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Monitoring of the Ceramic Kerf During the Laser Cutting Process through Piezoelectric Transducer †

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† Presented at the 6th International Electronic Conference on Sensors and Applications, 15–30 November 2019; Available online: https://ecsa-6.sciforum.net/

Published: 14 November 2019

Abstract: Advanced ceramics are widely used in industry due to their unique properties. However, the machining of ceramic components by conventional methods is difficult due to their high hardness and brittleness. In this sense, laser beam machining (LBM) is presented as an alternative to conventional methods, enabling the machining of workpieces through more accurate and less invasive techniques. Despite the advantages of laser machining, the process still needs to be studied in detail, as advanced ceramic machining is considered a stochastic process. Thus, real-time monitoring systems are required in order to optimize the ceramic laser machining. Therefore, this paper proposes a novel method for monitoring the cutting kerf in the laser cutting process of ceramic components using low-cost piezoelectric transducer (PZT) and digital signal processing. Tests were performed on the surface of an alumina ceramic workpiece under different machining conditions. The cutting kerf was measured by a digital microscope and the raw signals from the PZT transducer were collected at a sampling rate of 2 MHz. Time domain and frequency domain analyses were performed in order to find a frequency band that best correlates with the process conditions. Finally, a linear regression was calculated in order to correlate the PZT signal and the measured kerf. The results showed that the piezoelectric transducer was sensitive to the acoustic activity generated during the process, allowing the real-time monitoring of the cutting kerf. Thus, the approach proposed in this paper can be used efficiently in the monitoring of the laser cutting process.

Keywords: laser machining; ceramic; piezoelectric transducer; monitoring; digital signal processing

1. Introduction

Advanced ceramics have become a significant industrial material and have been widely used in many applications due to their excellent properties, such as high thermal, electrical and corrosive resistance, higher chemical stability, temperature strength, superior wear resistance, and high hardness [1].

However, the main characteristics of ceramics can be a limiting barrier in their manufacture. The machining of ceramic components by traditional methods is very difficult due to its high hardness and brittleness. Thus, laser machining has emerged as a good alternative for the manufacture of complex ceramic structures at high material removal rates. Laser machining is characterized as a thermal, flexible and non-contact process widely used for many applications in the manufacturing industries, such as aerospace, electronics, automobiles, and civil structures [2,3].

The thermal properties of ceramics (low conductivity and thermal diffusivity) makes them suitable for laser machining. The material removal process consists of a heat source concentrated on the surface of the workpiece, which absorbs the photons of light from the laser beam, converting the energy into heat. The material layer is first heated to fusion, vaporization or chemical change, and then easily removed by an assist-gas [4].

In laser cutting, the quality of the cut depends on the appropriate selection of the process parameters, e.g., cutting speed and laser power. The cutting quality can be assessed by the dimensional characteristics of the cut, such as the kerf width and the kerf deviation along the machined surface. A uniform kerf with a very small width is desired [5,6].

During laser cutting of brittle and low thermal conduction materials such as ceramics, there is the presence of high thermal gradients which generates thermal stress on the workpiece. An undesired presence of microcracks and cut deviation may appear, compromising the cut quality, thus it is important to control the process to avoid these thermal effects [7]. Monitoring of the laser cutting process is very important as it enables the evaluation of the surface quality of the workpiece, the extraction of the process characteristics, and the process control through the correct choice of the machining parameters. According to Lauro et al. [8], the detection of the acoustic activity generated during the machining process by means of acoustic emission sensors (AE) is an effective way to monitor machining processes. The AE sensors detect acoustic waves emitted by the material when exposed to a rapid release of energy in the form of mechanical stress or strain. Kek and Grum [9] showed AE monitoring in the laser cutting with the PZT contact sensors and the results presented a higher level of AE in the presence of a higher volume of dross and, consequently, low quality of the cut, showing that it is an efficient way to control the surface quality of the workpiece.

Viera et al. [10] proposed the use of a low-cost piezoelectric transducer to analyze the quality of the ceramic surface during the grinding process. The authors compared the results of the PZT transducer with a conventional AE sensor, and the results show a similarity between the both sensors. The use of low-cost PZT transducer has been reported in many researches in various applications due to their simple structure, and presents as an alternative for machining monitoring [11].

Therefore, this work proposes a novel method for monitoring the kerf in the laser cutting process of advanced ceramics using low-cost piezoelectric transducer and digital signal processing. The study considered the variation of the kerf width along the cutting region. The application of the low-cost PZT transducer in the laser cutting process has not been found in the literature, which makes this work a novel and significant approach to the industry.

2. Signal Processing

The signals collected during the laser cutting process provide information about the process characteristics and performance. Signal processing is performed digitally through statistics, which aims to extract characteristics from the signals and correlate them with a particular phenomenon studied, e.g., surface roughness, tool wear, burn or kerf.

The root mean square (RMS) statistic is the most used in the manufacturing process monitoring and can be expressed using the following Equation (1):

$$AE_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} AE^2} \quad (1)$$

where AE is the raw acoustic emission signal, and N is the number of discrete samples (i) considered in the calculation [12].

In addition to the RMS calculation, another widely used parameter in signal analysis is the discrete Fourier transform (DFT), which transforms the signal from the time domain to the frequency domain. The DFT calculation is usually implemented through the fast Fourier transform (FFT) due to its simplicity and better computational performance. Both frequency domain parameters result in identical results and can accurately separate the harmonic components of the collected signal [13].

3. Materials and Methods

3.1. Experimental Setup and Data Acquisition

The tests were performed in a CNC machine from JDR, model Router A12060, with a coupled laser made of semiconductor, with a maximum power of 15 W. An alumina workpiece (96% aluminum oxide and 4% of other oxides) with 110 mm length x 33 mm width x 9 mm height and a Vickers microhardness of 1339±47 HV1 (JIS R1610-1991 standard) was used in the tests.

Eight cutting tests were performed on the surface of the workpiece, with a length of 30 mm, each test consisted of a single laser pass over the workpiece surface. The distance between the laser nozzle and the surface of the workpiece was kept constant, while four cutting speeds were considered (2 tests for each speed): 3 mm/s, 6 mm/s, 12 mm/s and 20 mm/s. All cuts were carried out using the maximum power of the laser cutting machine. A permanent marker, from Faber Castell in black color, was used to paint the alumina workpiece surface (which is white) in order to prevent the laser reflection on the surface of the workpiece, ensuring greater energy absorption of the laser energy during the cutting process.

A low-cost PZT transducer, 7BB-20-6 model, from Murata Electronics North America, was employed in the tests as an acoustic emission sensor. The PZT transducer was attached to the end of the workpiece surface with a cyanoacrylate glue of medium viscosity, from Tekbond. According to [14], the 20 mm PZT model, used in the tests, has a higher sensitivity when compared to other Murata models.

During the tests, an oscilloscope, DL850 model, manufacture by Yokogawa, was employed to collect the raw PZT signals at a sampling rate of 2 MHz. An amplifier (with a gain of 25) was used to amplify the signals collected.

3.2. Workpiece Damage Analysis

A digital microscope (30 W and 1000x) was used to measure the kerf width values for each cutting speed. In order to facilitate the measurement of the kerf, the surface painting of the workpiece was removed by means of an acetone-based solution. The digital images were obtained for six selected equidistant points along the cutting length, through the images it was possible to measure the kerf width. Finally, the mean value and the standard deviation of the kerf width were calculated for each cutting speed.

3.3. Signal Processing

The signals collected were digitally processed in MATLAB. A low-pass digital filter was applied with a cutoff frequency of 250 kHz. As shown by De Freitas and Baptista [14], the PZT transducer has an efficient frequency response of up to 250 kHz, higher frequencies have attenuations that can lead to erroneous calculations.

The raw signals were divided into 2048-point blocks, which represent approximately 1 ms. Subsequently, the RMS statistic was calculated for each interval, the mean value and the standard deviation were computed and considered for the analysis. An analysis of the signal spectra was performed in order to choose frequency bands that best characterize the cutting conditions, the selection criterion was based on the search for frequency intervals with greater amplitude difference and a minimum of overlap [10]. The analysis in the frequency domain was performed through the FFT calculation.

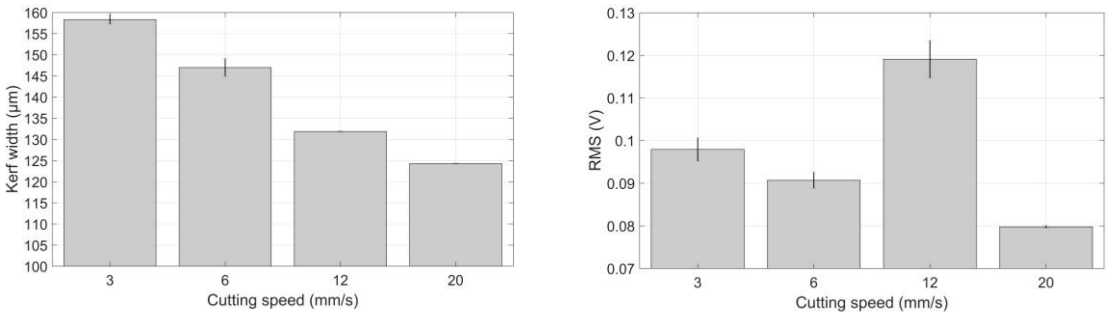
The signals were filtered through a digital bandpass filter in the chosen frequency band, the mean RMS statistic and the standard deviation were calculated. The correlation analysis between the RMS statistics (filtered and unfiltered) and the kerf width was performed by a linear regression and the coefficient of determination (R).

4. Results and Discussion

The results from the digital microscope are shown in Figure 1a. In Figure 1a it can be clearly seen that at low machining speeds the kerf width was larger, this is due to the increased energy intensity during the cutting process.

Laser cutting speed and power are related to the kerf width, slow machining speed increases the contact time between the laser beam and the workpiece surface. For speed of 3 mm/s, there is longer contact time, causing greater exposure of the material to the laser which generates a pronounced energy absorption. Due to the low thermal conductivity of alumina, heat remains concentrated in the cutting region resulting in a relatively wide molten region around the laser beam, so a wider kerf is formed. As the contact time decreases (increasing cutting speed), the heat conduction time and the size of the molten region is reduced, which reduces the kerf width as seen for 20 mm/s [15].

Analyzing the standard deviation values in Figure 1a, it is feasible to observe a significant variation of the values for lower speeds, while for higher speeds there was almost no variation. At low speeds there is a higher heat concentration and the material eventually reaches higher temperatures. High temperatures create thermal stresses, and if these thermal stresses exceed the fracture resistance of the material, damage occurs to the workpiece surface, leading to greater kerf variations along the cutting length [16]. This phenomenon can be seen at speeds of 3 mm/s and 6 mm/s. As the cutting speed increases, the thermal effect is reduced, and as a consequence, there is a reduced damage appearance, as seen at speeds of 12 mm/s and 20 mm/s.

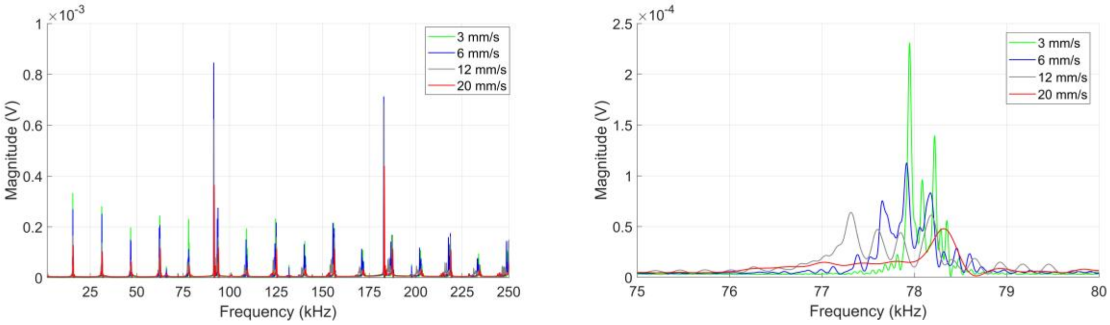


(a) (b)

Figure 1. (**a**) Kerf width and (**b**) RMS mean and standard deviation values of the raw signals.

The RMS mean and standard deviation values of the raw signals for each cutting speed are shown in Figure 1b. It can be seen from Figure 1b that the mean RMS values did not follow the process conditions when compared to the results of Figure 1a, making unfiltered signals poorly suited for monitoring the laser cutting process. The result of Figure 1b was influenced by the high incidence of noise and vibration of the system, which caused greater acoustic activity and, consequently, higher harmonic level. Thus, in order to analyze only the acoustic activity directly related to the process conditions, an analysis in the frequency domain was performed through the application of the FFT, as observed in Figure 2.

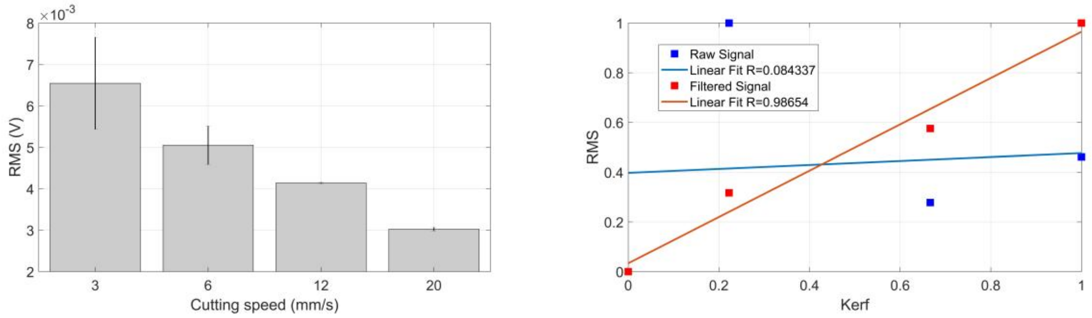
The raw signal spectrums corresponding to each cutting speed are shown in Figure 2a. It can be observed that the spectra presented a similar behavior, with the same frequency peaks but with different amplitudes, which was caused by the process severity. A frequency band with significant amplitude differences between each process condition and minimum overlap was chosen. Figure 2b shows a magnification of the chosen frequency band. As shown in Figure 2b, the chosen band for the frequency analysis was 75 – 80 kHz. As expected, the lowest speed (3 mm/s) generated the highest level of acoustic activity, while at the speed of 20 mm/s the level of acoustic activity was very small.



(a) (b)

Figure 2. (a) PZT spectrum and (**b**) Magnification of the chosen frequency band.

After applying the filter in the selected frequency band, the RMS statistic was calculated. The result of the filtered RMS mean value and standard deviation can be seen in Figure 3a. It is possible to observe that the acoustic activity behavior presented in Figure 1b was corrected with the application of the bandpass filter. When comparing the results of Figures 1a and 3a, the behaviors and the standard deviations obtained were similar. It is observed that at lower speeds, there is greater damage and greater acoustic signal activity. This phenomenon is justified by the higher exposure to the laser beam. At higher speeds, the damage was lower as well as its acoustic activity.



(a) (b)

Figure 3. (a) RMS mean and standard deviation values of the filtered signals and (**b**) Correlation between the RMS statistic (raw and filtered) and the kerf measurements.

Figure 3b shows the result of the correlation between the RMS statistic for the raw and filtered signals and the kerf width. The coefficient of determination R = 1 represents an ideal correlation (linear fit = 45°). The coefficient obtained for the filtered signal was of 0.98654, while for the raw signal was of 0.084337. Demonstrating that the use of filters makes the signals more suitable for real-time monitoring of the laser cutting process. This confirms the feasibility of applying the low-cost PZT transducer to monitor the kerf width during laser machining of ceramic components.

5. Conclusions

The purpose of this paper was to present a new technique for monitoring the ceramic kerf during laser machining using low-cost PZT transducer. The results show that the cutting conditions directly influence the acoustic activity generated during the process and the kerf values. Slower cutting speeds presented higher kerf widths along with higher acoustic activity, while faster cutting speeds presented smaller kerf widths and acoustic activity. This analysis was very significant to demonstrate the validity of the proposed method. It is worth mentioning that there are other frequency bands, which can be studied in future works. Finally, the results presented in this paper are preliminary and new investigations will be needed to improve the method.

Author Contributions: The authors contributed equally to this work.

Funding: This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), grant 001, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ), grant 3006435/2017-9 and the São Paulo Research Foundation (FAPESP), grant 2019/21480-7.

Acknowledgments: This work was supported in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ) and the São Paulo Research Foundation (FAPESP).

Conflicts of Interest: The authors declare no conflict of interest.

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