On multi-sensor monitoring of fiber laser fusion cutting

Nikita Levichev¹, Joost R. Duflou¹
¹Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, 3001 Heverlee, Belgium, Member of Flanders Make
nikita.levichev@kuleuven.be

Abstract. Laser cutting is a well-established industrial process for sheet metal applications. However, cutting thick plates is still accompanied by problems because of the characteristic limited process parameter window. Since cutting by means of fiber lasers has become dominant, tailored solutions are required in such systems for industrial applications. The development of a robust real-time monitoring system, which adapts the process parameters according to a specific quality requirement, implies a significant step forward towards automated laser cutting and increases the process robustness and performance. In this work, a coaxial multi-sensor monitoring system is tested for fiber laser cutting of stainless steel thick plates. A high-speed camera and a photodiode sensor have been selected for this investigation. Experiments at different cutting speeds, representing primary cut quality cases, have been conducted and various features of the obtained process zone signals have been examined. Finally, the feasibility of industrial application of the developed setup for high-power fiber laser cutting is discussed, followed by several implementation recommendations.

1. Introduction
Laser cutting of metals is a highly automated industrial process that offers excellent flexibility and productivity comparing to other technologies. Although the laser cutting process has unique advantages, it is susceptible to inner and outer influences, such as variability of plate thickness and chemical composition, changes of process parameters caused by the wearing of machine parts or any mistakes of the operator. Therefore, real-time quality monitoring techniques have to be applied to ensure a high-quality cut edge and cost-effective use of laser cutting machines in workshops.

Monitoring systems have been developed and applied for in situ quality inspection of laser processes [1]. However, laser cutting monitoring has several distinct difficulties. First, a confined process zone with a nozzle, which needs to be positioned close to the cutting front, limits the observation from the top. Second, a stream of molten material is ejected from the process zone, creating an aggressive environment that obstructs the observation from the bottom side of the plate. Third, the process is highly dynamic and typically accompanied by fast changes in cutting direction that complicates the off-axis observation. As a result, the natural solution to overcome these issues is to use a coaxial monitoring system that is proven to be able to provide essential information about cut quality [2].

One of the major challenges in laser cutting monitoring is identifying sensing parameters that correlate well with specific cut quality characteristics. In the ideal case, an appropriate sensing parameter based on a single sensor measurement should be found for all quality features. Several single sensors have been already tested and presented in literature. For instance, real-time monitoring of cutting with a fiber laser has been investigated applying a photodiode [3, 4] and a camera [5, 6].
In industrial practice, the combination of different sensors can offer increased robustness due to the redundancy between different information streams and the resulted reduced sensitivity for noise factors. The combination of parameters from different sensor types is better known as sensor fusion [7]. Sensor fusion is a promising technique because it can include complete information about the process and the corresponding cut quality by using the advantages of several optimally combined sensors.

Sensor fusion systems have been already investigated for laser material processing. For instance, a multi-sensor system consisting of two photodiodes and two high-speed cameras for different spectral ranges has been introduced for high-power disk laser welding [8]. Another multi-sensor data fusion system for laser welding monitoring with two photodiodes and a pyrometer has been developed to analyze different in-process defects [9]. An optical process monitoring system based on infrared, visual and polarization sensors has been designed for laser powder bed fusion [10].

The first example of sensor fusion in laser cutting can be represented by the combination of different information sources that is used by experienced operators responsible for process optimization. By interpreting visible and audible signals, they can typically obtain a general impression of the process status. As a result of such observations, high-power CO2 laser cutting has been monitored by means of an acoustic microphone and photodiodes [11]. However, it has been concluded that the acoustic signal does not deliver any additional information compared to the photodiode signals and requires advanced signal processing that makes a microphone less suitable for industrial applications.

A few studies reported that the combination of different spectral ranges might be beneficial for laser cutting monitoring. Cross-correlation of InGaAs and Si photodiodes has been used for cut interruption detection of laser fusion cutting [12]. Heat accumulation during laser flame cutting has been detected by applying both visual and near-infrared photodiodes, which has helped to distinguish this issue from other possible process defects [13].

In this paper, an example of a multi-sensor approach based on a photodiode and a high-speed camera is provided for fiber laser fusion cutting. The experiments are performed with different cutting speeds in order to cause several levels of cut quality deterioration. The robustness of the sensor fusion is analyzed compared to the performance of a single sensor monitoring.

2. Experimental description

2.1. Laser cutting

The experiments were performed on a commercial 2D flat-bed laser cutting machine with a 4 kW IPG Ytterbium multimode fiber laser source emitting at 1.07 μm wavelength with a top-hat intensity distribution. The laser beam was delivered from a 100 μm core optical fiber into a Precitec ProCutter laser head equipped with a 200 mm focusing lens and a 100 mm collimation lens. The beam parameter product and the beam waist diameter were measured using an Ophir BeamWatch device as 2.84 mm mrad and 224 μm, respectively.

The cutting samples were obtained from stainless steel 316L plates of 12 mm thickness. As commonly used in industrial practice and obtained from the machine supplier, the following process parameters were applied for the cutting experiments for this material-thickness combination. Nitrogen of 99.999 % purity with 18.0 bar pressure was used as an assist gas together with a 3.5 mm diameter nozzle and a stand-off distance of 0.4 mm. The focus position of the laser beam was set to 10.0 mm below the top surface of the plate. The nominal cutting was performed with a speed of 700 mm/min, further referred to as 100 %, a laser power of 4 kW and a duty cycle of 100 %.

A Keyence Digital Microscope VHX-6000 was used for high-resolution imaging of cut edge profiles. The surface roughness of cut edges ($R_z$) was measured by means of a Mitutoyo Formtracer CS-3200 using a Gaussian filter with a sample length of 2.5 mm and a cut-off of 0.008 mm. The measurements of each specimen were performed for five lines with an evaluation length of 12.5 mm. The measuring lines were spaced by 2.5 mm, starting at 1 mm from the top surface. The average roughness value was calculated as a mean value of these five measurements. The dross area was calculated by image processing of a corresponding cut edge picture for an evaluation length of 50 mm [6]."
2.2. Monitoring system

A coaxial monitoring setup, as depicted in Figure 1, was used with a dichroic mirror that transmits the radiation with wavelengths shorter than 800 nm and longer than 1200 nm towards the sensors. Next to the mirror, a diaphragm with a diameter of 1.5 mm was situated to decrease the optical aberrations after the laser head optics designed for the laser beam wavelength. After the diaphragm, a notch filter with an optical density of 6 and a bandwidth of 1064 ± 36 nm was placed to remove the scattered and reflected laser radiation. A non-polarizing beamsplitter cube that transmits half of the radiation and reflects the other half was used to ensure light propagation to both sensors.

Figure 1. Optical scheme of the coaxial multi-sensor monitoring system.

Depending on the considered spectral interval, different phenomena can be observed by a monitoring system. At the same time, laser cutting is a highly dynamic process that brings additional restrictions on the choice of the sensors. The photodiode selection was made assuming that its spectral range should cover the maximum of thermal radiation from the process zone to use minimum amplification. However, the camera sensors typically have limitations in achievable frame rate, resolution and pixel size. Consequently, the selection of the camera should be based on its capabilities to acquire maximum geometrical information from the process zone with acceptable time resolution.

Since the radiation peak of the process temperatures is around 1500 ± 100 nm, an InGaAs photodiode (FGA21) responsive to the near-infrared radiation with wavelengths from 800 to 1700 nm was selected. The photodiode signals were recorded by means of a data acquisition card with amplification and low pass filtering, allowing sample rates of up to 50 kHz. The signal was processed using a moving average filter with a window length of 1 ms to reduce the noise.

In order to be able to capture dynamic changes of the cutting front geometry, a Mikrotron EoSens MC1362 camera with a Si-based sensor and a pixel size of 14 μm has been used. Considering the best performance of the camera, images with a size of 320 × 250 pixels were acquired at a frame rate of 5000 fps with an exposure time of 100 μs.

2.3. Video processing

The analysis of the videos has been performed after experiments using MATLAB. A video frame is represented by a matrix $M$ with $I$ columns and $J$ rows where the matrix grayscale value $g_{ij} \in [0, 255]$ with $i \in [0, I]$ and $j \in [0, J]$ is the pixel intensity.
In order to compare the results of the two sensors, the overall image intensity ($I_{img}$) is calculated as:

$$ I_{img} = \sum_{i=1}^{1} \sum_{j=1}^{1} I_{ij} $$  \hspace{1cm} (1)

Then, in order to extract geometrical features, image transformations are performed as in detail described in [6]. An example of binarization with a threshold value of 50 and logarithmic transformation with an enhancement coefficient of 2.5 is shown in Figure 2.

In this paper, the dimensionless factor $l/w$ defined as a ratio between the length and width of the process zone is used instead of several geometrical parameters since it can be considered more general. The length and width of the process zone are computed based on the centroid position identification of the blob obtained after image binarization as the blob dimension parallel and perpendicular to the cutting direction, respectively [6].

In order to reduce the noise, the calculated parameters were processed using a moving average filter with a window length of 5 ms.

As a variability feature, the standard deviation of the process zone length to width ratio is computed as:

$$ \sigma_{l/w(n)} = \sqrt{\frac{\sum_{i=m}^{n} (l/w(i) - \overline{l/w})^2}{\tau - 1}} \hspace{1cm} (2)$$

where $\tau$ is the number of frames in a preceding time interval of 5 ms, $\overline{l/w}$ is the mean value on the time interval being used, $n$ is a frame number for which the standard deviation is calculated and $m = n - \tau + 1$. For standard deviation values, a bandpass filter with a lower cut-off frequency of 250 Hz and an upper cut-off frequency of 750 Hz was applied.

### 3. Results and discussion

Experiments at various speeds, slower and faster than the nominal one, have been performed by stepwise speed changes, leading to significantly different quality issues. Due to several factors that are hard to control in an industrial environment, the sets of optimal parameters recommended by machine tool builders usually have a certain safety margin. It allows obtaining a good quality cut even when a material that is different from the reference one, for instance in surface quality, chemical composition or heat...
treatment, is being processed. As a result, a certain material can be cut not at the fastest speed or without optimal quality.

The cut edge profiles with the corresponding quality parameters are shown in Figure 3. In this case, cutting at a speed of 120 % leads to the best quality with the lowest amount of dross. However, a further increase in speed results in an occurrence of the irregular striation pattern that is characterized by unacceptably high roughness and increased risk of a cut failure [14]. Cutting at speeds higher than 140 % led to a loss of full penetration. Cutting at low speeds, such as 60 % and 80 %, causes a lot of dross which is unsatisfactory for industrial practice.

| Cutting speed [%] | 60 | 80 | 100 | 120 | 140 |
|-------------------|----|----|-----|-----|-----|
| Dross area [mm²]  | 50.9 | 48.5 | 27.6 | 14.6 | 17.6 |
| Roughness [µm]    | 61.4 | 57.8 | 54.7 | 60.9 | 110.1 |

**Figure 3.** Cut edge profiles with corresponding quality obtained during cutting at different speeds.

The photodiode signal while cutting at different speeds is depicted in Figure 4. The signal level monotonously rises with an increase in speed. Similar behavior of the photodiode signal has been noticed before for laser flame cutting of mild steel since the cutting front inclination changes, leading to the elongation of the process zone and increase of the absorptivity [3]. However, a significant difference with the results of flame cutting might be observed when cutting too fast. The signal is considerably higher at a speed of 140 % which corresponds to the poor quality of the cut edge. It should be noted that relatively large nozzles are typically used for fusion cutting of thick plates in order to ensure appropriate gas flow, creating fewer obstacles to observe the process zone, especially in the cutting direction.

**Figure 4.** Photodiode signal during cutting at different speeds that were changed stepwise.

**Figure 5.** Overall image intensity during cutting at different speeds that were changed stepwise.
Figure 6. Comparison of the average photodiode signal and average camera image intensity.

The overall image intensity of the camera is shown in Figure 5. Similar to the photodiode signal, the image intensity is higher at faster speeds and a significant leap can be observed in the transition from 120 % to 140 %. Figure 6 depicts the comparison of the average photodiodes signal and camera image intensity. The image intensity has been calculated so that it represents the overall amount of light coming to the camera sensor, imitating the principle of the photodiode light acquisition.

As can be noticed in Figure 6, the difference between 120 % and 140 % speed for the camera parameter is more pronounced. It might be explained by the fact that the camera and the photodiode acquire radiation of different spectral ranges. Laser fusion cutting at elevated speeds is characterized by the phenomenon of local vaporizations accompanied by intense flashes. During evaporation, the temperature becomes much higher and iron atomic emission lines (Fe I) can be observed in the spectrum emitted from the process zone [15]. Therefore, taking into account Planck’s law, the intensity of the emission in the visual spectral range is significantly higher, explaining a slightly different behavior of the camera image intensity.

Another essential issue of the local vaporizations occurrence is their duration. An example of three consecutive frames when a flash appears is presented in Figure 7. The flashes may be observed for a very short time which is mostly less than 0.4 ms. Therefore, a sensor with an acquisition rate higher than several kfps is required to detect the flash formation without missing any of them. In theory, state-of-the-art high-speed visual cameras can provide process observations with an acceptable resolution with a frame rate of up to 100 kfps. However, using such scientific cameras for real-time applications in industrial practice seems unrealistic due to their costs and the enormous amount of created data that needs to be transferred and processed.

Figure 7. An example of the temporal evolution of the process zone at 140 % speed. The time interval between consecutive frames is 0.2 ms. The dashed circle indicates the nozzle border.
Since information about process zone intensity is sufficient for detecting local vaporizations on the cutting front, using relatively low-cost photodiodes that are available with ultra-high bandwidths might be relevant for possible industrial implementation. Moreover, bandpass filters designed for certain emission lines of Fe I can be coupled with photodiodes to monitor only the spectral range of interest. However, as can be seen in Figure 4 and Figure 5, the detection of flashes does not guarantee cutting with the best edge quality and performance since the increase of the process zone intensity occurs stepwise at low and moderate speeds before the start of local vaporizations appearance. Therefore, in order to select the optimal set of cutting parameters, the geometrical features of the process zone have to be evaluated.

The evolution of the length to width ratio of the process zone for different cutting speeds is shown in Figure 8. Cutting faster causes an increase in the process zone length since the cutting front inclination becomes less steep. As a result, even though the process zone width slightly increases, the process zone has minor ellipticity. However, the dross attachment has the main influence on the length to width ratio since it leads to a sudden increase in the process zone length. Consequently, as can be observed in Figure 8, the amplitude of the length to width ratio is high for slow and nominal speeds even taking into account that a moving average filter has been used. At the same time, cutting at 140% speed does not lead to significant ratio changes since both length and width of the process zone typically increase during an intense flash (Figure 7).

Since the absolute value of the length to width ratio is affected by the stability of the process zone shape, its standard deviation shown in Figure 9 has been calculated in order to measure the variability of the process zone geometry. The consistency of the process zone shape directly influences the amount of generated dross. The lowest standard deviation level for 120% speed corresponds to the best cut edge quality, while the highest values of standard deviation for 60% speed correlate with the largest amount of dross (Figure 3).

An example of consecutive frames during cutting at 100% speed is shown in Figure 10. Due to the fluctuations of the melt ejection stream, some of the molten material can attach to the kerf walls on the bottom edge. As a result, a relatively low-intensity tail of the process zone can be observed that is a typical indication of possible dross formation. As can be seen in Figure 10, the process zone can arbitrarily increase in length, keeping the width relatively constant. It can be concluded that the detection of the absolute value for such an elongation provides less information about the process status than statistical analysis of how frequently that happens.

![Figure 8](image8.png)  
**Figure 8.** Process zone length to width ratio evolution during cutting.

![Figure 9](image9.png)  
**Figure 9.** Standard deviation of process zone length to width ratio evolution during cutting.
Figure 10. An example of the temporal evolution of the process zone at 100% speed. The time interval between consecutive frames is 0.2 ms. The top row images underwent the logarithmic transformation. The bottom row pictures represent the top row after binarization.

The formation of dross during fusion cutting occurs if the lateral melt flow adheres when flowing backwards from the cutting direction along the lower edge [16]. As a consequence, the material on the bottom edge can still be hot and emit radiation even a few millimetres away from the cutting front. This typically results in the appearance of several blobs on the processed camera image as shown in Figure 11. In general, the detection of a couple of blobs can also be used as a monitoring signal for dross recognition. For instance, the number of such frames during cutting at 120% speed is negligible while dozens of such images have been observed per 1 mm during cutting at slow speeds. However, high-intensity flashes of local vaporizations typically are dominant and do not allow using this approach for high speeds since a flash irradiates the kerf walls creating additional blobs, which are not related to the dross attachment.

On the contrary to laser fusion cutting, laser flame cutting is characterized by higher process zone temperatures with noticeable gradients in the thickness direction [17] which might be used as a monitoring signal in a multi-sensor system if dross attachment cannot be observed.

Figure 11. An example of a video frame where several blobs can be detected: raw image with pseudo colors representation on the left and its processed version on the right. The dashed circle indicates the nozzle border.

4. Conclusion
Laser fusion cutting is a rather complicated process that involves several phenomena. In order to efficiently distinguish different problems occurring during cutting, a multi-sensor approach that accumulates advantages of different sensors can be used. Sensor fusion in a coaxial optical configuration offers specific advantages, which are mainly relevant for potential industrial implementations. A fast and low-cost photodiode signal can be used to detect local vaporizations on the cutting front since it only requires the high-speed acquisition of process zone intensity data and provides great flexibility for the spectral range being used. A significant increase in the intensity of both sensors has been observed when cutting too fast that can be used as an indication of a cut failure risk. However, defining the set of process parameters that allows cutting with the lowest dross area demands geometrical information
about the process zone, especially about its dimension in the cutting direction. As it was found, the lowest values of the standard deviation of the process zone length to width ratio correlate well with the lowest amount of dross. Therefore, a camera is preferred for real-time optimization of cut edge quality in terms of dross amount. In this case, ultra-fast cameras and computationally expensive data processing are not necessary, significantly reducing the costs and complexity of a monitoring system.

Future work will be dedicated to further exploring the synergy of using multi-sensing for laser flame cutting where the process zone information is limited due to the obstruction by the nozzle. Moreover, other sensors that provide spectral information might be considered for monitoring both fusion and flame cutting processes.

ORCID IDs
N Levichev https://orcid.org/0000-0001-8929-9843
J R Duflou https://orcid.org/0000-0002-7265-9686

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