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Optical monitoring of fiber laser based cutting processes for in-situ quality assurance

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Abstract

In this study we present a simple experimental set-up for optical monitoring of cutting processes with fiber laser. The developed sensor uses two Si-photodiodes, each attached to four optical fibers that collect radiation at four symmetrical off-axis orientations around the processing zone. The photodiodes allow monitoring the scattered light from both sides of the sample regardless of the cutting direction. The development allows easy change of the filters as well as the photodiodes in order to monitor different spectral ranges. In this study we focus on a narrow range around the wavelength of the processing laser. At the top of the sample the photodiode signal is related to scattering processes at the sample surface and processing zone. The photodiode shows a constant behaviour when the process parameters give rise to a high quality cut and either saturates or presents noisy oscillations when irregular or incomplete cutting is obtained. At the bottom of the sample, the collected radiation contains information about the exact penetration time as well as laser scattering by the ejected material during the cutting process. An analysis of both signals allows to resolve non-optimal effects such as cutting tears/burrs or incomplete cut zones. In addition, a correlation with the overall cutting quality can be established. This characteristic would allow in-situ process controlling in industrial production tasks.

Keywords: Monitoring; fiber laser; laser cutting; photodiode; quality control.

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1. Introduction

Fiber laser cutting is nowadays a widely established technique for cutting metallic plates and parts. Despite of this, there are still uncontrolled and unknown aspects that influence the process and hence, the overall quality of the result. Therefore, a lot of ongoing research with the aim to optimize the process is still performed. On the other hand the industry demands a maximized production along with high quality of the end product. For this reason, in order to avoid non-optimized results, on-line monitoring and control might be necessary in certain applications.

Regarding laser cutting processes, CO_2 lasers are the most known and broadly sold cutting systems on the market, characterized by a high reliability and flexibility. Nevertheless, with the emergence of modern fiber laser cutting systems, with an ever higher power and enhanced beam quality, new possibilities have been opened up to enhance the cutting performance. Mahrle and Beyer, 2009, described the theoretical aspects of fiber and CO_2 laser cutting based on experimental results and concluded that fiber laser is mainly preferable in thin metal sheet cutting, whereas CO_2 laser is a better choice in thicker sheets with a broad range of thicknesses. In addition, they presented a theoretically achievable cutting speed as function of the sheet thickness, and determined that there is a significant increase in the achievable speed in thin metal sheet fiber laser cutting.

During laser cutting, a moving focused laser beam hits the material surface. The energy of the laser is absorbed by the material, leading to melting of the processing zone and forming a so-called cutting front in the cutting direction. As stated above, the laser radiation is mainly absorbed by the material but it can also be reflected, refracted, scattered or transmitted. For most materials, the most significant physical processes of the laser-material interaction during a cutting process are the absorption and the scattering of the laser beam at both the top surface and the material ejections from the bottom surface. This is the reason why the most used monitoring techniques consist in optical and thermal emission measurements (Purtonen et al. 2014). In Golubev et al. 2010, a two color pyrometer and photodiodes are used to monitor the CO_2 laser cutting of 3, 6 and 10 mm thick steel plates. Kaebernick et al. 1998 developed a spectrum analysis of a co-axially mounted photodiode in CO_2 laser cutting of 3 and 6 mm thick metal sheets obtaining a correlation between striation frequencies and the photodiode signal. A similar technique was used by Adelmann et al. 2015 for an optical cutting tear detection using Si and InGaAs photodiodes. Apart from detecting the perforation of 2 mm stainless steel sheets, they established a relationship between both photodiode signal variations and tear formation. De Keuster et al. 2007, monitored the cutting of thick steel plates with microphones and photodiodes concluding that photodiode signals present much less noise than acoustic signals and do not require advanced signal processing. Furthermore, the three off-axis photodiode monitoring system proved a negligible cutting direction dependence of photodiode signals. The quality and the occurrence of defects, such as loss of penetration or tears, could be predicted by the photodiode signal evaluation.

Instead, there are not many works in the literature related to the use of monitoring signals for in-situ controlling the laser cutting performance in an industrial application. One of these controls may be found in the paper of Wen et al. 2012. In this work the sparks behavior was observed under different cutting speeds by side visual monitoring and a system of coaxial visual detection with closed-loop control was developed to automatically adjust the cutting speed in order to optimize the cutting quality.

In this paper we present results of a monitoring system made by using an optical fiber bundle 4:1 with four fiber ports aiming at the processing zone and the fiber output attached to a Si photodiode. The system captures emissions and scattered light from the processing zone. In this paper, we focused on the scattered laser light by using a 10 nm bandwidth filter centered at 1064 nm placed between the fiber output and the photodiode. The system allows us both to monitor the cutting performance and to detect cutting defects or incomplete cuts enabling the use of control strategies in real applications.

2. Experimental setup

In fig.1 the experimental setup is shown. The monitoring system consists of two photodiodes that receive the scattered light from both sides of the metal sheet. The light is transmitted from the cutting zone to the photodiode trough four symmetrically positioned optical fiber ports for each photodiode. The optical fibers are attached to the laser head thanks to a fixture made using rapid prototyping. This self-made assembly allows the monitoring regardless of the cutting direction. The used photodiodes are two Si detectors, with sensibility in the range from 350 to 1100 nm. The photodiodes are equipped with a 10 nm bandwidth filter centered at 1064 nm, to only detect the laser scattered light, and a neutral density filter adjusted to avoid saturation and record a clear capture of the voltage signal acquired. The processing fiber laser used was a single mode quasi continuous laser source with a maximum peak power of 1.5 KW. The laser output is collimated with a 100 mm collimating unit and attached to a conventional cutting laser head with a 150 mm focusing unit. A home made three linear motor axis machine with a 1 µm precision and travel distance of 650 x 850 x 400 mm (X, Y, Z) has been used for positioning the laser head over the plates to be cut. A 0.2 mm distance is maintained between the top surface of the sheet and the nozzle, leading to an approximately 0.02 mm diameter spot at the metal sheet. For the experimentation and validation of our system, aluminum sheets of 1.5 mm thick are cut using argon as protective gas flow at 18 bar pressure.

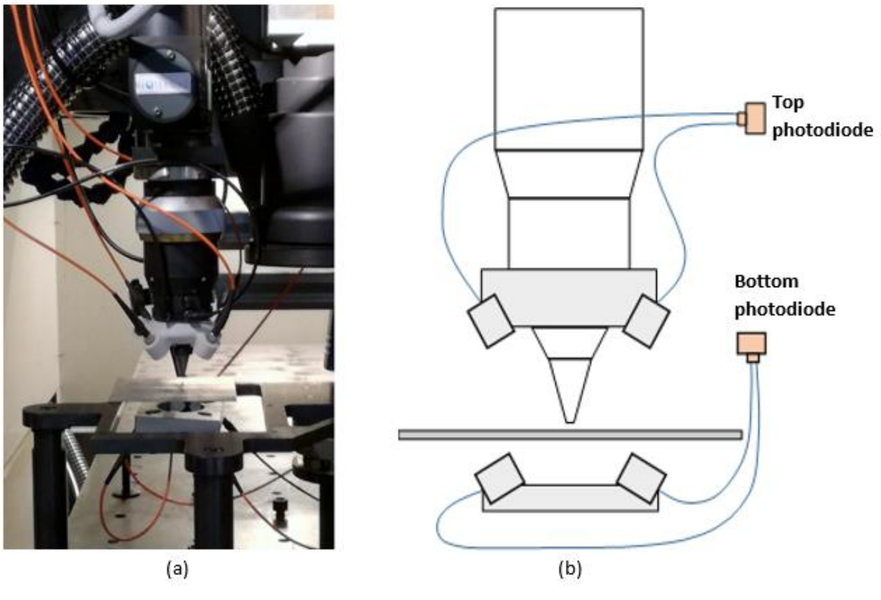


Fig. 1. (a) Experimental setup; (b) scheme of experimental setup.

Experiments with different laser powers and cutting velocities have been performed in order to evaluate the behavior of the acquired signals and the quality of the resulting cuts. Apart from the quality of the cut, the photodiode signal level varies depending on further aspects such as the material finish, the distance from the surface to the nozzle, etc. For this reason, only the signal behavior and the relative signal changes in experiments conducted with same conditions should be considered for analysis tasks. The experimental campaign has consisted in performing 20 mm length straight cuts at different powers and speeds. In order to ensure a constant velocity during the cut, a 10 mm distance before the beginning of the cut is set as the starting point of the movement. This strategy exhibits more clearly the differences of the cuts as function of the speed and allows to obtain the relationship between the velocity and photodiode signal values instead of piercing the material before moving, which results in velocity variation at the beginning of the movement.

3. Results and discussion

3.1. Monitoring Cutting performance

Figure 2 shows the photodiode signals from both sides of the sheet at 450 W laser power and 3800 mm/min velocity. The final result is shown at the bottom of the figure in the pictures taken from both sides of the metal sheet. As observed, at this speed and power, the sheet is not totally perforated at the beginning of the process and tears appear at the top side. After a few millimeters, the behavior improves and a complete perforation is achieved. Since no initial piercing has been established for constant speed measurements, this fact is attributed to the progressive formation of a cutting front in the material as function of the speed and the time elapsed.

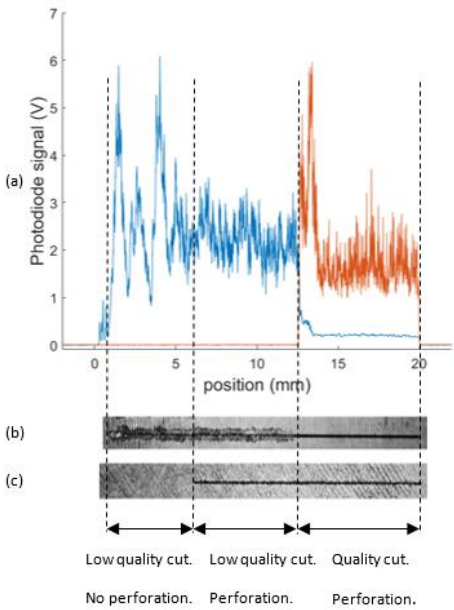
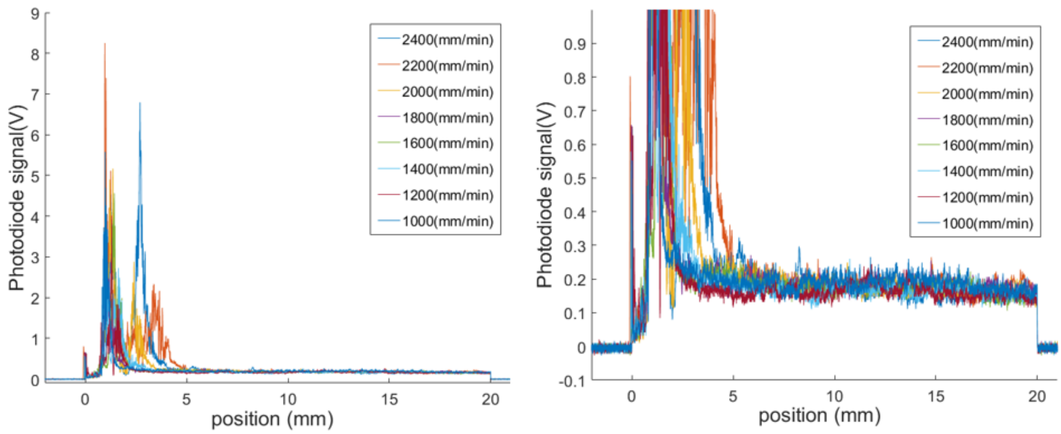


Fig. 2. (a) Signal of top (blue) and bottom (red) photodiodes; (b) cut from top side; (c) cut from bottom side.

The cut can be divided in three sections. In the first one, the cut quality is low and tears appear at the top of the sheet. Then, in the second one, a total perforation is achieved, but tears continue to appear. In the last section, a complete perforation with good quality cut is achieved. As shown, the top photodiode exhibits a noisy behavior when the quality of the cut is not good and a nearly constant value when a complete cut with good quality is being performed. Due to the fact that the filter only permits to capture wavelengths similar to that of the laser, the noisy behavior that corresponds to the low quality cutting performance is attributed to the laser scattering by tears and other non-wished material depositions at the top surface. In addition, when the perforation is achieved without tears at the top side, the scattered light detected in the photodiode decreases significantly and the noise of the signal vanishes. At the bottom side of the Al sheet, the photodiode captures a relative noisy signal when the cut is being performed with good quality. This behavior is attributed to the scattering of the laser beam by the ejected material when the material is completely perforated. Moreover, it seems that the bottom photodiode presents a nearly zero voltage signal when there is no perforation or there is a perforation with poor quality. These results reveal useful information that can be used for developing a control or detector in laser cutting applications, in which the setting parameters are not always optimal for all the parts to be processed (see for example the application described in section 4).

3.2. Signals at the top surface

In order to find a relationship between the signal captured by the photodiode and the cutting speed, different tests as function of the velocity have been performed at constant laser power. In figure 3, the scattered light recorded at the top surface for cuts with velocities from 1000 to 2400 mm/min at 400 W laser power are presented. As shown in the detailed view of the signal at the right part of the figure, the photodiode signal apparently exhibits a nearly constant behavior as the velocity increases. This non-dependence between the cutting velocity and the captured scattered signal at 1064 nm corresponds to the zones in which the cutting quality is high considering the top side of the sheet.



(a) Photodiode signal for different velocities.

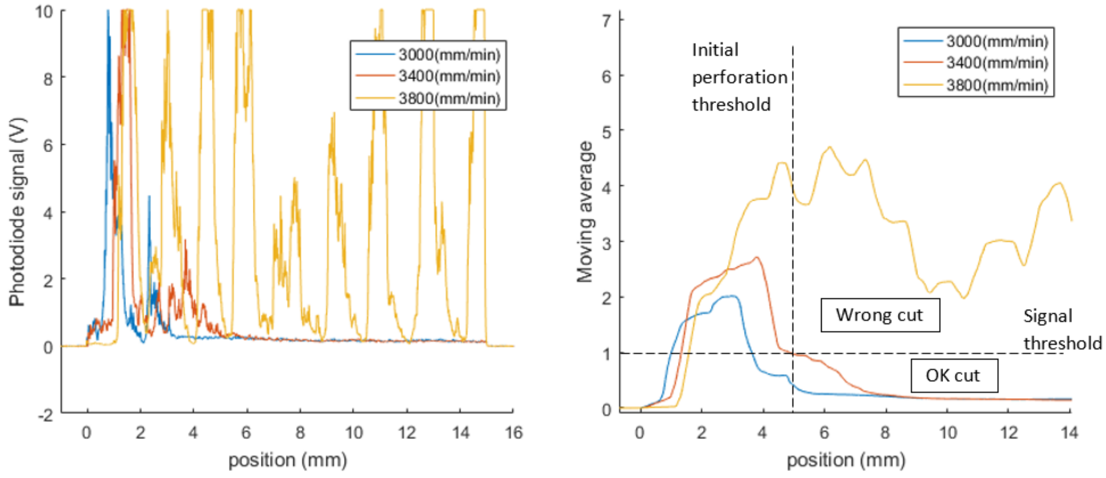
(b) Detailed view of the signals.

Fig. 3. (a) Scattered light captured by the top photodiode for different velocities; (b) detailed view of the nearly constant region.

As pointed out above, the verification of a nearly constant behavior and low value at the top photodiode signal when the cutting quality is high can be used as a quality detector in cutting processes. In fig. 4, signals recorded when cutting at 400 W laser power and 3000, 3400 and 3800 mm/min are illustrated. An initial noisy behavior can be apreciated at the beginning of each signal. In this region, incomplete cutting of the sheet takes place. After approximately 5 mm, perforation of the sheet is achieved at 3000 and 3400 mm/min while the noisy behaviour continues at 3800 mm/min. In fig. 4b a moving average with a 1 mm averaging range has been applied for the three signals with the aim to show an example of how a quality control may be developed. Firstly an starting threshold of 5 mm is set where a complete perforation of the sheet should be obtained. Secondly, a signal threshold of 1 V is defined to determine if the cut is correct or not.

4. Industrial application of the quality detector

In order to evaluate the performance of our monitoring and controlling system, we have tested the developed detector in a real application in which optimal cutting parameters not always produce the whished result due to the large tolerance range in the thickness of the material to be cut. This application is related to the production of forged parts. In fact, in the forging process, the initial piece contains more raw material than the objective geometry, so that the complete filling of the volume is guaranteed. The excess of material, also called flush, flows through the space between the two dies, generating what is known as the partition line. Thus, a deburring operation is needed to obtain the final shape. In this case, the parts to be deburred are large bolts. Deburring forged parts with lasers is a promising field of application as it allows automatic operations without wear of mechanical tools and the use of manual operators.



(a) Photodiode signal for different velocities.

(b) Moving averaged signal and applied thresholds.

Fig. 4. (a) Top photodiode signal for different velocities: 3000, 3400 and 3800 mm/min. Laser power: 400 W; (b) moving averaged signal and wrong cut detector.

Since the generated burrs are usually irregular in shape and thickness, it is hard to determine the necessary laser power and the velocity for a complete cutting. For this reason, in principle, permanent human supervision or a post-inspection by means of a vision machine system would be needed to determine whether the piece has been correctly processed or needs further treatment. Because of space requirements, it was not possible to locate the bottom set of fibers and photodiode in this application, so the monitoring system only captured data from the top surface.

As in our previous measurements, the photodiode recorded signal disturbances when incorrect cutting was performed. In that case, the system detects the defect, and the cut is repeated until the complete detachment of the material excess is achieved. In fig. 5 the photodiode signals of two bolt edge cutting are shown. Both cuts were performed with the same conditions using the most optimal parameters: 1300 W laser power and 2500 mm/min travel speed. The initial piercing and the scattering of the light at the end of the material excess to be cut can be clearly distinguished. The signal presents small irregularities due to the changes in thickness and surface finish of the parts. A cutting defect with loss of penetration is shown in fig. 5a, whereas fig. 5b presents a complete removal of the burr.

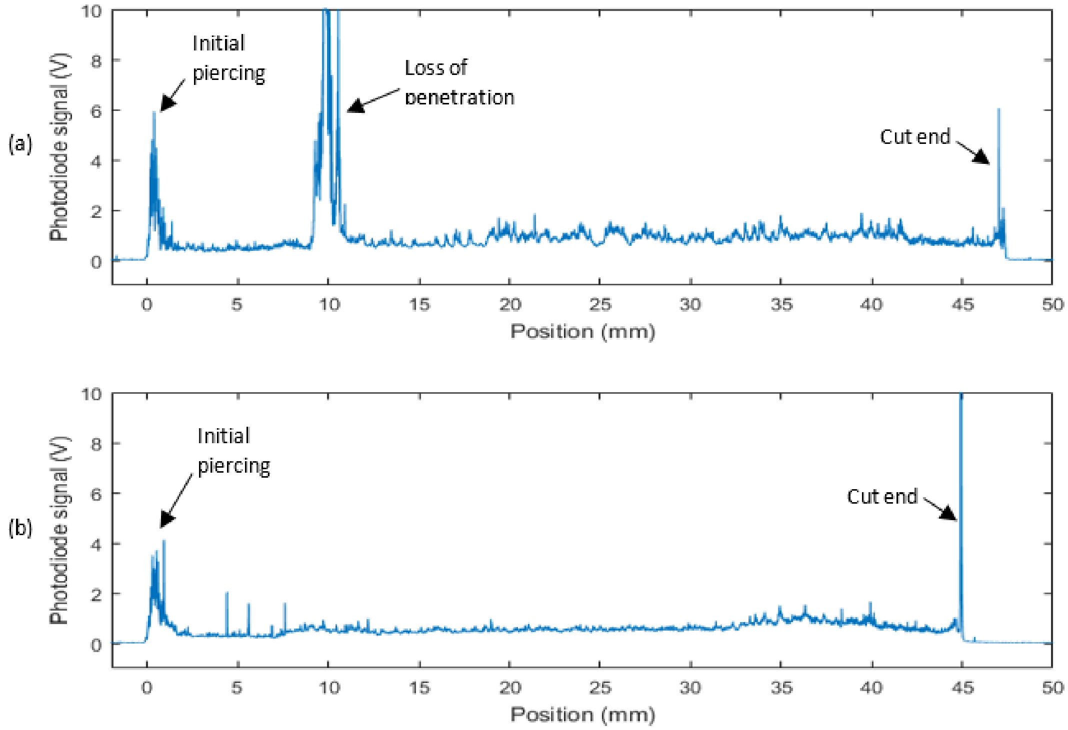


Fig. 5. Photodiode signal for bolt edge cutting. a) Cut with loss of penetration ; (b) good quality cut.

5. Conclusions

A monitoring system for cutting processes with single mode fiber laser based on a bundle of four optical fibers attached to a Si photodiode with narrow bandpass filter centered at 1064 nm and neutral density filter to correctly capture the scattered light of the processing laser beam at the top and bottom surface have been developed. The conducted experiments prove the applicability of the photodiode based monitoring system for controlling tasks. Both the photodiode collecting light at the top side of the sheet and the one capturing the light at the bottom side present different behaviours that can be correlated with the cutting quality. The gained knowledge from the signal monitoring and signal processing can lead to the development of a detector for loss of penetration or a cutting quality indicator in real applications. In this sense, a real industrial case for deburring parts with an in-situ monitoring-controlling system has been described showing a correlation between the disturbances of the signal and cutting defects in zones where the overall setting parameters are no fully optimal for removal the excess of material.

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References

Adelmann, B. et al., 2015. Optical Cutting Tear Detection System for Industrial Fiber Laser based Cutting Machines. In *Lasers in Manufacturing Procedings*.

Golubev, Y.S. et al., 2010. Diagnostics of laser radiance penetration into material by multi-channel pyrometer. In *International Conference on Advanced Optoelectronics and Lasers*. pp. 182–184.

Kaebernick, H., Jeromin, a. & Mathew, P., 1998. Adaptive Control for Laser Cutting Using Striation Frequency Analysis. *CIRP Annals - Manufacturing Technology*, 47(2), pp.137–140.

De Keuster, J., Duflou, J.R. & Kruth, J.P., 2007. Monitoring of high-power CO2 laser cutting by means of an acoustic microphone and photodiodes. *International Journal of Advanced Manufacturing Technology*, 35(1–2), pp.115–126.

Mahrle, a & Beyer, E., 2009. Theoretical aspects of fibre laser cutting. *Journal of Physics D: Applied Physics*, 42(17), p.175507.

Purtonen, T., Kalliosaari, A. & Salminen, A., 2014. Monitoring and adaptive control of laser processes. *Physics Procedia*, 56, pp.1218–1231.

Wen, P., Zhang, Y. & Chen, W., 2012. Quality detection and control during laser cutting progress with coaxial visual monitoring. *Journal of Laser Applications*, 24(3), p.32006.