CONTROL SYSTEM EVALUATION AND IMPLEMENTATION FOR THE ABRASIVE MACHINING PROCESS ON WOOD

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Continuous process improvement and automation have proven to be powerful tools for the wood processing industries in order to obtain better final product quality and thus increase profits. Abrasive machining represents an important and relevant process in the manufacturing and processing of wood products, which also implies high cost of materials and labor; therefore, special attention to this process is necessary. The objective of this work was to evaluate and demonstrate a process control system for use in the abrasive machining of wood and wood-based products. A control system was created on LabView® to integrate the monitoring process and the actions required, depending on the abrasive machining process conditions. The system acquires information from the optical sensor to detect loading and activate the cleaning system. The system continuously monitors the condition of the abrasive belt (tool wear) by using an acoustic emission sensor and alerts the operator of the status of the belt (green, yellow, and red lights indicating satisfactory, 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. The process control system proved that automation permits enhancement in the consistency of the belt cleaning technique 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.

Keywords: Abrasive machining; Process control system; Loading; Belt life

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INTRODUCTION

Previous research has considered the importance of abrasive machining due to its complexity when performed on wood (Saloni et al. 2010). It was also discussed by Saloni et al. (2010) that loading on abrasives as well as belt life are very critical variables among those that need to be considered and studied in abrasive machining.

Ratnasingam et al. (1999) explained that an increase in material removal rate will inevitably increase the temperature, which could result in an increase of the belt loading, and has been shown to reduce the life of the belt (by prematurely discharging the abrasive belts). Furthermore, Ratnasingam et al. (2002) found that high stock removal rates accelerated belt loading, which can considerably shorten the belt life.

In addition, Date and Malkin (1976) found that a reduction in the performance of the abrasive mineral was associated with clogging from material chips and adhesive particles within the grains for finer grit size.

Moreover, because the more the abrasive becomes loaded with wood fiber material, the lower will be the material removal rates in abrasive machining, as reported by Grivna (2004). 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.

Abrasive machining represents an important investment in the machining process because the sanding belt price per unit is high and the abrasive belt life is short. It is not unusual to spend more than twice the cost of a machine for a year's worth of abrasives. Norton Abrasives specialists' estimates (2006) that a typical wide belt sanding abrasive machine costs $75 per hour of processing (labor and overhead). This is substantially 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.

A multi-level research effort is needed 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 considerable amount of research has been done to understand, perform, and improve the abrasive machining process; from understanding the mineral, abrasive, workpiece, and the machine parameters, to the monitoring of the different variables affecting the process. Thus, Saloni et al. (2010) provided a broad discussion of process monitoring as well as the development of a system to continuously monitor loading with optical sensors, belt life with acoustic emission sensors, and temperature with thermal sensors. Once the sensors were able to monitor the key variables, a set of actions were required to correct and/or warn when a specific situation has arisen. Thus, a control system was designed and implemented.

Control systems have been used and integrated into many applications for years. 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 was 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.

Tönshoff et al. (2002) 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.

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.

Franklin et al. (1994) emphasized the importance of process 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 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.

The objective of this study was to evaluate and demonstrate a process control system for use in the abrasive machining of wood and wood based products.

PROCESS CONTROL SYSTEM

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 detailed analysis of the input or inputs signals and the subsequent output or outputs signal is critical for sensor selection. As discussed in Saloni et al. (2010), the optical sensor signal measures the belt loading level and sends the information to the control system in order to determine the action required (cleaning), on the other hand, the acoustic emission sensor monitors the condition of the belt in terms of wear and warn the user when the belt should be replaced.

Based on the three parameters to be controlled, loading, belt life, and temperature, three different signals were obtained.

The output from the optical sensor was analyzed based on the experimental work. It was observed that this output 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. On the other hand, analysis of the data collected from the AE sensor facilitated prediction of the condition of the belt by monitoring the belt life. According to McIntire and Miller (1987), acoustic emission is the elastic energy that

is spontaneously released by materials when they undergo deformation. They also discussed that sources of acoustic emission include many different mechanism of deformation and fracture. In regards to sanding, potential AE sources are wood fiber fractures as well as machine bearing noise. By measuring the AE signal during idling as well as during cutting, the contribution of the machining operation to the AE signal can be determined.

The Wenglor® optical sensor was used to continuously detect the belt loading.

Temperature monitoring was used as a safety indicator because overheating could cause damage to the operator, machine, workpiece, or abrasive belt.

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.

Figure 1 represents the proposed control 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 alerts the operator to stop the process depending on the condition of the abrasive belt.

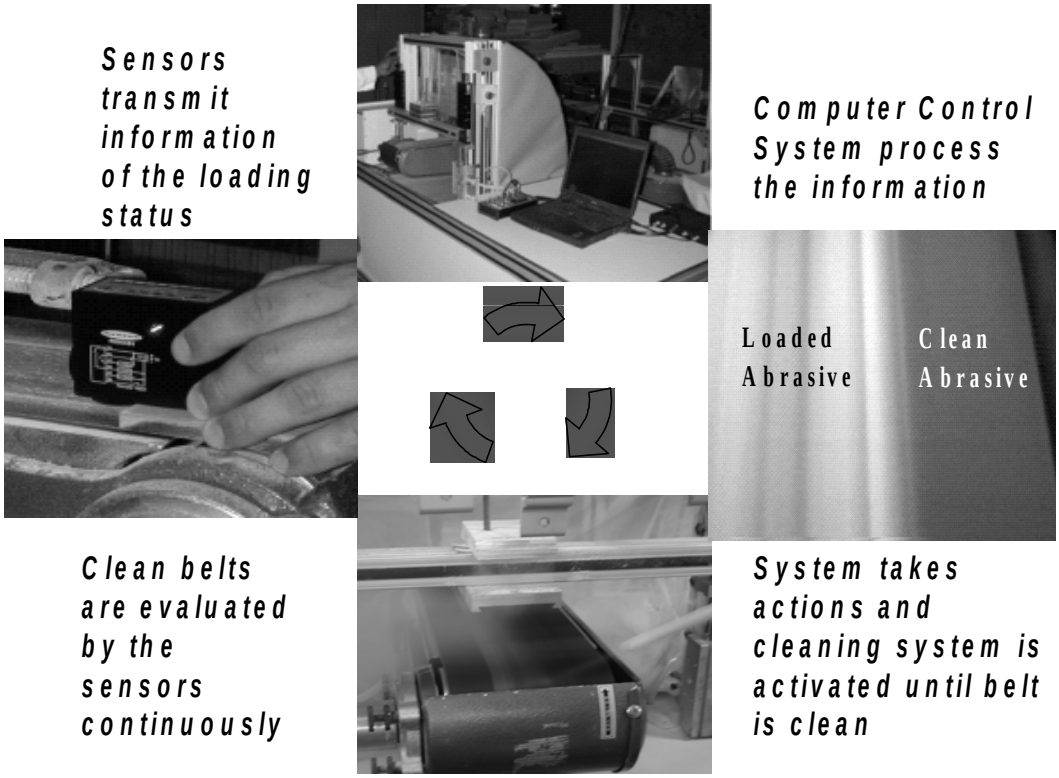

Fig. 1. Components of the process monitoring prototype and belt cleaning control system

The control system design, as shown in Fig. 1, 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. This experimental abrasive machine was designed and built at the Wood Machining and Tooling Research Program (WMTRP). It uses standard 0.15 m × 1.22 m sanding belts of various grit sizes (aluminum oxide in this case). It also has a variable abrasive belt speed (3.62 m/s constant for this experiment) with a 3 hp electric motor and a transmission that permits changing the belt speed, and a weight-frame that holds and supports a group of weights that permits the application of the desired interface pressure (8,618 Pa for this experiment).

The data were 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. LabView® by National Instruments® was used to collect and process the signals from the sensors. It is important to note that the process monitoring and control system was designed keeping in mind the industrial implementation and application. Thus, the system can be easily installed in any industrial abrasive machine. In fact, drawings of a prototype of the industrial implementation of the system can be observed in Saloni (2007).

The analysis of the output showed that a simple discrete control methodology could be used to take the required actions, since each action was basically a onetime 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. It is important to note that the light intensity would change depending on the type of mineral used (silicon carbide belts are normally black), the wood species (white pine will be different than Purple Heart), as well as others; therefore, the thresholds must be adjusted depending on the specific characteristics and variables of the process to be monitor.

Analysis of the data in Fig. 2 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 at which cleaning was required, such as when the slope tended to zero. Moreover, a 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 CO_2 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.

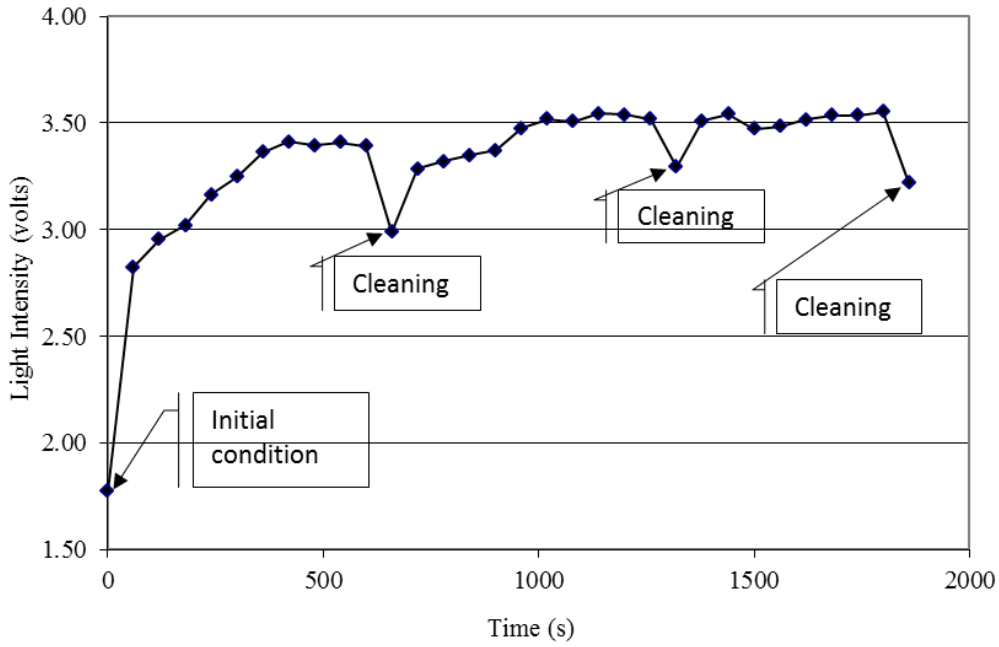

Fig. 2. Wenglor® optical sensor signal after cleaning with CO_2 flakes (white pine workpiece)

Figure 3 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 for the belt life in the control system based on the slope of two consecutive points of the cumulative acoustic emission data. It is important to note that this threshold was established based on using an aluminum oxide abrasive belt type with a grain size of P100 when machining particleboard. Regardless of the type of mineral, grain size, and material used, the threshold was automatically 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.

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 a warning signal on the program to indicate when the belt temperature reaches the maximum safety temperature limit.

Finally, a program in Labview® was designed that integrates the inputs coming from the sensors, compiles the information, compares it with the defined thresholds, and then takes the respective action such as cleaning (activate the cleaning system), belt status (give a signal/alarm to the operator to replace the belt), and temperature level (alert for abnormal increase in temperature that can cause damage to the material, the belt or the operator).

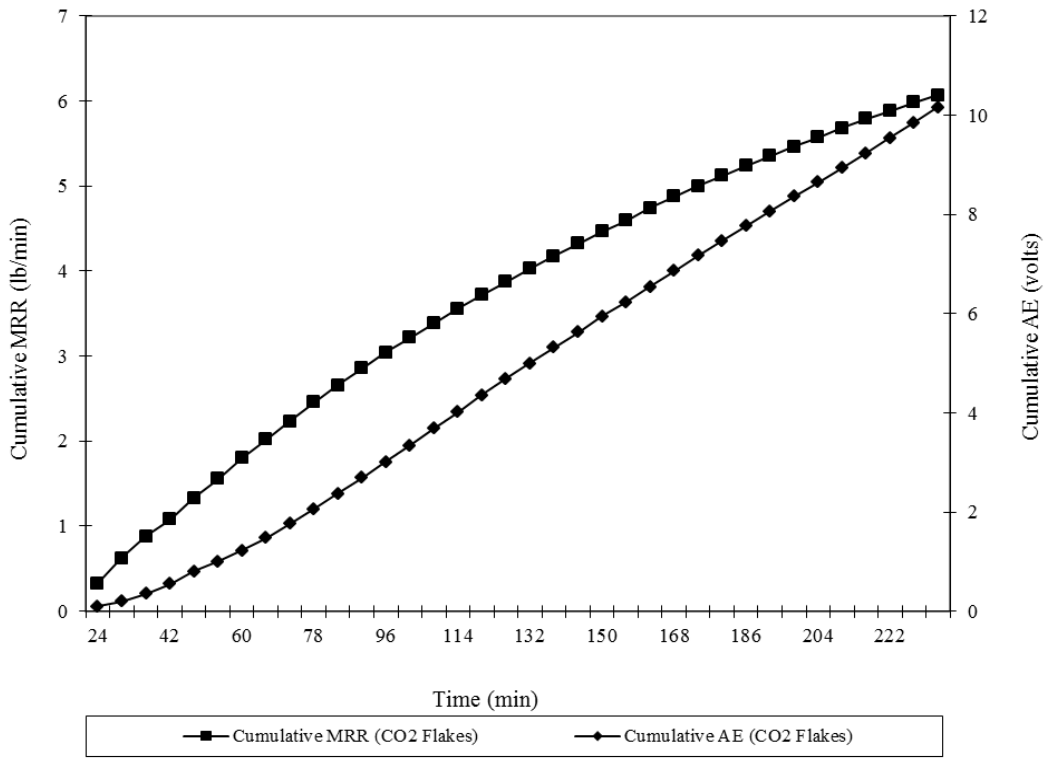

Fig. 3. Cumulative MRR and contact resonant AE signal for belt life threshold

Figure 4 presents the program screen designed in LabView® of the process monitoring and control system for the abrasive machining process. Figure 4 shows three graphs, the loading monitoring, the cumulative acoustic emission root mean square (AE-*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 root mean square (AE-*RMS*) activates the light system (green, yellow and red), indicating the condition of the abrasive belt. In addition, a red light activates when an elevated temperature has been reached. Figure 4 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. It can also be seen in Fig. 4 that the output from the monitoring can be saved into a file on a box called "Destination file name".

Figure 4 also 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.

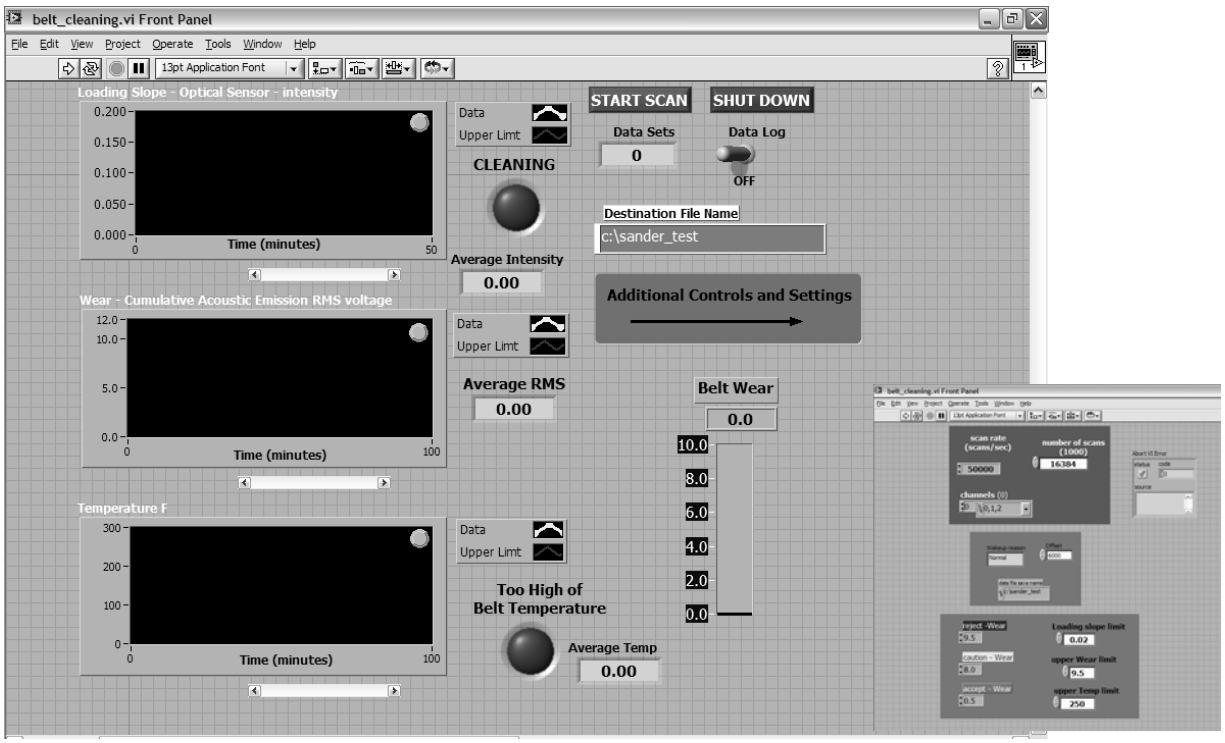

Fig. 4. Process monitoring and control system program developed in LabView®

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®. 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 Fig. 5. A delay was also programmed into the system so that data were 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 different 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 (Fig. 5).

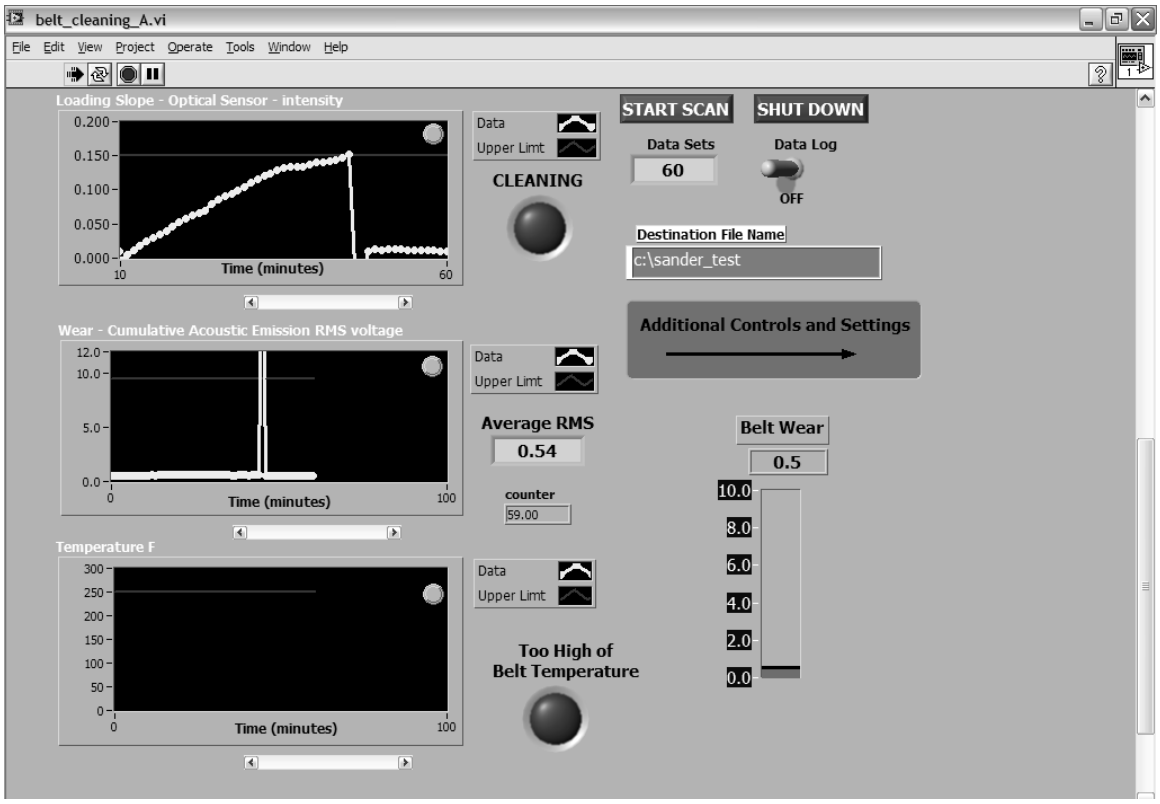

Fig. 5. Cleaning activation due to loading for the control system program developed in LabView®.

Additionally, a yellow light indicated that the end of the life of the belt was approaching and no additional belt cleaning would be performed. Finally, a red light indicated that the belt was worn out and should be changed immediately. 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); it is just to warn the operator that the belt needs immediate replacement, since 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. A single threshold was established for the temperature sensor to warn when the sanding temperatures were too high (Fig. 5).

RESULTS AND DISCUSSION

Results from the research are presented and discussed next in order to show the implementation of the process control system for continuously detecting loading and cleaning the belts when abrasive machining is performed. This was done by performing a series of abrasive machining tests in order to verify the capability of the system to monitor and control the process.

Saloni et al. (2010) included a literature review of abrasive machining and an experimental program that provided a solid background in the various aspects of abrasive machining. Important factors included 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, optical, and thermal sensors), and the use of belt cleaning techniques for extending belt life by removing belt loading.

Moreover, Saloni et al. (2010) discussed a process monitoring system that was developed and implemented for abrasive machining to continuously monitor loading and belt life. Thus, a combination of sensors optical (loading), temperature (safety) and acoustic emission (belt life) were selected, calibrated, and tested.

Saloni et al. (2010) 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 as 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.

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 are 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 temperatures are observed). It is important to note that the system is also able to determine when applying a cleaning technique 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), and it was designed to integrate 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 to 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 shows the different indicators of the condition of the abrasive belt while continuously being monitored by the different sensors. It is important to note that the cleaning action occurs automatically based on the information obtained from the optical sensor until the cleaning process is not economically justified. On the other hand, a 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, while avoiding sudden stoppage of the abrasive machining process. This is in contrast 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 burning of the workpiece.

In addition, Fig. 6 presents the calibration of the optical sensor (intensity calibration) based on the loading level. It is possible to see from Fig. 6 that adjustments in the thresholds are required in order to obtain the desired action such as cleaning, warning, and stoppage due to belt wear or excessive belt / workpiece temperature.

Furthermore, Fig. 6 shows the cumulative action of the acoustic emission signal that predicts the belt status. Moreover, the system was sensitive enough to show that no value is cumulated when there is no abrasive machining action, and then, data starts cumulating again when abrasive machining is engaged.

Finally, Fig. 6 shows the control of the process by monitoring the belt temperature, which varies throughout the process but did not approach the excessive temperature level.

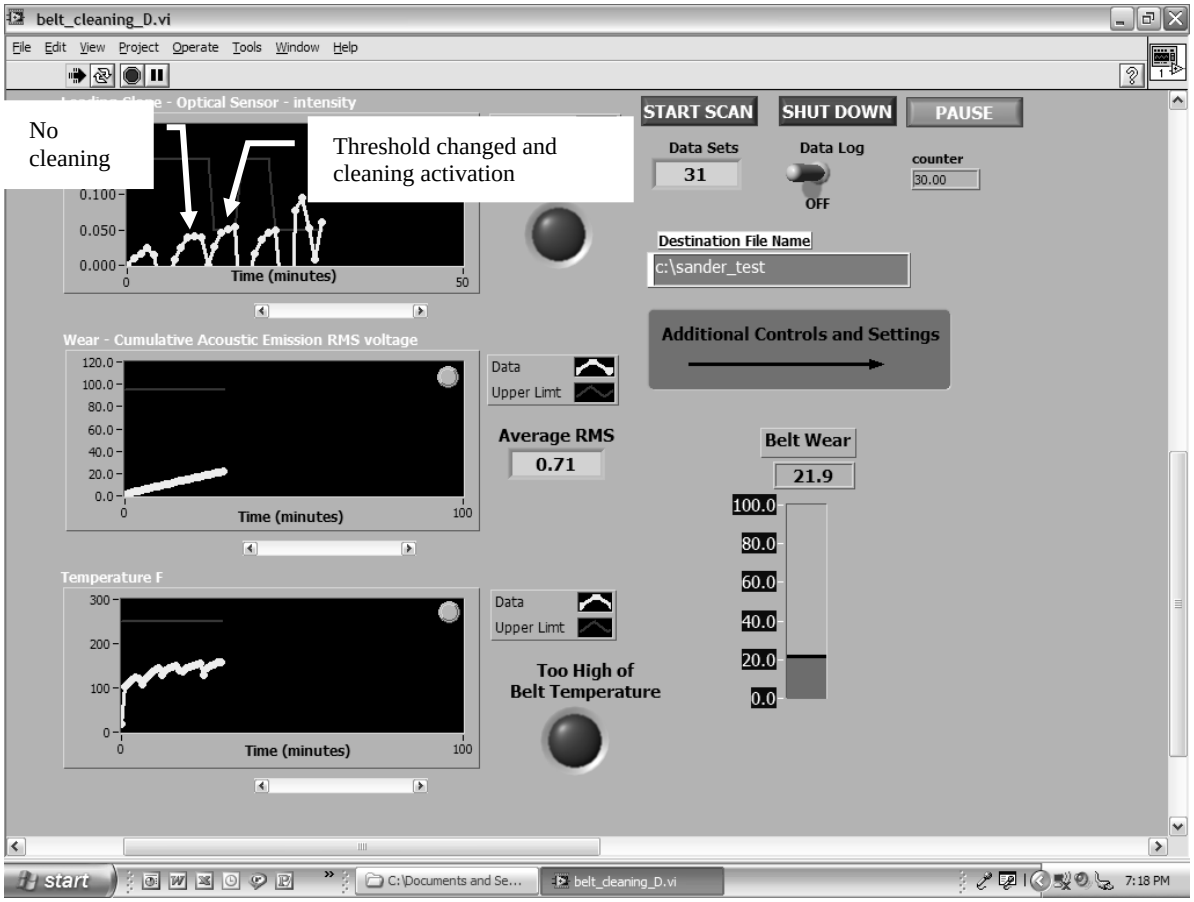

Fig. 6. Screen shot of the control system in action

It was possible to observe that the use of the optical sensor permitted the activation of the cleaning system only when it was required, regardless of the machining time or appearance of the belt. This helps to save cleaning media and results in a reduction in the operation and material costs.

In summary, the main objective of the process monitoring (Saloni et al. 2010) 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 of 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; technically by improving the cleaning process (less blasting for similar results of the material removal rate) and economically by reducing overall machining cost (setup time reduction, less blasting material, longer belt life, higher material removal rate, as well as others).

CONCLUSIONS

1. A control system was designed, verified, and refined in the laboratory for the process control (cleaning system, belt wear signal, and safety signal based on temperature) components.
2. The process control research led to the use of process monitoring sensor signals to activate a cleaning system, which effectively cleans the belt without the need to remove the belt or clean up after the belt cleaning process. 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).
3. In addition, the belt life signal indicated the operation when abrasive belt life was approaching as well as the time when the belt needed to be replaced. It is important to note that the control can be easily modified to automatically stop the machine when life belt is reached if it is desired.
4. Finally, temperature signals were placed as a safety indicator in case the temperature reaches levels that can cause damage to the operator, workpiece, abrasive belt, or machine.

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