Damage detection in grinding of steel workpieces through ultrasonic waves

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Abstract. The quality control of the workpieces through reliable tests is of utmost importance in the manufacturing of a precision component. In this context, the monitoring of damages towards automation of the grinding process is essential for the manufacturing industry and of great interest for researchers of the area. This work proposes a technique for monitoring damages in steel parts in the grinding process, using low-cost piezoelectric diaphragms in the emitter and receiver configuration. The tests were performed in a surface grinding machine with aluminum oxide grinding wheel and SAE 4340 steel workpiece. The hardness measurements of the workpieces were carried out to identify the changes occurred from the grinding process. The signals from the transducers were sampled at a rate of 2 MHz. A spectrum analysis of the obtained signals was performed with the aim at characterizing the frequency ranges that were most related to the workpiece surface condition. The results demonstrated that the proposed method is effective to detect surface damage in steel parts in the grinding process.

1 Introduction

The grinding process is a cutting operation performed by a grinding wheel holding randomly distributed abrasive particles [1]. The aim of this process is to conceive workpieces with high finishing quality and accurate dimensions [2]. Many factors, such as the workpiece, the machine, the grinding wheel and the process parameters influence the grinding process, making it difficult to control [3], [4]. Thus, the grinding process is considered highly complex, dependent on a large number of input variables and not stationary, justifying the need of monitoring [5].

The evaluation techniques for the monitoring of manufacturing processes are traditionally divided in two approaches: direct and indirect [6]. Direct methods require the interruption of the process to evaluate the observed component (workpiece, tool or system). Indirect methods use sensors, acoustic emission, force (dynamometer), vibration (accelerometer) and power, jointly with signal processing techniques to extract characteristics of interest from the monitored process.

The piezoelectric diaphragms are an alternative to traditionally sensors used in monitoring the grinding process. These transducers are generally employed in audio signalling devices due to its simple structure, which consists of a piezoelectric ceramic disc adhered to a brass plate [7].

The damage that may occur during the grinding process cause huge losses to the productive chain since the workpiece has high added value from the previous manufacturing processes. The most common types of grinding damage are burn, crack and residual stresses [8]. Burning occurs during the contact of the cutting surface of the grinding wheel with the workpiece, when the amount of energy generated in the contact zone increases the temperature substantially, causing the change of phase in the material [9]. This phenomenon has adverse effects on the properties of fatigue and resistance of the workpiece, and cause irreversible changes in the material microstructure [10]. In general, grinding burn can be visually observed by the bluish temper color on the workpiece surface, but more generally time-consuming tests are required for determining the phenomenon with accuracy [7].

Thus, this work proposes a new technique based on the root mean square (RMS) values of ultrasonic waves for condition monitoring of steel surfaces in the grinding process. In order achieve this aim, low cost piezoelectric diaphragms were used in the emission and reception of ultrasonic waves. In addition, digital signal processing techniques were used, such as the spectral analysis and digital filter. Thus, this work aims to open new possibilities of condition monitoring of workpiece surface in grinding process and also contribute towards its automation.

2 Material and Methods

2.1 Experimental Setup

The grinding tests were carried out in a surface grinding machine from Sulmecânica, model RAPH 1055, with an aluminum oxide grinding wheel, from NORTON company, model 38A150LVH. The workpiece used in the test was SAE 4340, with dimensions 150 x 7 x 43 mm, respectively length, width and height. The tests consisted of a single grinding pass through the workpiece surface, with a cut depth of 20 μm. To promote damage intentionally to the workpiece while grinding, the cutting fluid was not used. The peripheral speed of the grinding wheel (vs) of 29 m/s and the workpiece speed (vw) of 0.124 m/s were set constant during the tests. Two low-cost piezoelectric diaphragms of lead zirconate titanate (PZT) were attached to the workpiece holder. An oscilloscope, model DL850, from Yokogawa company, collected the signals at a sampling rate of 2 MS/s. A data acquisition system (DAQ), model USB-6221, from National Instruments, was employed to generate the excitation signal to the PZT emitter. This signal consists of a chirp with frequencies from 1 Hz to 250 kHz. The time window of 500 ms for the excitation signal was used. In addition, five equally-spaced excitation packages were sent to the PZT emitter in order to verify the repeatability of the measurements.

2.2 Workpiece surface assessment

The workpiece surface assessment was performed through visual inspection and hardness measurements. These evaluations were carried out before and after the grinding process, i.e., when the workpiece is intact and damaged, respectively. The visual inspection was initially performed through visual inspection (naked eye) and then by analysis of high-resolution images (1200 dpi) obtained from a G4050 Hewlett-Packard scanner. The workpiece surface hardness was measured by a microhardness tester, model HM211, Mitutoyo. The indentations were performed with a load of 300 g at 12 equally-spaced locations along the workpiece surface, and three repetitions were conducted. The hardness measurements were taken in accordance with the ASTM E92 standard.

2.3 Signal processing

The data set from the tests was digitally processed in MATLAB. First, the selection of three data packages out of five available was carried out, i.e., the data packages # 2, 3 and 4 were selected. The data packages # 1 and 5 were discarded, as to ensure the integrity of the selected signal packages. The selected packages were composed of the excitation (emission signal) and the received signals. A study of the received signal spectra was performed using the Fast Fourier Transform (FFT). The FFT magnitudes were computed for each selected package and then the mean values obtained. The purpose of this procedure is to find the frequency bands that are strongly related to the workpiece surface conditions. The criteria for selection of bands herein described was based on the work [7]. According to these authors, the best frequency bands are not necessarily those with the higher peaks in the spectrum, but those with the greatest magnitude differences between the conditions that are related to the surface of the part.

3 Results and Discussion

3.1. Workpiece surface assessment

The surface images of the SAE 4340 workpieces for two grinding conditions, normal and severe, are shown in Figure 1. The difference in color is the main feature visually observed between the surfaces, i.e., the undamaged surface at the top of Figure 1 shows uniform light grey color, while the damaged surface at the bottom of Figure 1 shows a darker color dubbed bluish temper color. This phenomenon is caused by the oxide layer that is formed during the removal of material [11]. According to [12], the workpiece burn is accompanied by reaustenization at the surface layers of the workpiece, which gives rise to a re-hardened zone near the surface and a softened, tempered zone beneath it. Thus, based on the previous statement and the behavior of hardness shown in Figure 2, it can be clearly seen in this figure a significant difference in values between the healthy (baseline) and damaged workpiece, i.e., there exists a re-hardened zone close to the surface of the damaged workpiece (higher hardness values), which is the characteristic of grinding burn.

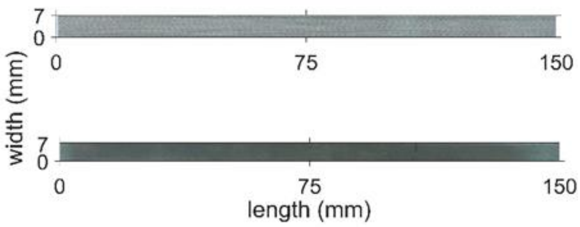


Figure 1. Workpiece conditions, at the top: normal, and the bottom: severe.

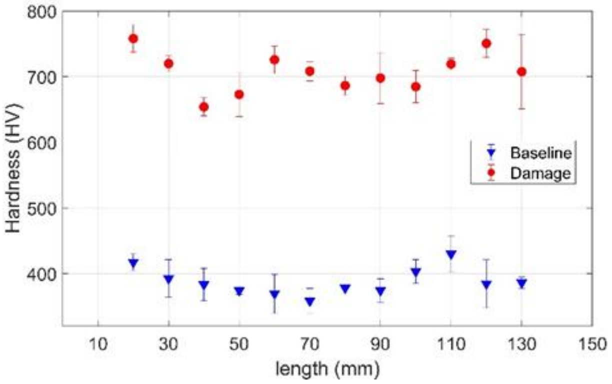


Figure 2. Hardness for the workpiece conditions.

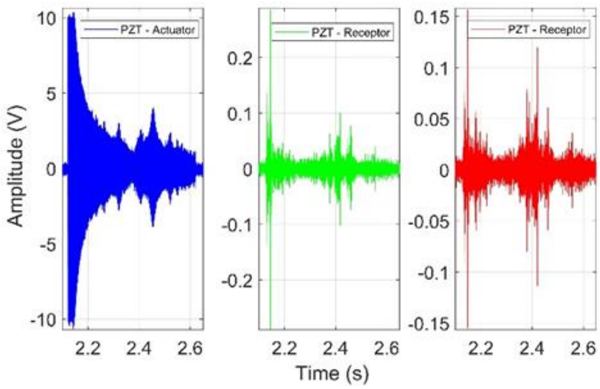
3.2 Signal processing

The excitation signal (chirp) and the received signal of the piezoelectric diaphragms for both grinding conditions, normal and severe, are shown in Figure 3. It can be observed that the amplitudes of the signals for both conditions (Figure 3b and 3c) are similar, however, the received signal for severe condition (burn) in Figure 3c, has more frequency components. This behaviour can be elucidated by the microstructural changes that occurred in the workpiece after the severe grinding process, enabling the transmission of a greater amount of frequencies in contrast to the workpiece in normal grinding.

The average spectrum of the received signal for each workpiece surface condition, normal and burn, is shown in Figure 4. It can be observed that the activity of the spectrum is greater at higher frequencies, i.e., from 100 kHz to 170 kHz. In addition, the higher amplitudes are seen for burn condition. As it is well known, the wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. The velocity of sound waves in a certain medium is fixed, which is a characteristic of that medium. As can be noted from the mentioned relationship, an increase in frequency will result in a decrease in wavelength. For instance, the velocity of longitudinal waves in steel is 5850 m/s and that results in a wavelength of 5.85 mm when the frequency is 1 MHz. Therefore, the higher amplitudes observed for the damaged workpiece at higher frequencies may be explained by the change in the material microstructure, i.e., the change in the medium characteristic played a key role in the propagation of the ultrasound waves. In order to extract additional signal features related to the workpiece conditions, and based on the criteria presented in section 2.3, a frequency band of 120 kHz to 150 kHz was selected and, in turn, the received signal packages were digitally filtered into that band.

The RMS values were computed for each 32 samples of the received signal packages with and without filtering for both workpiece conditions, and then the mean and standard deviation were calculated. Figure 5a shows the mean RMS values and standard deviation for the unfiltered received signal packages. It can be observed in this figure slightly higher mean RMS values for the undamaged workpiece (Figure 5a), which is about 6%.

The decrease of the RMS value for the damaged workpiece may be due to some cancelation of frequency components in the whole spectrum when the material undergoes metallurgical changes, but such behavior must be better investigated.



(a) (b) (c)

Figure 3. Received and emitted signals from piezoelectric diaphragms in two grinding condition: normal (a), severe (b)

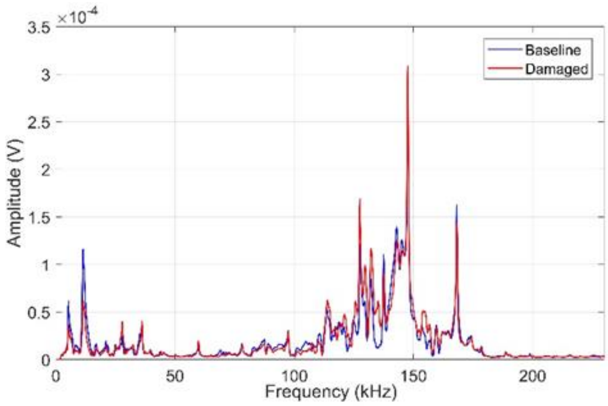


Figure 4. Average spectrum of received signal for normal and burn conditions

These results show, however, a low sensitivity of the RMS values to detect damage to the workpiece, and then such a monitoring system would be a little attractive for practical implementation. On the other hand, a significant difference of about 50% between healthy and damaged workpieces is observed when the received signal packages are filtered into the selected band, as shown in Figure 5b. In this case, an increase of the RMS value is observed when the damage occurs, which can be explained by the behaviour of the signal amplitudes within the selected frequency band, i.e., the damaged workpiece presented higher amplitudes levels. Finally, it is worth mentioning that the standard deviation values were very small, which show the consistency and repeatability of the technique The proposed method presented satisfactory results and its main difference compared to other methods that identifies surface damage in grinding, as presented in [7], [9], [11], is the simplicity and cost of this method.

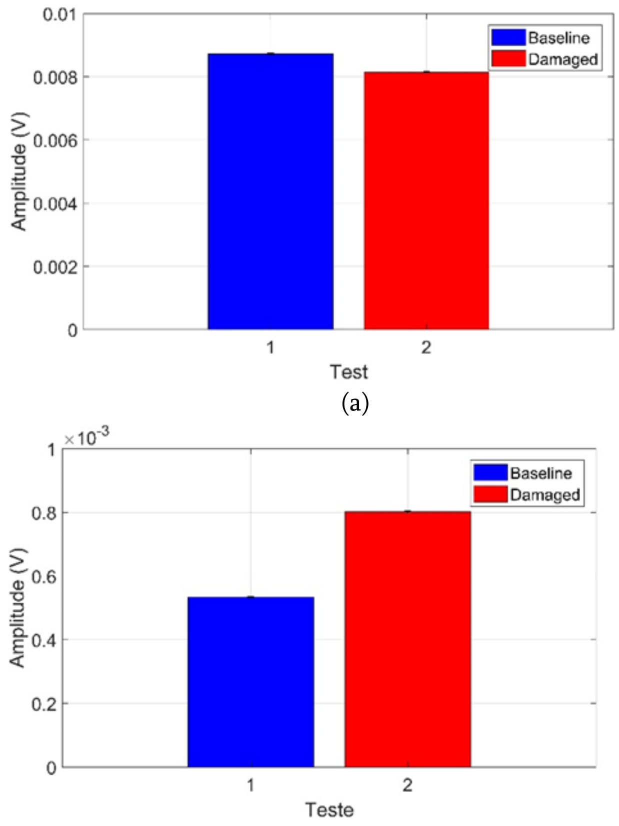


Figure 5. Mean RMS values and standard deviations for healthy and damaged workpieces: (a) unfiltered received signal packages (b) filtered received packages

4 Conclusion

This paper proposed a new damage detection technique of SAE 4340 steel workpieces in the grinding process. An experimental setup using low-cost piezoelectric diaphragms in the emitter-receiver configuration was built. Tests were conducted in such a way that signal packages regarding the healthy and damage workpieces were acquired at high sampling rate during the grinding process. The study of the emitted and received signals in time and frequency domain was accomplished, which showed important features related to the workpiece conditions as herein described. In addition, this work has investigated frequency bands of the received signals that are best related to the surface condition. It can be concluded from the unfiltered signals that there is a low sensitivity of the RMS values to detect damaged in grinding process, and therefore it is unattractive for practical purposes. On the other hand, the filtered signals have shown a good response of the RMS values when the grinding burn takes place, which represented a difference of 50% between the conditions studied. Therefore, the RMS values computed from the filtered signals for a proper frequency band can be useful to detect grinding burn. Notwithstanding, the results presented in this work are preliminary and, therefore, further investigations need to be conducted towards improvements and verification of the method proposed.

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