon carbide. The trend of the cumulative signal was consistent with what has been observed previously in which the slope
of the curve tended to increase towards the end of the life of the belt. An interesting result can be observed when comparing the two curves minerals.

The aluminum oxide exhibited a higher acoustic emission signal which could be a result of the aluminum oxide removing more material than silicon carbide (Saloni, 2003) which can cause a higher acoustic emission signal due to the increased cutting action. It is important to note that the inflection points on the aluminum oxide cumulative curve are due to the two workpiece changes (minute 14 and minute 42) as opposed to no workpiece changes for the silicon carbide. In addition, figure 5.11 shows that the initial “grains breaking” effect was larger for aluminum oxide than for silicon carbide demonstrating that the aggressiveness of the grains during the machining process can also be monitored by the acoustic emission signal. This “grains breaking” effect was observed during the first few minutes of the machining process, lasted for about 14 minutes for aluminum oxide, and lasted only 4 minutes for silicon carbide. The aluminum oxide acoustic emission signal cumulative trend showed a higher slope towards the end of the life of the belt than silicon carbide. This could be due to the higher aggressiveness of the aluminum oxide mineral when compared to the silicon carbide.

Figure 5.12 shows a comparison of the cumulative acoustic emission signal between grain size P150 and P220 for belt with aluminum oxide mineral.
Figure 5.12 shows that the cumulative contact resonant AE sensor signal from both P150 and P220 grain sizes. The slope of the cumulative contact resonant AE sensor signal was relatively small during the first minutes of machining and increased towards the end of the life of the abrasive belt. Grain size P220 reached the steep slope faster than the P150 as a result of wearing out faster. It is important to note that the acoustic emission signal for P220 was not higher but the belt simply wore out faster.

In summary, it can be said that the cumulative mathematical artifice is valid regardless of the type of mineral or grain size. Thus, this artifice and the mathematical ratio...
of the sloped were used to determine the thresholds of the control system to monitor the status of the belt by acquiring the acoustic emission signal.

Additional experiment were performed in order to verify the necessity of calibrate the acoustic emission threshold based on different type of grit size and type of material. Thus, the cumulative acoustic emission signal was compared to the material removal rate.

Figure 5.13 shows cumulative contact resonant AE sensor signal versus material removal rate when sanding particleboard with aluminum oxide P100.

![Graph showing cumulative AE signal versus material removal rate for aluminum oxide P100](image)

**Figure 5.13. Cumulative contact resonant AE sensor signal versus material removal rate for aluminum oxide P100 when sanding particleboard.**

Figure 5.14 shows cumulative contact resonant AE sensor signal versus material removal rate when sanding particleboard with aluminum oxide P220.
Figures 5.13 and 5.14 shows that adjustments in the threshold are required since the cumulative acoustic emission signal values for P100 when sanding particleboard with aluminum oxide was different when compared to P220 under the same machining conditions.

In addition, white pine was used to verify that the type of material has different behavior and requires a change in the threshold of the acoustic emission level.

Figure 5.15 shows cumulative contact resonant AE sensor signal versus material removal rate when sanding white pine with aluminum oxide P220.
Figure 5.15. Cumulative contact resonant AE sensor signal versus material removal rate for aluminum oxide P220 when sanding white pine.

Similar to the results obtained previously, figure 5.15 shows that adjustments in the threshold are required since the cumulative acoustic emission signal values for P220 when sanding white pine with aluminum oxide was different when compared to P220 when particleboard was used as a material to be machined (figure 5.14) under the same machining conditions.
5.6 Control System Design.

The total control system was designed as a combination of several different control systems; belt life control, cleaning control and temperature control. As established before, three main actions were designed, cleaning system activation, light bar signal to indicate the status of the abrasive belt, and warning signal on the program to indicate when the belt temperature reaches the maximum safety temperature limit.

Figure 5.16 shows the control system screen designed to test the cleaning system based on the threshold previously defined.

Figure 5.16. Cleaning activation program in LabView® 8.2.

Figure 5.16 shows the control screen designed to activate the cleaning system based on the threshold established. Thus, the program written in LabView® 8.2 served to test the action required when the optical sensor indicates that the belt needs to be cleaned based on
the loading level. Thus, a separate program was tested, refined and validated before being included into the main process monitoring and control system.

In addition to the cleaning system activation, a program to indicate the condition of the belt based on the information from the acoustic emission sensor was designed.

Figure 5.17 shows the screen program designed in LabView® 8.2 to activate the light signal for the status of the belt.

![Figure 5.17. Abrasive belt condition program in LabView® 8.2.](image)

Figure 5.17 shows the program screen made in LabView® 8.2 used to test the system that indicates the condition of the abrasive belt based on the threshold specified according to the output from the acoustic emission sensor. Thus, a green light indicates an optimal condition of the belt (accepted wear). A yellow light serves as a warning that the belt is approaching the end of its life. Finally, a red light indicates that the belt needs to be replaced immediately.
Finally, a program in Labview® 8.2 was designed that integrates the inputs coming from the sensors, compiles the information and compare it with the defined thresholds and then takes the respective action such as cleaning, belt status, and temperature level.

Figure 5.18 shows the process monitoring and control system program screen designed in LabView® 8.2 to monitor and control the abrasive machining process.

Figure 5.18. Process monitoring and control system program developed in LabView® 8.2.

Figure 5.18 presents the program screen designed in LabView® 8.2 of the process monitoring and control system for the abrasive machining process. Figure 5.18 shows three graphs, the loading monitoring, the cumulative acoustic emission RMS and the temperature level. For each graph, two lines are shown, the data coming from the sensors and the upper
limit that indicates when an action needs to be taken. The cleaning action is taken automatically by the system activating the cleaning system. In contrast, the acoustic emission cumulative RMS activates the light system (green, yellow and red) showing the condition of the abrasive belt. In addition, a red light activates when an elevated temperature has been reached. Figure 5.18 also shows indicators (boxes) of the current values of the signal inputs (light intensity, AE-RMS and temperature). In addition, a thermometer style bar graph was employed that changes its color when a certain level is reached indicating the status of the abrasive belt based on exceeding a threshold from the acoustic emission sensor. Finally, it can be seen in figure 5.18 that the output from the monitoring can be saved into a file on a box called “Destination file name”. Finally, figure 5.18 shows a box in blue with an arrow inside that indicates that more controls and settings can be found in a next screen. This is where the sampling rate, thresholds, etc are entered. Figure 5.19 shows this portion of the screen of the process monitoring and control system developed in LabView 8.2.

Figure 5.19. Additional control and threshold settings for the process monitoring and control system program developed in LabView® 8.2.
Figure 5.19 shows the main settings for the number of scans to be collected and the scan rate in scans per second as well as the channels defined from which to obtain the sensor information. In addition, the thresholds for abrasive belt condition (accept, caution and reject) can be modified. Moreover, the upper temperature limit and the loading slope limit for the light intensity signal can be changed. It is important to note that the program was designed in order to change these values since some thresholds or belt conditions may change depending on many factors such as the machine type, the abrasive belt type (ceramic, aluminum oxide, silicon carbide, grit size, backing type, etc), the wood species, the process parameters (rotational speed, pressure, surface quality), as well as others. Thus, the program can be customized based on the different settings by allowing the operator to make changes to the settings in order to obtain the most appropriate performance of the process monitoring and control system.

A series of programs were constructed in Labview™8.2. These routines collected data from the sensors for belt loading, belt life, and belt temperature. A series of thresholds were established from preliminary tests for each sensor. If the threshold for the belt loading was exceeded then a signal was sent to a digital to analog converter that provided the voltage to turn on the solenoid to activate the belt cleaning system as shown in figure 5.20. A delay was also programmed into the system so that data was not collected until the debris from the belt cleaning operation had time to dissipate.
A series of thresholds were established for the AE sensor to indicate the degree of belt wear. Three levels of belt wear were defined. Each of these three levels corresponded to a differently color of light both on the program display as well as a light bar. Signals were sent to digital outputs of the same National Instruments™ data acquisition board used to collect data from the sensors. A green light indicated that the condition of the belt was good (figure 5.20).

Additionally, a yellow light indicated that the end of the life of the belt was approaching (figure 5.21) and no additional belt cleaning would be performed.
Figure 5.21. Yellow light indicator due to moderate belt wear for the process monitoring and control system program developed in LabView® 8.2.

A red light indicated that the belt was worn out and should be changed immediately (figure 5.22). It is important to note that the control system is not programmed to stop the abrasive machining process due to excessive belt wear (red light indicator in figure 5.22), it is just to warn the operator that the belt needs immediate replacement otherwise damages on the belt, quality problems, workpiece surface burning, low production due to limited material removal rate as well as other situations could arise.
Figure 5.22. Red light indicator due to excessive belt wear for the process monitoring and control system program developed in LabView® 8.2.

Figure 5.23. Temperature indicator due to excessive temperature for the process monitoring and control system program developed in LabView® 8.2.
A single threshold was established for the temperature sensor to warn when the sanding temperatures were too high as can be seen in figure 5.23.
6. EVALUATION AND REFINEMENT OF THE PROTOTYPE.

This chapter covers the evaluation of the prototype system design. This was done by performing a series of abrasive machining tests under different conditions in order to verify the capability of the system to monitor and control the process.

The main factor considered in the validation of the prototype system design was belt life, which was evaluated by measuring the material removal rate. In addition belt, loading, temperature and belt life were measured for various combinations of the different factors and their levels such as mineral type, grit size, type of wood, belt rotational speed, interface pressure, and other factors.

Experiments discussed in Chapter 4 established the technical feasibility of monitoring loading by using optical sensors and belt wear by implementing acoustic emission sensors. In addition, it was found that temperature sensors can be used a safety devices to prevent damage to the machine or the workpiece being machined. The experiments also defined the most appropriate sensors to be used in order to continuously monitor the abrasive machining process in terms of loading and belt life. Additional experiments discussed in chapter 4 showed the most appropriate cleaning technique not only to extend the life of the belt but also with the best cost/benefit.

The acquisition system was developed through evaluation of different candidate sensors. Additionally, a control system was designed to process the information obtained from the sensors and compare the acquired data relating to the status of the process as compared to defined threshold criteria.

Once the sensor data is analyzed, a series of actions are taken depending on the condition of the belt (for instance, no action is required when loading is within acceptable
limits and appropriate belt life and normal operating temperature are observed. It is important to note that the system is also able to determine when applying cleaning is no longer economically acceptable resulting in termination of the application of cleaning media.

The control system was created on LabView® version 8.2 from National Instruments (www.ni.com) which integrates the monitoring process and the actions required depending on when a specific condition is encountered. Thus, the system is able to acquire information from the optical sensor to detect loading and then, when required, activate the cleaning system.

The system continuously monitors the condition of the abrasive belt by using acoustic emission sensors data and alerts the operator of the status of the belt (green, yellow and red lights indicate optimal, medium and poor belt condition).

In addition, the system also incorporates a safety device that prevents damage the belt, equipment or workpiece by alerting the operator when an excessive temperature has been reached. Temperature of the process is monitored by the use of a simple, inexpensive infrared thermometer.

Figure 6.1 shows a screen shot of the process monitoring and control system program developed in LabView® 8.2.
As discussed in Chapter 5, figure 6.1 shows the different indicators of the condition of the abrasive belt while continuously monitor by the different sensors. It is important to note that the cleaning action is taken automatically based on the information obtained from the optical sensor until the cleaning process is not economically justified. On the other hand, series of lights (green, yellow and red) indicates the condition of the life of the abrasive belt based on the acoustic emission signal but the action is executed by the operator according to the machining criteria avoiding sudden stoppage of the abrasive machining process. Contrary to the temperature sensor that indicates the operational temperature of the process and stops the process when temperature exceeded the upper temperature operational limit indicating risk of fire or workpiece burnt.
Figure 6.2 shows a screen shot of the process monitoring and control system program developed in LabView® 8.2 refinement.

Figure 6.2. Screen shot of the process monitoring and control system in action.

Figure 6.2 shows the calibration of the optical sensor - intensity calibration based on the loading level. It is possible to see from figure 6.2 that adjustments in the thresholds are required in order to obtain the desired action such as cleaning, warning and stop due to belt wear or excessive temperature.

Figure 6.3 shows a screen shot of the process monitoring and control system program developed in LabView® 8.2 refinement.
Figure 6.3 shows that the process monitoring and control system was sensitive enough not only to activate the cleaning until it is absolutely required but also to detect that self belt cleaning was in progress and no cleaning was required. This is an important advantage from manual cleaning since the cleaning was performed only when was needed instead of a specific time and frequency or based on an operator decision.

In addition, figure 6.3 shows the cumulative action of the acoustic emission signal that predicts the belt status. Moreover, the note on figure 6.3 denotes that no value is cumulated when there is not abrasive machining action, and then, start cumulating again.
when abrasive machining is engaged.

Finally, figures 6.3 shows the control of the process by monitoring the belt temperature, which varies throughout the process but it did not approached the excessive temperature level.

Figure 6.4 shows a material removal rate comparison when to different cleaning system were used such as manual system (cleaning every six minutes) and automatic system (using the process monitoring and control system and cleaning based on sensors information).

![Graph showing material removal rate comparison between automatic and manual cleaning](image)

**Figure 6.4.** Material removal rate comparison for automatic and manual cleaning for abrasive machining particleboard with aluminum oxide P100.
Figure 6.4 shows that the material removal rate for when using the process monitoring and control system was similar than when the cleaning was performed manually every six minutes when machining particleboard with aluminum oxide P100. Moreover, the average material removal rate for manual cleaning was 0.257 lb/min compared to 0.253 lb/min for automatic cleaning (using the process monitoring and control system designed).

In addition, the process monitoring and control system triggered the cleaning system four times while the manual cleaning required six cleaning during the period of time studied.

Figure 6.5 shows a simulation that compares the manual and automatic cleaning for a better visualization of the evaluation.

![Graphical representation of a simulation for manual and automatic cleaning](image)

**Figure 6.5.** Graphical representation of a simulation for manual and automatic cleaning.
Figure 6.5 shows a simulation that compares the manual and automatic cleaning (using the process monitoring and control system). Thus, four cleanings were required when the process monitoring and control system was system in contrast to the manual cleaning. Therefore, less amount of cleaning media was used obtaining similar effect in the material removal rate (as shown in figure 6.4). It was possible to observe that the use of the optical sensor permitted to activate the cleaning system only when was required regardless the machining time or appearance of the belt. This helps to save media that it reflected in a reduction in the operation and material costs.

The utilization of the system introduces this improvement in addition to the enhancement in the consistency of the cleaning by the elimination of the human errors. Furthermore, this improvement also affects the cost by extending the life of the belt, which reduces setup time, belt cost, operation cost, as well as others.

In summary, the main objective of the process monitoring and control system was to improve the abrasive machining process by extending the life of the belt when using different sensors that monitor the process and a control system that automatically takes action based on the condition of the belt. Thus, the process monitoring and control system was able to adequately perform regardless the machining status, time or appearance of the abrasive belt. This is an indication of the technical feasibility of the implementation of this type of system in an industrial machine. Moreover, the system was able to improve the abrasive machining process from two different points of view like technical by improving the cleaning process (less blasting for similar results of the material removal rate) and economical by reducing cost (setup time reduction, less blasting material, longer belt life, higher material removal rate, as well as others).
7. DESCRIPTION OF RESEARCH MACHINE DESIGN AND APPLICATION OF THE PROCESS MONITORING AND CONTROL SYSTEM TO AN INDUSTRIAL MACHINE

Due to the importance of using controls in industry and the need for the wood industry to continuously improve its processes to be more competitive, the Wood Machining and Tooling Research Program at North Carolina State University has engaged in multilevel research in order to understand and optimize the machining processes through the use of process monitoring and control systems.

7.1 Design and Development of the Abrasive Machining Research Machine

The research, design, and development work for the process monitoring and control system for abrasive machining processes was carried out with the aid of a specialized abrasive machine designed and fabricated at the Wood Machining and Tooling Research Program (WMTRP) laboratories. This research machine was designed with the intention of easily modifying and implementing changes to the abrasive machining process variables such as interface pressure, abrasive rotational speed, belt type, and wood species, etc. In addition, the machine design allows for the use and implementation of a wide variety of sensors and instrumentation required to continuously monitor the abrasive machining process. Figure 7.1 shows the abrasive machining research machine and associated instrumentation interface.
The research machine data acquisition system was designed to accurately collect data on power, vibration, belt loading, and material removal rate simultaneously. Customized data acquisition software, capable of high sampling rates was developed. For ease of construction, the structural support for the machine was built with 80-20™ extruded aluminum profiles which also permits the easy attachment of sensors and other instrumentation and equipment. The research machine is equipped with a three-horse power (3-HP) electric motor with a variable speed transmission (figure 7.2) and is capable of speeds between 400 - 3000 feet per minute (33.2 m/min – 2500 m/min).
A 3-Phase power true power sensor, designed by Load Control, Inc (www.loadcontrol.com) was used to monitor the power requirements of the motor during the machining process. This allowed the measurement of electrical power applied to the sander along with simultaneous monitoring of the reduction in belt speed that occurs as the machine is loaded. The measurement of belt speed was accomplished by the use of a photocell based tachometer, which was able to detect instantaneous reductions in speed (figure 7.3).
The research machine was designed to use standard 6” x 48” (152.4 mm x 1219.2 mm) abrasive belts of various grit sizes and materials. In an effort to minimize positioning errors, the fixture for holding the wood samples was outfitted with two air cylinders mounted on linear ball bearing slides that are used to raise and lower the wood sample onto and off of the belt (figure 7.4). When the system is activated, the air cylinders smoothly lower the workpiece onto the belt. The machine also includes a traversing slide to facilitate monitoring across the entire width of the belt. The abrasive machining of the workpiece is carried out for the programmed amount of time and then the workpiece is raised off the belt. The workpiece is then removed and weighed to determine the material removal rate.

The data is collected and analyzed by custom designed software developed by the WMTRP. This software is used in conjunction with Labview™, the software program is able to collect the following data: horsepower, material removal rate, belt surface temperature, acoustic emission signal and optical belt loading data. The software also monitors belt loading and controls the belt cleaning process. With the current technology used by the WMTRP, it is possible to record 300,000 samples of data per second across 16 channels, as well as output signals on 8 channels.

The abrasive machining research machine allowed designing, testing and refining the abrasive machining monitoring and controlling systems. Chapters 4, 5 and 6 explained the process of selection, implementation, validation, and refinement of sensors, the design of a control system to monitor loading and belt life, and the process control actions including belt cleaning, warning due to excessive temperature, or indication of needed belt replacement.
7.2 Application of the Abrasive Machining Monitoring and Control System to an Industrial Machine

The most important objective of this research was to develop and disseminate the technology needed to make improvements in abrasive machining operations found in wood products applications. The key to achieving this objective is effectively transferring this technology to industry. The most effective means of doing this was to interface directly with machinery manufacturers to provide technical assistance in the actual system detail design and implementation of the technology.

Following completion of the prototype system design and validation, the system was adapted for implementation on an industrial machine. Wide belt machines are among the most commonly used abrasive machines in wood industries. Currently, most wide belt machines employ state of the art technology to optimize the sanding process. This has resulted in
tremendous improvements in surface quality, material removal, and power consumption. However, to date many of the opportunities to employ modern process monitoring and control techniques have not been explored or implemented. This is contrary to the recent trends in industry, which involve more automation and less human intervention.

For years, the wide belt machine manufacturers have been implementing systems that include the use of sensors to continuously monitor the process and correct undesired conditions. Proximity sensors have been used in wide belt machines to evaluate movement of the belt during sanding and to optimize belt tracking. Power consumption and temperature sensors have been used to monitor the condition of the tool. Light sensors are used to determine the location of the workpiece on the conveyor belt during machining in order to activate the individual platens on a wide belt machine. In isolated cases, acoustic emission sensors and/or accelerometers have been used to continuously monitor the abrasive machining process.

The application of the abrasive machining process monitoring and control system was explored with a well-recognized woodworking machinery manufacturer (Newman Whitney (www.newmanwhitney.com of Greensboro, NC) in order to determine the technical feasibility of the implementation of the system in one of their machines. The willingness and experience at taking new concepts and developing them into new products made Newman Whitney a logical choice for this part of the research.

The conceptual design and technical feasibility of the implementation of the process monitoring and control system design for use on an industrial wide belt machine was evaluated by Mr. Jim Laster, Executive Vice President and Head of Research and Development for Newman-Whitney.
The discussions and evaluations focused on the technical and practical feasibility of the system and focused on the location (and traversing across the belt) of the sensors and the cleaning device, which is critical to the performance of the system. These design objectives must, of course, be compatible with the sensor application criteria, which includes no reduction of the static or dynamic of the machine, no restriction of the working space, resistant to dirt and dust as well as mechanical, electromagnetic and thermal influences, and reliable performance. The sensors must not affect the devices currently installed in the machine or the replacement of parts and materials such as sanding belts. Furthermore, an important consideration for the cleaning system is to locate the cleaning nozzle as close as possible to belt area nearest the exit of the sanding operation (i.e. the contact between the belt and the workpiece) for the best performance of thermal shock cleaning (CO₂ flakes, dry ice, etc.).

The wide belt machine selected for this initial application is the Newman PST 4000 planer/sander. This machine is a dual station design with a stand alone planing head module and a stand along abrasive machining module. Figure 7.5 shows the in-feed end of the machine (which performs the planing operation).
Figure 7.5 shows the in-feed side of the machine that corresponds to the planer side. The wood is first goes through the planer section for heavy stock removal and then through the abrasive machining section to achieve finer surface quality and prepare the material for the subsequent steps (additional machining or finishing). The main advantage of this machine is that both planing and sanding operations can be achieved in one pass through the machine. Moreover, factory space is saved since only one machine is required instead of in traditional machining where two machines are required.

Figure 7.6 shows the sander end of the PST4254 series wide belt Planer / Sander.
Figure 7.6 shows the abrasive machining end of the machine along with three electric motors. One for the planer head, one for the wide belt and the smallest motor for the feed system (see appendices for technical details of the wide belt Planer / Sander).

Figure 7.7 shows another view of the abrasive machining end of the machine with the access door open to show the wide abrasive belt and tracking system.
Figure 7.7. View of the machine wide belt and roll system.

The location of the cleaning system and the sensors must be such that damage to the machine and interference with other devices is avoided. The out-feed facing side of the belt, as shown in figure 7.7, was selected for sensor installation based primarily on the dust collection system requirements. This location also permits easy access to the system for sensors and cleaning nozzle maintenance.

Once the general location of the sensors was established, the specific location of the traversing rail, which carries the loading detection sensor and cleaning systems, was determined. Based on the requirements of the system, it was agreed that the best location of the traversing system would be located at the highest accessible point of the belt (which corresponds to the highest belt temperature) which provides better performance of the thermal shock action.
Figure 7.8 shows the design and mounting of the traversing rail, which provides the means for the optical sensor (and cleaning nozzle) to continuously monitor the loading on the belt. The sensor and nozzles move back and forth to detect changes in loading during the abrasive machining and thus activate the cleaning process (based on the information from the optical sensor and the thresholds defined).

![Figure 7.8. Design model for the sensor and cleaning nozzle-traversing system.](image)

Figure 7.9 shows the area of the frame selected for location of the temperature sensor. As described in chapters 4 and 5, the temperature sensor is not sensitive to changes in loading or belt wear. It is, however, a good indicator of abnormal behavior such as burning during the machining process. The sensor will be located at the point with the highest temperature of the abrasive process. Thus, if an abnormal condition arises, the sensor will send a signal to the control system indicating that the temperature has reached an unsafe level.
warning the operator of the situation and the recommended action to be taken.

Figure 7.9. Location of the temperature sensor.

As discussed previously, the proper location and coupling of the acoustic emission sensor on the machine is of critical importance. Obtaining the correct and consistent signal from the acoustic emission sensor requires that the signal is primarily coming from the machining process instead of other types of sources. Several researchers have spent years of time trying to identify the best location for the acoustic emission sensor in a machining process. Their findings are: “it depends of the process”. This means that the best location for an acoustic emission sensor is mainly based on the proximity of the sensor to the source of the signal and the coupling between the sensor and the source.

There are many possible locations for the acoustic emission sensor on an industrial
wide belt machine; however, the optimal location depends on not only on obtaining a clean signal, but also the technical feasibility of attaching the sensor to the machine.

Analysis of possible scenarios to attach the sensors to the Newman PST4254 series wide belt Planer / Sander led to several positions; including:

1. The bearing housing of the top roll
2. The top solid roll with a rotary sensor device
3. The underside of the platen on a segmented platen/roll head sander
4. The underside of the platen that supports the feed conveyor belt

Figures 7.10 and 7.11 show possible locations of the acoustic emission sensor to continuously monitor the condition of the abrasive belt.

Figure 7.10. Possible locations of the acoustic emission sensor.
Figure 7.10 shows two possible locations for the resonant acoustic emission sensor. The first location is on top of the bearing housing of the top roll. The second location shown is directly on the steel roll using a rotational device that allows the acoustic emission sensor to be located on surfaces that rotates. Both locations are technically feasible, but each have their own set of disadvantages. Previous research has shown some inconsistency with the signal when a sensor is attached to the bearing housing since it is not easy to separate the acoustic emission signal of the abrasive machining from the bearing related signal. However, the accessibility and easy of mounting the sensor on this location justifies preliminary testing to evaluate the feasibility of monitoring the abrasive belt when the sensor is located on the bearing housing. Rotary type AE sensors can be used to detect AE activity through a rotating drum or shaft such as the wide belt roller. However, it is expected that this location will not be desirable for monitoring the sanding process due to the high rotational speed. An alternative location could be one of the feed rollers close to the belt, which rotates slowly enough to allow for good coupling between the roller sensor and the feed roller.

Preliminary experimentation has shown that locating the sensor on the underside of the belt platen could be a suitable appropriate location. It is important to note that wide belt sander can come in a large variety of configurations and sizes including machines with only a single solid roll, which eliminates the possibility of locating the acoustic emission sensor on the platen. A possible alternative is the feed conveyor belt that transports the parts throughout the machine, which is supported by a platen, which is in intimate and continuous contact with the conveyor belt. This should insure that the AE signal from the sanding process is transmitted from the machining process to the sensor using the platen and the conveyor belt as the coupling agent. This signal should be similar to the location under the
platen on the research machine in which the belt backing, the platen, and a gasket adhesive were used as coupling agents.

Figure 7.11 shows this possible location of the sensor under the feed conveyor belt on a Newman PST4254 series wide belt Planer / Sander.

Figure 7.11. Alternative location of the acoustic emission sensor.

Figure 7.12 shows the PST4254 series wide belt Planer/Sander control panel.
Figure 7.12. Control panel for Newman PST4254 series widebelt Planer / Sander.

The control panel shown in Figure 7.12 allows the operator to manage all the machine parameters. This panel receives input from various sensors on the machine to evaluate when a specific condition arises (such as when the sanding belt is moving and approaching the edges of the sanding rolls) and activates the tracking system that moves the rolls to maintain the sanding belt inside of the specified limits. Therefore, this control panel is already capable of obtaining information from sensors in the machine and taking action based on the status required. Consequently, the control system can easily receive the information from the new sensors implemented to the machine such as loading detection, acoustic emission, and temperature and then take the necessary action based on the status of the process.
Table 7.1 shows a matrix with several of the conditions that the control system would manage.

Table 7.1. Control system actions initiated by sensors.

<table>
<thead>
<tr>
<th>Belt Condition</th>
<th>Acoustic Emission</th>
<th>Optical Sensor</th>
<th>Temperature Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>NA</td>
<td>No action</td>
<td>NA</td>
</tr>
<tr>
<td>Medium Loading</td>
<td>NA</td>
<td>No action</td>
<td>NA</td>
</tr>
<tr>
<td>High Loading</td>
<td>NA</td>
<td>Cleaning</td>
<td>NA</td>
</tr>
<tr>
<td>Sharp</td>
<td>No action</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Medium wear</td>
<td>Warning</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>High Wear</td>
<td>Stop</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Abnormal temperature</td>
<td>NA</td>
<td>NA</td>
<td>Stop</td>
</tr>
</tbody>
</table>

Finally, the process monitoring control system for the abrasive machining process designed for an industrial application is shown in Figure 7.13 and 7.14.

Figure 7.13. 3D plot of the monitoring and control system implementation on an industrial machine.
Figure 7.13 shows a 3D view plot of the design of the sensors mounted on the machine based on the previous discussion on the most appropriate location of the sensor that allows them not only to continuously monitor the condition of the belt but also the cleaning system to remove loading according to the monitoring system. On the other hand, figure 7.14 shows the details of the location and configuration of the transverse movement device (detail A) and the optical sensor location to measure belt loading (detail B).

Figure 7.14. Detail of the monitoring and control system implementation on an industrial machine (detail A – transverse device and detail B – optical sensor).
8. CONCLUSIONS AND FUTURE WORK.

This research addressed the use of process monitoring and control techniques for improving productivity and reducing costs for abrasive machining applications in the wood products industry. The research included a complete literature review of abrasive machining and an extensive experimental program which provided a solid background in all aspects of abrasive machining, including; the abrasive machining process as related to wood products, abrasive belt wear mechanisms for woodworking applications and the design of abrasive belts for these applications, the characteristics of various sensors which could be useful in monitoring abrasive machining processes (including acoustic emission, vibration, optical, and thermal sensors), and the use of belt cleaning techniques for extending belt life by removing belt loading.

Based on the background research and experimental investigation, a process monitoring and control system that provided online detection of belt loading, belt wear, and belt/workpiece interface temperature was designed and developed into a working prototype system. This system used a combination of sensors to provide a reliable method of assessing belt loading and belt life. The process control research led to the use of process monitoring sensor signals to activate a dry ice blasting system, which effectively cleans the belt without the need to remove the belt or clean up after the belt cleaning process.

The process monitoring and control system design was verified and refined in the laboratory for both the process monitoring and the process control (cleaning system)
components. The laboratory prototype version of the process monitoring and control system resulted in a substantial improvement in belt life and a reduction in the use of the blasting media (which would result in a major cost reduction for industrial users of abrasive belts). The system has received positive feedback from users and manufacturers of abrasive machinery equipment. Based on the positive feedback from industry, the prototype design has been adapted for use on an industrial wide belt machine. As of this writing, the system is being included as an integral part of a new generation of planer/sander machines being developed by a major US based manufacturer of woodworking equipment.

**FUTURE WORK**

The main future work will be in the optimization of this system as far as the length of blasting time and the threshold levels in which blasting will occur. In addition, work will be conducted on the calibration of this system when using different abrasive minerals, grit sizes, as type of workpiece material. A series of field tests to help in the implementation and adoption of this system into industry is also planned.
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10. APPENDICES

Figure 10.1 Acoustic emission sensor technical information.
Figure 10.2 Acoustic emission sensor calibration sheet.
Wideband Sensors

Wideband sensors are typically used in research applications or other applications where a high fidelity AE response is required. In research applications, wideband AE sensors are useful where frequency analysis of the AE signal is required and in helping determine the predominant frequency band of AE sources for noise discrimination and selection of a suitable lower cost, general purpose AE sensor. In high fidelity applications, various AE wavemodes can be detected using wideband sensors, providing more information about the AE source and distance of the AE event.

Features

- Used in high fidelity and research applications
- Wide frequency response
- Various sensors to choose from

<table>
<thead>
<tr>
<th>Model</th>
<th>Dimensions (dia x ht) mm/ inches</th>
<th>Weight (grams)</th>
<th>Operating Temperature (ºC)</th>
<th>Peak Sensitivity V/(m/s) [V/µbar] (dB)</th>
<th>Operating Frequency Range (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D9202B</td>
<td>18 x 17 / .7 x .65</td>
<td>**</td>
<td>-65 to 125</td>
<td>55' [-53]*</td>
<td>400 - 1000</td>
</tr>
<tr>
<td>D9203B</td>
<td>18 x 17 / .7 x .65</td>
<td>**</td>
<td>-65 to 125</td>
<td>65' [-60]*</td>
<td>150 - 1000</td>
</tr>
<tr>
<td>S9208</td>
<td>25 x 25 / 1 x 1</td>
<td>90</td>
<td>-54 to 121</td>
<td>45' [-85]*</td>
<td>20 - 1000</td>
</tr>
<tr>
<td>UT-1000</td>
<td>18 x 17 / .7 x .65</td>
<td>20</td>
<td>-65 to 177</td>
<td>64' [-73]*</td>
<td>60 - 1000</td>
</tr>
<tr>
<td>WD</td>
<td>18 x 17 / .7 x .65</td>
<td>**</td>
<td>-65 to 177</td>
<td>55' [-62.5]*</td>
<td>100 - 1000</td>
</tr>
<tr>
<td>WDI</td>
<td>29 x 30 / 1.13x.1.16</td>
<td>70</td>
<td>-35 to 75</td>
<td>87' [-28]*</td>
<td>100 - 1000</td>
</tr>
<tr>
<td>WSa</td>
<td>19 x 21 / .75 x .85</td>
<td>32</td>
<td>-65 to 175</td>
<td>55' [-62]*</td>
<td>100 - 1000</td>
</tr>
</tbody>
</table>

Notes:
+ Denotes response to surface waves (angle of incidence transverse or parallel to face of sensor).
* Denotes response to plane waves (angle of incidence normal to face of sensor).
** Sensor supplied with integral cable. Weight of sensor is not available.

Figure 10.3 Wide Band Acoustic emission sensor technical information.
Figure 10.4 Wenglor Optical sensor technical information.
Figure 10.5 EMX ColorMax 1000 color sensor technical information.

R55 Expert™ Series – Specifications
<table>
<thead>
<tr>
<th>Supply Voltage and Current</th>
<th>10 to 30V dc (10% max. ripple) @ less than 80 mA (exclusive of load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>10 mm</td>
</tr>
<tr>
<td>Supply Protection Circuitry</td>
<td>Protected against reverse polarity and transient voltages</td>
</tr>
<tr>
<td>Output Configuration</td>
<td>Discrete and analog output</td>
</tr>
<tr>
<td></td>
<td><strong>Discrete:</strong> One NPN (current sinking) and one PNP (current sourcing)</td>
</tr>
<tr>
<td></td>
<td><strong>Analog:</strong> 0-10 mA</td>
</tr>
<tr>
<td>Output Rating</td>
<td><strong>Discrete output:</strong> 150 mA max. each output</td>
</tr>
<tr>
<td></td>
<td><strong>OFF-state leakage current:</strong> less than 10 µA @ 30V dc</td>
</tr>
<tr>
<td></td>
<td><strong>Saturation voltage (NPN):</strong> less than 2.0V @ 150 mA dc</td>
</tr>
<tr>
<td></td>
<td><strong>Saturation voltage (PNP):</strong> less than 1.5V @ 150 mA dc</td>
</tr>
<tr>
<td></td>
<td><strong>Analog output:</strong> 0-10 mA</td>
</tr>
<tr>
<td></td>
<td><strong>Max. load voltage drop:</strong> 2V max.</td>
</tr>
<tr>
<td>Output Protection Circuitry</td>
<td>Protected against false pulse on power-up and discontinuous overload or short circuit of outputs</td>
</tr>
<tr>
<td>Output Response Time</td>
<td>Less than 50 microseconds</td>
</tr>
<tr>
<td>Delay at Power-up</td>
<td>1 second; outputs do not conduct during this time.</td>
</tr>
<tr>
<td>Sensing Image</td>
<td>Rectangular: 1.2 x 3.8 mm @ 10 mm from face of lens; image oriented either parallel or perpendicular to sensor length, depending on model</td>
</tr>
<tr>
<td>Adjustments</td>
<td>Using push buttons—<strong>Dynamic (+) and Static (-):</strong></td>
</tr>
<tr>
<td></td>
<td>Manually adjust discrete output switchpoint using + or - buttons</td>
</tr>
<tr>
<td></td>
<td>Dynamic TEACH (TEACH on-the-fly) sensitivity adjustment</td>
</tr>
<tr>
<td></td>
<td>Static TEACH sensitivity adjustment</td>
</tr>
<tr>
<td></td>
<td>Light operate/dark operate</td>
</tr>
<tr>
<td></td>
<td>OFF Delay select: 0, 20 or 40 milliseconds</td>
</tr>
<tr>
<td></td>
<td>Using Remote TEACH input (gray wire):</td>
</tr>
<tr>
<td></td>
<td>Dynamic TEACH (TEACH on-the-fly) sensitivity adjustment</td>
</tr>
<tr>
<td></td>
<td>Static TEACH sensitivity adjustment</td>
</tr>
<tr>
<td></td>
<td>Light operate/dark operate</td>
</tr>
<tr>
<td></td>
<td>OFF Delay select: 0, 20 or 40 milliseconds</td>
</tr>
<tr>
<td></td>
<td>Lockout of push buttons for security</td>
</tr>
<tr>
<td>Indicators</td>
<td>10-element <strong>Green moving LED light bar:</strong> displays signal strength relative to switchpoint setting</td>
</tr>
<tr>
<td></td>
<td><strong>LO Green ON steady:</strong> light operate</td>
</tr>
<tr>
<td></td>
<td><strong>DO Green ON steady:</strong> dark operate</td>
</tr>
<tr>
<td></td>
<td><strong>Output Yellow ON steady:</strong> output conducting</td>
</tr>
<tr>
<td></td>
<td><strong>OFF-delay LED indicator:</strong></td>
</tr>
<tr>
<td></td>
<td><strong>SETUP Mode:</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Green ON steady:</strong> 40 millisecond delay</td>
</tr>
<tr>
<td></td>
<td><strong>Green flashing:</strong> 20 millisecond delay</td>
</tr>
<tr>
<td></td>
<td><strong>Green OFF:</strong> no delay</td>
</tr>
<tr>
<td></td>
<td><strong>RUN Mode:</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Green ON steady:</strong> 20 or 40 millisecond delay</td>
</tr>
<tr>
<td></td>
<td><strong>Green OFF:</strong> no delay</td>
</tr>
<tr>
<td>Construction</td>
<td><strong>Housing:</strong> zinc alloy diecast with black acrylic polyurethane finish</td>
</tr>
<tr>
<td></td>
<td><strong>Cover:</strong> steel with black acrylic polyurethane finish</td>
</tr>
<tr>
<td></td>
<td><strong>Lens and light bar display window:</strong> acrylic (glass optional)</td>
</tr>
<tr>
<td></td>
<td><strong>Lens port cap and lens holder:</strong> ABS</td>
</tr>
<tr>
<td>Environmental Rating</td>
<td>IP67; NEMA 6</td>
</tr>
<tr>
<td>Connections</td>
<td>2 m or 9 m 6-wire attached PVC cable with strain relief, or 6-pin Euro-style quick-disconnect fitting.</td>
</tr>
<tr>
<td></td>
<td>QD cable are ordered separately.</td>
</tr>
<tr>
<td>Operating Conditions</td>
<td><strong>Temperature:</strong> -10 to +55° C</td>
</tr>
<tr>
<td></td>
<td><strong>Relative humidity:</strong> 90% @ 50° C (non-condensing)</td>
</tr>
<tr>
<td>Vibration and Mechanical Shock</td>
<td>All models meet IEC 68-2-6 and IEC 68-2-27 testing criteria</td>
</tr>
</tbody>
</table>

**Figure 10.6 R55 Optical sensor technical information.**
SNO GUN-II™ CLEANER

You have just purchased the very latest in dry ice snow cleaning systems, the SNO GUN-IITM manufactured by Va-Tran Systems, Inc. This innovative system employs the use of interchangeable Linear Flow nozzles, Metering Tubes, and Snow Flake generating tubes for selecting exactly the correct flowrate and aggressiveness for your cleaning application. There are at least 9 different flow and aggressiveness combinations that come standard with every SNO GUN-IITM dry ice snow cleaning system. These interchangeable nozzles can be removed and replaced without the use of tools, for your convenience. Va-Tran dry ice snow cleaning systems are presently in use by many companies in a variety of different applications. This system is engineered to provide an environmentally and economically sound substitute for the use of CFC based cleaners in many current applications.

All cylinders should be adequately restrained in an approved cylinder rack or securely fastened to a structural wall or bench clamp unit to avoid any possibility of the cylinder tipping over. Use only approved compressed gas cylinder restraining devices. A generous supply of stainless steel braided hose has been provided to eliminate the need to try to stretch the gun from the cylinder ‘just a little further’. This hose is provided only to transport carbon dioxide to the gun, it should under no circumstances be used as a leash to push, pull, restrain, or tie down a cylinder.

The SNO GUN-IITM cleaning system starts with a Teflon gasket secured by a stainless steel nut that connects to your liquid carbon dioxide source. Make sure that the fittings match, that the Teflon gasket is in place inside the stainless steel nut, and that the nut is wrench tight before opening the CO2 liquid supply line. Please note that there is no regulator in the line. Regulators do not work with liquefied gasses, and this system has been designed to use the full pressure of liquid from the tank.

Connect the SNO GUN-IITM to a room temperature CO2 cylinder capable of delivering liquid CO2. A cylinder marked "Liquid Carbon Dioxide", "Siphon" or "Dip Tube" is the correct type. This cylinder will have an internal pressure of 800 to 1200 psi depending upon the ambient temperature. The Teflon seal will compress easily, and should not be overtightened. Typically 1/4 to 3/8 turn from handtight with a wrench is sufficient to seal the block to the tank. If a leak develops at the tank seal, turn off the tank and drain the line by holding the gun trigger open until all gas vents, then tighten nut another 1/8 to 1/4 turn with a wrench and re-try. A spare tank gasket is included with your unit should the original become distorted beyond use.

The quality of CO2 is of some concern but there is no simple answer regarding which grade is correct for you. A good way to start is to locate a room temperature cylinder of 99.99% pure CO2. This is usually available in cylinders holding 20 or 50 pounds. Pricing varies depending on where you are located but is typically less than $5.00 per pound. You may be able to find it for less than $2.00 per pound if you shop around. Do not use "Welding Grade" CO2 which contains far too much contamination for use in precision cleaning equipment.

In addition to lowering the operating cost of the SNO GUN-IITM, a Va-Tran Systems Purifier provides more dry ice per pound of CO2 resulting in additional cleaning power and efficiency. Purification equipment is priced according to flow rate requirements but $5,000 is typical for a single cleaning station. Please contact Va-Tran Systems for additional information.

If you are using a Va-Tran Systems Purifier, it must be attached to a source of CO2 vapor and never to liquid from a siphon cylinder. Please fully read and understand the instructions provided with the Purifier before connecting the SNO GUN-IITM to a Purifier.

Figure 10.6 Sno Gun Liquid Carbon Dioxide blaster information.
The Newman PST4000 Series Widebelt Planer Sander has been designed to provide increased production volume and increased width requirements in heavy workload environments. Solid steel plate weldments and modular design are trademarks of Newman quality woodworking machinery. The PST4000 Series has been designed and built in America for the American market. Designed to be the heaviest in the industry, the PST4000 Series will provide tight tolerance work and high quality surface finish for all of your tough abrasive finishing requirements.

The PST4000 Series has been designed for quick and easy setup. The heart of the control system is a high visibility color touch screen operator interface. The Newman Abrasive Control System puts system optimization at your fingertips. With the ability to add user designed custom information screens the PST4000 Series Widebelt Planer Sander will make any sanding job quick and profitable.

FEATURES
- ON-SCREEN DATA COLLECTION
- RUN TIME CLOCK DISPLAY
- ON-SCREEN LOAD METERS FOR ALL HEADS
- OVER-THICKNESS SHUT-OFF PROTECTION
- ELECTRONIC DIGITAL POSITION INDICATOR AND AUTOMATIC SET-UP FEATURE
- ANTI-KickBACK FINGERS ON ALL MODELS
- ELECTRONIC PHOTO EYE BELT SENSOR AND QUICK SHUT-OFF
- EASY MAINTENANCE FEATURE SUCH AS SLIDE OUT HEAD ASSEMBLY
- Quietcut™ CUTTERHEAD HEAD
- AIR TENSIONED AND TRACKED ABRASIVE BELTS
- SAFETY DOOR INTERLOCKS
- ENDLESS CONVEYOR BELT
- AC VARIABLE SPEED CONVEYOR DRIVE
- COLOR TOUCH SCREEN OPERATOR INTERFACE
- DIGITAL THICKNESS INDICATOR FOR BED POSITION
- QUICK RELEASE ON ALL SANDER HEADS FOR BELT CHANGE
- 110 VAC CONTROL CIRCUIT
- ELECTRIC BELT TRACKING EYE
- ON SCREEN DATA COLLECTION SYSTEM
- ON SCREEN LOAD METERS FOR ALL HEADS
- OVER-THICKNESS SHUT-OFF PROTECTION
- ANTI-KickBACK FINGERS ON ALL MODELS
- EASY MAINTENANCE FEATURES SUCH AS SLIDE OUT HEAD ASSEMBLY

Figure 10.7 Newman Whitney PST4000 Series Widebelt Planer/Sander Technical Information.
Figure 10.8 Infrared temperature sensor technical information.