euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Monitoring of engraved surface textures during femtosecond pulsed laser micromanufacturing

Kerim Yildirim[1], Yam Alcaraz[2], Balasubramanian Nagarajan[1], Tegoeh Tjahjowidodo[2], Sylvie Castagne[1]

[1]*Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, 3001 Leuven, Belgium and Flanders Make @KU Leuven-MaPS*
[2]*Department of Mechanical Engineering, KU Leuven, Jan Pieter de Nayerlaan 5, 2860 Sint-Katelijne-Waver, Belgium*

kerim.yildirim@kuleuven.be

Abstract

Laser texturing with excellent surface quality and geometrical accuracy is made possible using a femtosecond (fs) pulsed laser process with pulse lengths below 10 ps. Considering that a direct monitoring and a real-time control of the fs laser pulsed micromanufacturing process is challenging, it is difficult for operators to produce a geometrically accurate complex microtextured part. Therefore, an in-process monitoring strategy is essential to improving the reproducibility and quality of textures fabricated by fs pulsed laser micromachining. Acoustic emission (AE) is one of the common non-destructive real-time detection techniques for capturing local changes in materials, which can be used for monitoring the fs laser-induced ablation. Previous studies have shown the potential of analysing structure-borne acoustic emission in additive manufacturing, laser welding and pulsed laser machining. However, there is limited literature evaluating its potential for fs laser micromachining. The mapping between the evolution of the AE band and the average grove depth is provided in this work. Laser-induced shock waves are measured for the changes in laser parameters such as laser fluence throughout the processing period. Altered process parameters are attributed to the changes in the textured surface geometry. The results in terms of power spectrum show that the band power has a decreasing trend with increasing cavity depth. This research illustrates how structure-borne AE monitoring can be expanded to fs laser micromachining by correlating AE signals to the depth of the textured geometry.

Femtosecond laser, acoustic emission, laser ablation, surface modification, process monitoring

1. Introduction

Three dimensional surface structuring using a femtosecond (fs) laser is a promising technology for several industrial applications. Fs pulsed laser machining, which is capable of microscale material ablation, is used for the fabrication of micromechanical components, surface functionalization of mechanical parts and medical devices, and structuring of mould. Literature has shown the potential of fs laser micromachining to fabricate micro/nanostructures more precisely than nanosecond laser micromachining [1].
However, the use of the fs laser machining is currently restricted by its incapability to predict accurately the process response due to a large number of process variables and a lack of reliable process models. This leads to an increased process cycle time and manpower cost. Therefore, real-time monitoring of the ablation process is required to track the effect of experimental parameters during laser processing (e.g., the number of laser pulses, laser power) on the process outcomes. This is necessary to account for the impact of random fluctuations in the laser beam parameters (e.g., peak fluence of the laser pulse, pulse duration) and sample properties (e.g., absorbance, reflectance) [2]. Moreover, the integration of real-time monitoring increases the ablation rate as it allows for a better control of the process parameters and refocusing the laser beam to the bottom of the ablated surface.
Various factors (such as plasma and particle shielding) affecting the ablation mechanisms and the resulting surface quality increase the difficulty of real-time control during the ablation process. A few studies have been reported in the past decade on the development of monitoring systems in laser ablation processes using various types of sensors; including photodiodes [3], acoustic emission (AE) sensors [4], and microphones [5]. Compared to the other sensors, AE offers the advantages of simple installation and strong correlation to the shock waves formed by various laser ablation conditions. It is also proven to be an effective sensor for monitoring other laser-based processes such as laser welding [6] and laser powder bed fusion [7].
In this study, a structure-borne acoustic emission (SBAE) sensor is utilized to monitor the shock-waves propagating through the irradiated material during fs laser ablation. The process response is monitored using SBAE for different laser power levels and pulse repetition rates.

2. Methodology

The experiments were aimed to find correlations between the AE signals acquired during fs laser ablation and the corresponding feature dimensions. The schematic of the AE monitoring set-up for fs laser ablation experiments is presented in Figure 1. The monitoring system is integrated into a 5-axis ultrafast laser micromachining system.
The laser beam is emitted by a mode-locked fs laser source (Carbide, Light Conversion) and directed to the sample through the beam delivery module. The tunable parameters include pulse duration from 290 fs to 10 ps, a repetition rate up to 1 MHz, maximum pulse energy of 400 µJ for the fundamental harmonic (λ = 1030 nm), and average power of 20 W. The laser

beam is controlled by a galvo-scanner composed of fast-rotating X and Y mirrors (up to 1000 mm/s) to achieve high-speed laser scanning on the target surface.

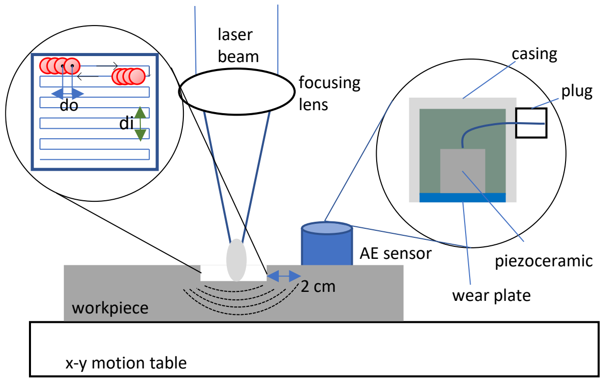

Figure 1. Schematic of AE sensor integration during fs laser micromachining

A telecentric lens with a focal length (f) of 118 mm focuses the laser beam to a 15 µm size spot to obtain an intensity greater than 10^{12} W/cm^2 on the irradiated surface. The focusing lens is mounted on a linear stage, which enables movement perpendicular to the working field. The mechanical system consists of an air-bearing XY-stage assembled on a flat and rigid granite base. The sample was placed on the air-bearing XY stage. Experiments were conducted on 2 mm-thick steel plate samples. The laser-induced shock waves propagating through the sample were detected by AE sensor that was mounted 2 cm away from the ablation zone on the steel plate (as seen in Fig. 1). Glycerin was used as a coupling agent to guarantee a reproducible coupling between the sample and the sensor. For the detection of the acoustic emissions, a wideband AE sensor (AE1045S model, Vallen Systems) was used. It is a structure-borne piezoelectric detector for acoustic emissions with a frequency ranging from 100 kHz to 1500 kHz. The signal was then fed through a preamplifier (AEP5) with a gain of 40 dB. Furthermore, a decoupling box was used to separate the high-frequency AE signal from the DC voltage and measure the AE signal via an ADC-board at 4 MHz sampling rate. By using a trigger generated by the Simulink software, a single measurement file for each layer in each specimen is acquired in waveform and data form on the data acquisition (DAQ) card and is then processed with the MicroLabBox system from dSPACE.

As shown in Fig. 1, rectangular grooves were created in all experimental parts, where parameters pulse distance (do) and hatch distance (d_i) are interpulse and interline (center to center) distance, respectively. To minimize the geometry influence, all the ablated grooves had a constant dimension of 100 µm by 100 µm with a constant number of 10 layers (scanning passes). Each cavity was structured with a different laser fluence by varying the average laser power. Other parameters were held constant (scanning speed – 200 mm/s, pulse duration – 600 fs).

The shape of the ablation crater is measured quantitatively by an optical confocal profiler, Sensofar S-Neox. The dimensions (depth and width) of the ablated groove were measured at three different areas of the scanning region.

3. Result and Discussion

Short time Fourier Transform (STFT) is used to extract the monitoring features. As a result, a spectrogram is generated for each experiment with specified laser parameters – with time resolution of 40 ms. The band power, i.e. the extracted sum of values from a defined frequency range, is taken with a central band of 200 kHz and 400 kHz according to the laser parameters and with a bandwidth of 20kHz.

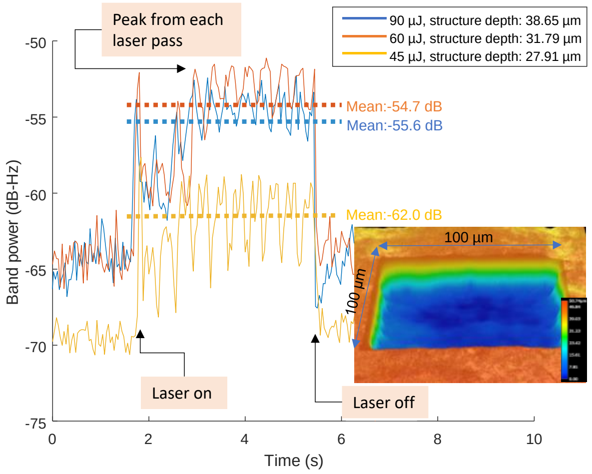

Figure 2. The influence of fs laser ablation on AE power spectrum domain and the depth profile of the ablated cavity

Fig. 2 shows the band power trend during fs laser micromachining for different processing conditions. In each of the measured signals, peaks can be observed that correspond to a single layer pass. Three groups of AE signals under pulse energy of 45 µJ, 60 µJ and 90 µJ are selected for STFT. The depth of the ablated cavity increases, whereas the mean band power drops as the laser fluence increases. All of the signals show a similar trend of repeated peaks for each layer pass. AE signals are produced by laser ablation, hence they are closely linked to laser material interaction. The dynamics of this removal process is governed by the intensity of the laser beam and thus the energy density exceeding the ablation threshold. Consequently, AE is capable to monitor the fs laser ablation process. Besides, there is a correlation between the AE signals and the ablated feature depth, which will be further analyzed for several process conditions with varying laser fluence, pulse duration in order to define a correlation matrix.

4. Conclusion and Future Work

In this work, an acoustic emission system was adopted to monitor the fs laser machining process. A correlation can be seen between the structure depth and the power spectrum of the AE signals. Further advancements in robust signal intensity extraction are required because large uncertainties must be reduced for real-time detection by acoustic emission without any microscopic validation. Furthermore, the AE signals' dependence on the location of the piezoelectric sensor in relation to the AE source must be investigated.

References

[1] C. W. Cheng, X. Z. Tsai, and J. S. Chen, *Int. J. Adv. Manuf. Technol.*, vol. 85, no. 9–12, pp. 1947–1954, 2016

[2] M. Stafe, C. Negutu, and I. M. Popescu, *Shock Waves*, vol. 14, no. 1–2, pp. 123–126, 2005

[3] M. Zuric, O. Nottrodt, and P. Abels, J. *Laser Micro/ Nanoengineering* vol. 14, no. 3, 2019

[4] X. Xie, *J. Mater. Process. Technol.*, vol. 290, p. 116990, 2021

[5] S. Kradolfer, K. Heutschi, J. Koch, and D. Günther, *Spectrochim. Acta Part B At. Spectrosc.*, vol. 179, p. 106118, 2021

[6] M. C. Lu, S. J. Chiou, B. S. Kuo, and M. Z. Chen, *Appl. Sci.*, vol. 11, no. 15, 2021

[7] N. Eschner, L. Weiser, B. Häfner, and G. Lanza, *Addit. Manuf.*, vol. 34, no. p. 101324, 2020