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LOW-COST PIEZOELECTRIC TRANSDUCER APPLIED TO WORKPIECE SURFACE MONITORING IN GRINDING PROCESS

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Abstract. *Grinding is a precision finishing process widely used, which has great importance in the industry. Low surface roughness values and a high level of the workpiece surface are expected in this process. However, there are many variables involved, which makes the process monitoring an important aspect to be approached. The objective of this paper is to analyze the workpiece surface with regard to its surface roughness and burn occurrence by using low-cost piezoelectric transducer. To perform this work, workpieces of SAE 1045 steel were used with aluminum oxide grinding wheel in a surface grinding machine. The tests consisted of grinding ten workpieces with different depths of cut, maintaining the other grinding parameters constant. A passive piezoelectric transducer was fixed in the workpiece support, and the signals were collected by an oscilloscope with a sampling rate of 2 million samples per second. Digital signal processing techniques such as digital filters and RMS were used for the extraction of characteristics related to indicative parameters of the surface quality of the workpiece. The results showed a strong correlation between the characteristics extracted from the collected signals, the behavior of the surface roughness of the workpieces and the burn occurrence. Therefore, it can be concluded that the workpiece surface monitoring by the piezoelectric transducer is an efficient alternative when compared to the common methods of monitoring.*

Keywords: *Grinding, Piezoelectric Transducer, Roughness, Burn, Monitoring*

1. INTRODUCTION

In the metal and mechanical industry, grinding is usually the final finishing process of a precision component. This process is used in the fabrication of parts of a wide variety of materials, requiring results such as low surface roughness, control of dimensional errors and shape of the workpiece, maximum tool life and time, and minimum cost (Aguiar et al., 2012).

It is extremely important to assure the quality of the workpiece surface in grinding, and indeed, any damage caused on the workpiece, during the grinding pass, is very costly, since it already has a high aggregated value from the previous manufacturing processes. The most common types of damage in grinding are burn, cracking, and undesirable residual stresses. In the case of metals, the most common cause of damage is excessive heat generation on the ground surface (Aguiar et al., 2006).

According to Malkin (1989), the high temperatures produced in grinding process can cause various types of thermal damage on the workpiece, such as burn, excessive hardening of the surface layer with possible rehardening and increased brittleness, undesirable residual tensile stresses, reduced fatigue strength, and cracking.

Grinding burn occurs during the cutting process when the amount of energy generated in the contact zone produces a sufficiently high increase in temperature in order to cause a localized phase change in the workpiece material. This occurrence can be observed visually from the discoloration of the part surface. Also, burn is expected when a critical temperature (approx. 720°C for steels) is exceeded in the grinding zone (Aguiar et al., 2012b).

A typical surface is characterized by clean cutting paths and plowed material to the sideway of some grooves. However, many other marks can be found such as cracks produced by thermal impact, back transferred material, and craters produced by grain fracture. Other factors that characterize a ground surface are the traverse and longitudinal waviness produced by the random nature of the grinding process and by machine vibration. When considering all these factors, a complete prediction of the surface topography is a complicated problem. A typical parameter that has been used to quantify the quality of a surface topography is the surface roughness, which is rep- resented by the arithmetic mean value, *Ra*, the root-mean-square-average, *Rq*, and the maximum roughness height, *Rt*. In general, the longitudinal surface roughness has a lower value than the traverse surface roughness; therefore, the latter is more frequently used in industry (Hecker & Liang, 2003).

Many transducers have been used over the last years as a monitoring device with the aim to collect all types of generated signals after some manufacturing process. The objective is to allow for behavior analyses correlating all the characteristics obtained about the workpiece surface quality.

In the last decades the use of piezoelectric transducers (PZT) for vibration and noise control, as well as damage detection for structural health monitoring (SHM) applications has been gaining more and more ground (Dugnani, 2009). One of the advantages of these transducers is certainly its low cost and high accessibility. It is even quite possible to combine the use of more than one PZT.

This type of transducer has great importance in many techniques employed for monitoring, and the most widely used piezoelectric transducers are the PZT (Pb-lead Zirconate Titanate) ceramics and MFC (Macro-Fiber Composite), which have thickness in the order of a few tenths of millimeters (Baptista and Filho, 2011). Piezoelectric materials have received the most attention for obtaining electric energy from the surrounding environment for their ability to directly convert vibrations into electrical energy (Sarker et al., 2013).

The root mean square (RMS) value of the acoustic emission signal has been the main parameter studied in previous researches on grinding over a carefully selected frequency band. This signal has provided a reasonable parameter, because it is rich in sound waves carrying a lot of useful information (Aguiar et al., 2012b). The RMS can be expressed by the Eq. 1, where $x(t)$ is the raw signal and T is the integration time constant (Moia et al., 2014).

$$Xrms = \sqrt{\frac{1}{T}\int_{-T/2}^{T/2} x^2(t)dt} \tag{1}$$

Many papers have used signal such as AE and/or statistics to infer a suitable method of monitoring in grinding. In paper of (Aguiar et. al. 2006) a surface grinding machine were used on the experimental tests and also AE sensor in order to collect all the signals. In paper of (Wang et. al. 2001) a set of tests was made using the AE sensor, the signals collected were prepared for a neural network, the objective was detect burn occurrence.

According to Teti et. al, (2010), it is unreliable using a system of monitoring processes that works based on a unique feature. Therefore, the calculation of a sufficient number of characteristic related to the tool and/or process conditions is crucial for machining monitoring systems. This is obtained by signal processing methods that are composed by preprocessing (filtering, amplification, A/D conversion, and segmentation). The parameter that has been studied mostly in earlier studies using acoustic emission has been the root mean square value (RMS) of the filtered signal EA through a carefully selected frequency range.

This paper aims to analyze the workpiece surface with regard to its surface roughness and burn occurrence by using a low-cost piezoelectric transducer as an alternative to the conventional AE sensor widely used in grinding process monitoring. The main contribution of this paper is the use of this kind of piezoelectric sensor, which has not been yet employed in grinding monitoring.

2. MATERIALS AND METHODS

A set of ten tests were carried out with workpieces of SAE 1045 steel upon a surface grinding machine equipped with a conventional aluminum oxide grinding wheel, from NORTON company. The grinding parameters were kept constant in the runs, except the depth of cut that was responsible for different grinding conditions and, consequently, several types of surface finish of the workpieces tested. These grinding conditions were varied from mild to severe, which produced workpieces surfaces with burn, no burn, slight burn and severe burn.

The following parameters were used in the tests: the workpiece speed of 0.124 *m/s*, workpiece width of 7 *mm*, workpiece length of 15 *mm*, grinding pass elapsed time of 3.0 *s*, water-based fluid of 4% as coolant; grinding wheel diameter of 307.8 *mm*; and peripheral cutting speed of 29.00 *m/s*.

The data were collected using a PZT (lead zirconate titanate) component that was disposed on the workpiece holder fixed by silicon. The piezoelectric transducer adopted for the tests had a diameter equal to 15 *mm* (see Fig. 1).

The tests and setup were prepared based on the paper of (Aguiar et al., 2006), which consisted of sequential runs with different depth of cut. An oscilloscope from Yokogawa manufacturer, DL 850, was used to acquire the signal at 2 MHz.

Table 1 shows the depths of cut employed, which varied from the first to the last test. However, some changes occurred with the parameters in some tests as follows: the depth of cut was reduced and the grinding wheel was dressed in order to restore the efficiency of the cutting tool (Moia et al., 2014). The reason for this change is that some desired surface condition was not achieved as predicted in the preliminary tests, making necessary to adapt the parameters for the 9th and 10th tests.

Each test consisted of a single pass of the wheel along the workpiece surface length. During the run, the generated signals were individually stored into the Oscilloscope hard disk. All tests were performed at room temperature and humidity (Marchi et al., 2015).

Figure 1 presents details on how the grinding setup and tests were performed.

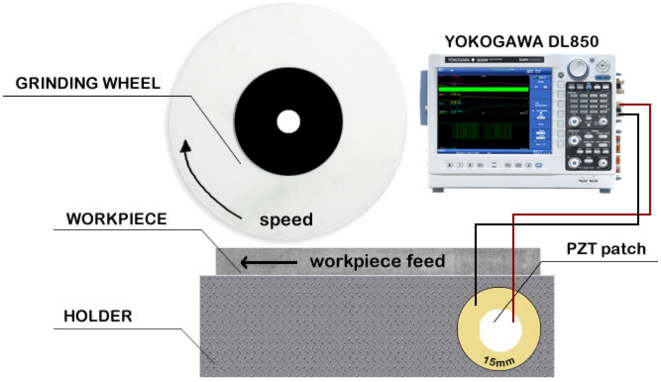

Fig. 1. Experimental Setup.

Table 1 shows information about the tests and from the visual inspection of the workpiece surfaces.

Table 1. Experimental tests with SAE 1045 steel.

Test	Depth of cut [µm]	Visual Condition
1	5µm	No burn
2	10µm	No burn
3	15µm	Slight burn
4	20µm	Slight burn
5	25µm	Slight burn
6	35µm	Slight burn
7	45µm	Severe burn
8	55µm	Severe burn
9(1)	35µm	Severe burn
10(1)	35µm	Slight burn

(1) All the parameters were changed

The data was submitted into digital filters and processed using the software MATLAB for extraction of the characteristics that were relevant for this analysis. With the help of mathematical manipulation, these signals can be treated to obtain information such as the RMS values, standard deviation, etc (Aguiar et al., 2012a). For this paper, the RMS value and the standard deviation of the transducer raw signal were calculated. The surface roughness measurements were made by using a portable instrument provided by Taylor Hobson, model Surtronic 3, and all these values were correlated.

The procedure for signal processing was as following: loading the raw signal of each test; obtaining the RMS values of the grinding passes; selecting the range of signals that corresponds to the exact moment when the grinding wheel is in contact with the workpiece; calculating the RMS values and the standard deviation for each grinding pass; generating the graphs for analyses.

Generally, the more aggressive the cutting depth, the more likely the burn to occur (Wang et al., 2001), and that is because of the cutting forces increase as the material is removed from the workpiece. Some other aspects such as the grinding wheel wear, the internal structure of the grinding wheel clogged with chips and other aspects are also relevant.

During the grinding process, mechanical, thermal and chemical loads are applied to the grinding wheel. One effect of these loads is wear, where macro wear describes the deterioration of the macro geometry consisting of radial wear and edge wear. The other is micro wear, which describes the change of the micro topography referring to wear on the grain level. During grinding, there is by definition a contact between cutting edges and material. This contact is responsible for grain abrasion, leading to grain wear which consists of attritious wear and therewith to flat and blunt cutting edges, micro fracture and macro fracture. The sequence of damage begins with attritious wear in the contact zones accompanied by an increase in the forces per grain or a weakening of the grain retention forces, giving rise to more prominent grit failure and furthermore leading to increased heat generation, which in turn increases wear and damages the workpiece surface integrity (Wegener et al., 2011).

The burn condition on the workpiece surface and the surface roughness are influenced by the grinding wear and according to previous information, the surface roughness values are higher for the workpieces where burn took place. Thus, the surface roughness may be considered a parameter to indicate the existence of burn on the workpiece, since it provokes a metallurgical transformation of the part and in turn a loss of its surface quality with a possible softening and sudden hardening of the material in certain regions (Aguiar et al., 2006).

3. RESULTS AND DISCUSSION

It can be seen in Figure 2 the visual conditions for each workpiece, and can be inferred that low surface roughness is desirable, indeed, this characteristic is an important parameter to be considered for grinding monitoring, indicating the existing relationship of surface roughness and grinding depth (Ma et al., 2014).

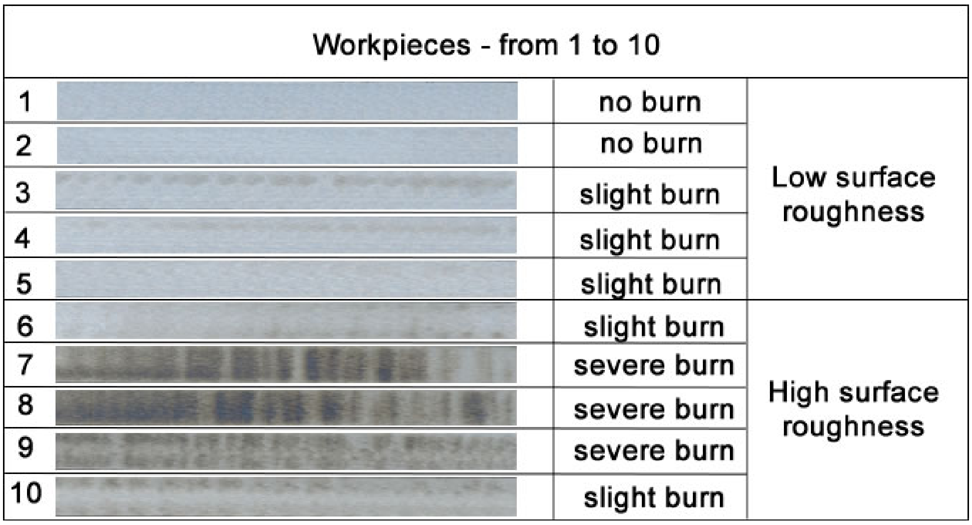

Fig. 2. Workpieces surface with surface roughness.

In this research, surface roughness values lower or equal to one were considered adequate for the ground surfaces. Therefore, surface roughness values higher than one, were considered inadequate, which means the surface quality of the workpiece was compromised. Figure 3 shows the behavior of the surface roughness for each workpiece.

It is possible to correlate the RMS values obtained from the raw signal of each workpiece with its finished condition. The range of the signal selected to produce the RMS values was exactly the moment of contact between the grinding wheel and the workpiece. Figure 4 presents details about the RMS values for each run.

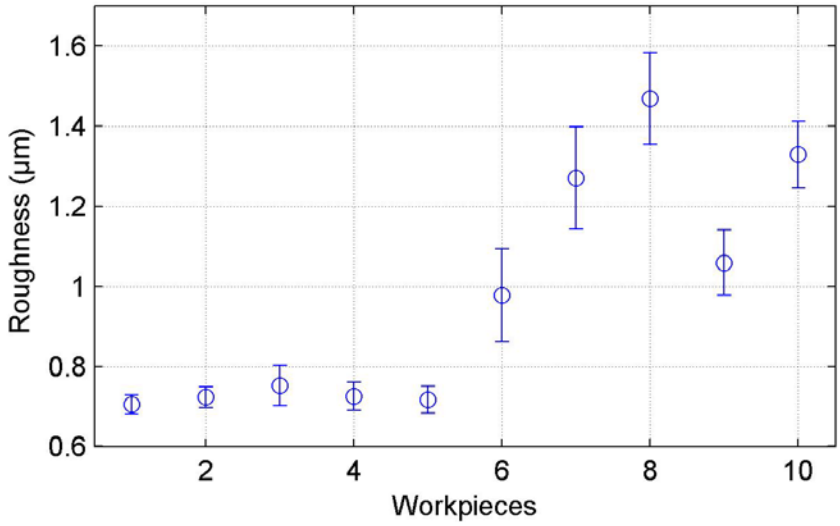

Fig. 3. Average surface roughness and Standard Deviation.

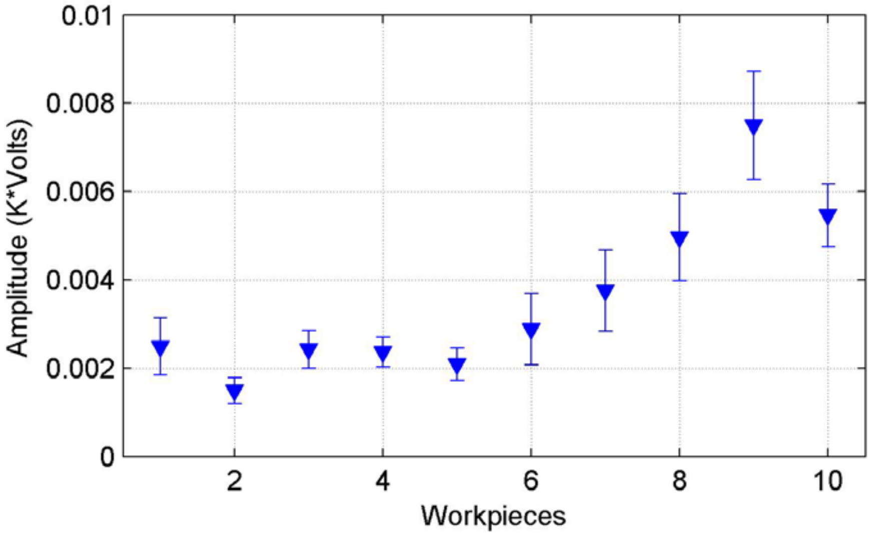

Fig. 4. RMS PZT SAE steel 1045.

According to a comparative procedure found in paper of (Hassui and Diniz, 2003), it is possible to shows the comparison between two distinct values. The graph exhibited in Figure 5 shows the average surface roughness correlated against the RMS values of PZT signal, which makes possible to analyze the behavior of one signal related to another. It can be inferred that high average surface roughness is connected with high amplitudes of the RMS values, especially when conditions of burn were detected.

It can be observed in Figure 5 that, only the last four workpieces were found with surface roughness values higher than 1.0 μm, which specifies a critic and undesirable conditions for the these workpieces. It can also be seen that none of the workpieces had surface roughness values lower than 0.5 μm; the range between 0.5 μm and 1.0 μm is therefore considered acceptable for workpieces with good quality regarding the surface roughness.

The workpieces 3, 4, 5 and 6 had slight burn with low surface roughness values. Nevertheless, bluish temper colors on the workpiece are a consequence of oxide-layer formation. However, this effect is cosmetic and the absence of temper colors on the ground surface does not necessarily mean that workpiece burn did not occur (Malkin, 1989a). Grinding burning is best-detected by optical microscopic examination of the ground surface or by using Nital (Deiva Nathan et al., 1999).

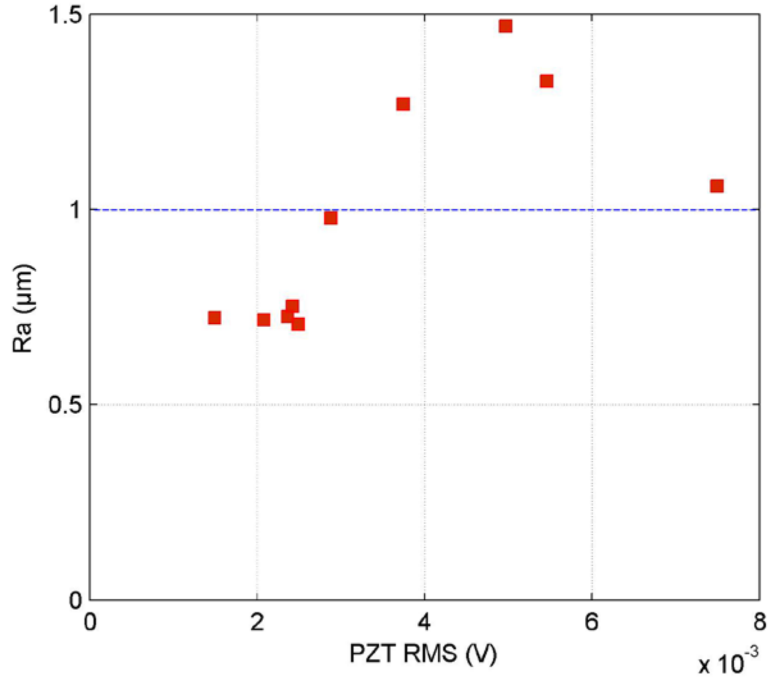

Fig. 5. RMS of PZT against average surface roughness.

4. CONCLUSION

The use of piezoelectric transducer have been shown as an alternative to the AE sensor for monitoring of grinding and, it can be concluded that the results are satisfactory in order to use this transducer for severe burning detection. The RMS values obtained from the raw signals have shown effective to extract important characteristics that represent evidences about the conditions of the finished workpiece. The RMS values were also correlated with the surface roughness, which clearly showed the behavior of good and bad surface finish of the workpieces tested.

Besides the method herein studied, other studies can be investigated by using, for instance, the Discrete Fourier transform to select frequencies bands as well as digital filtering related to burn and surface roughness behavior, and thus contributing to other aspects towards grinding process monitoring using the PZT sensor. Indeed, spectral analysis has been used in many cases to give a better representation of what the signal behavior means when compared to the conditions of workpieces.

From the perspective of manufacturing process, especially grinding, which has a high aggregated value, an effective and low-cost system capable of detecting undesirable problems, such as burn, is really expected for the industry. Thus, the low-cost piezoelectric transducer is a suitable option for this type of application and there are still many features that can be studied and also lots of improvement to achieve in monitoring of grinding process.

5. ACKNOWLEDGEMENTS

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