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Optical Cutting Tear Detection System for Industrial Fiber Laser based Cutting Machines

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Abstract

In this study, we demonstrate an optical cutting tear detection and evaluation system affixed to a 4 kW fiber laser cutting machine. The sensor is mounted between the cutting head and collimator and collects the thermal radiation from the process zone. The process radiation is detected by a stacked silicon and InGaAs photodiode combination and digitalized with 20 kHz sample rate. The acquired signal for two exemplarily chosen cuts in 2 mm stainless steel which one of them include cutting tears are shown wherein the piercing, the waiting time and laser switch on/off are clearly be resolved. These signals are high pass filtered and the fluctuation range is calculated. In the resulting signal, a cutting tear is indicated by the fluctuation range of the Si diode exceeding the fluctuation range of the InGaAs diode multiplied with a correction factor. With this characteristic signature, 193 cuts including 83 cutting tears were analyzed revealing 96.4 % detection rate (alpha error 3.6 %) and 0 % beta errors. The easy integration in existing cutting systems, the direction independent signal and the high detection rate highlight the systems potential for cutting tear detection in industrial cutting machines.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

High power near infrared fiber and disk lasers in the range of several kilowatts are commonly used since many years with increasing market share in modern cutting machines. Various different materials are cut with these lasers such as stainless steel [1] electrical sheets [2] or aluminum [3] with thicknesses up to several centimeters [4] [5] [6], e.g., 30 mm carbon steel are cut with a 6 kW fiber laser [7]. To cut thick materials with high quality, process parameters such as gas pressure, nozzle to workpiece distance, feed rate

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and laser power have to be adjusted very precisely. At the same time the influence of disturbance variables e.g. material impurities, unclean optics or thermal lens effects have to be considered in order to keep up the cut quality and avoid cutting tears [8]. To follow the trend towards unmanned operating machines and still keeping up the high quality requirements a sensor system tracking the cut process is highly desirable. Until now, sensor systems for NIR laser cutting systems are hardly in practice while monitoring systems for laser welding are nowadays commonly in use [9] [10] [11]. Systems for monitoring laser welding can be pointwise using spectrometers [12] [13] or diode based pyrometers [14] [15]. Also 2 dimensional welding monitoring is applied by CCD cameras [16] [17] or CMOS camera [18].

In literature, reported monitoring systems for cutting applications encompass mostly optical and rarely acoustic methods [19]. An example for analyzing the acoustic emission during laser cutting is provided by Kek and Grum [20] revealing that generation of burr emits evaluable acoustic bursts. For optical detection systems cameras are used. Thombansen et al. [21] demonstrate monitoring the cut kerf width and focus position during CO_2-laser cutting with a camera at 4 kHz sample rate. During cutting the surface is illuminated by an external laser source at 808 nm and the reflected CO_2 laser radiation is removed by a beam splitter in front of the camera. A NIR camera system without external light source is used by Sichani et al. [22] [23] to monitor the size and temperature distribution of the process zone during cutting 15 mm steel sheets with a 6 kW CO_2 laser. At a sample rate of 40 Hz the burr formation, roughness and striations were calculated from the picture. Ermolaev et al. [24] placed a high speed camera behind glass in one level with the workpiece observing the cut kerf from the side. In a comparative study the results show vanishing differences between fiber and CO_2 laser cuts. Alippi et al. [25] placed a camera below the workpiece determining the width and angle of flying sparks during CO_2 laser cutting and calculated with an artificial neural network the cut quality. Beside the advantage of camera based monitoring of providing more information with a 2 dimensional image [26] cameras have the disadvantage of high costs and low sample rates.

Beside cameras also optical monitoring which are not space-resolved are under study to monitor cutting processes. Optical fibers are used by Golubev at al. [27] to observe the thermal radiation revealing a higher temperature at higher feed rates. This system was also able to detect cutting tears. Jurca et al. [28] used three attached optical fibers to monitor the nozzle to workpiece distance and the process zone temperature. Zavalov et al. [29] mounted a multi-channel pyrometer consisting of two photodiodes next to the cutting head determining the velocity of the melt flow due to temperature fluctuations. In the last three named monitoring systems, the sensor is placed with a lateral off-set on the cutting head. Because during shape cutting the movement direction changes the sensor must be retraced to watch with constant angle into the process zone. Especially at high dynamic machines such a retrace system is not practicable.

Even due to the increasing share of fiber- and disc laser cutting machines, there is still a lack of monitoring systems working for these lasers [19]. Therefore, we present in this contribution a new optical cutting tear sensor for industrial fiber laser cutting machines. The function of this system is demonstrated in an exemplarily chosen pair of a complete and an incomplete cut in 2 mm stainless steel.

2. Experimental

2.1. Sensor signal

The sensor system used in this study is mounted between the collimator and cutting head according to figure 1. An optical fiber with 100 µm diameter guides the laser radiation from the 4000 W multi-mode fiber laser (1070 nm) to the collimator. The laser radiation with a beam parameter product of 2.9 mm x mrad is guided from the collimator through the sensor system to the cutting head (dashed line). In the cutting head the laser beam is focused with a lens (focal length of 200 mm) through the protection window and the 2 mm diameter nozzle onto the workpiece. Nitrogen is used as a process gas flowing through the nozzle with a pressure of 8 bar. The cutting head with the sensor and collimator is moved with 3D linear stages over the workpiece. For laser cutting temperatures higher than the melt temperature of the workpiece are required in the process zone which is for steel more than 1500° C. Due to its high temperatures the process zone

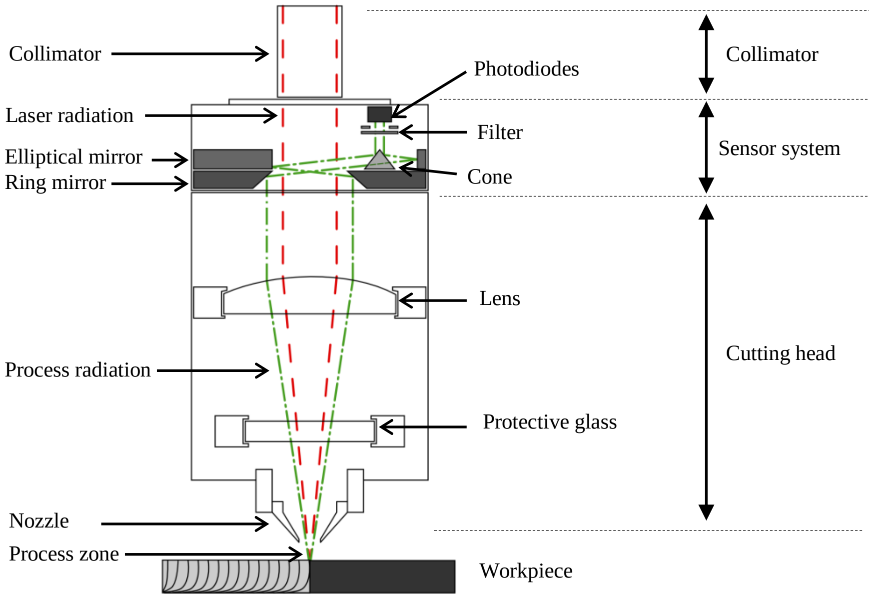

Figure 1: Design of the sensor system

emits thermal radiation (dash-dotted line), also called process radiation, with an intensity maximum in the range of 1 µm which is in the spectral region of the fiber laser radiation. The thermal radiation propagates omnidirectional and therefore partly through the nozzle into the cutting head as shown in figure 1. Inside the cutting head the process radiation passes the protective glass and gets collimated by the lens and propagates parallel to the laser radiation toward the sensor system. The sensor has an aperture in the middle which is wider than the collimated laser beam diameter, so the laser radiation can pass unhindered. On the bottom side of the sensor a ring mirror reflects the process radiation on the brink in slightly upwards direction. Above the ring mirror an elliptical mirror is placed which has two focal points. One of these focal points is identical with the center point of the ring mirror, so the radiation reflected from the ring mirror is guided into the elliptical mirror. In the other focal point of the elliptical mirror a reflecting cone is placed guiding the process radiation out of the elliptical mirror to a filter. This multi-level filter separates reflected laser radiation, which is several orders of magnitude higher than the process radiation from the thermal radiation. The thermal radiation is then guided to a silicon and InGaAs sandwich photodiode. The output of the sensor system is a voltage signal for each diode which is proportional to the logarithm of the diode´s current (analog logarithm amplifier). These voltage signals are digitalized with a sample rate of 20 kHz enabling a signal evaluation by PC or digital signal processor.

3. Results and discussion

3.1. Sensor signal description

The function of the sensor system is demonstrated at a pair of exemplarily chosen cuts in 2 mm thick stainless steel which one of them include cutting tears. The parameter combination for both cuts is chosen to a nominal velocity of 100 mm/s and a gas pressure of 8 bar (nitrogen). The laser power is adjusted to 3.5 kW for the complete cut and 2.5 kW to achieve cutting tears. The cut geometry is a rectangle with the

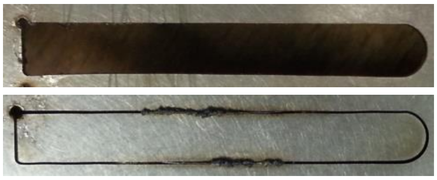

Figure 2: Topview of a complete cut (top) and incomplete cut (bottom) in stainless steel

dimensions of 37.5 x 5 mm² which is rounded at two adjacent edges with a radius of 2.5 mm as shown in figure 2. The piercing occurs in the top left of the shape and then the shape is cut in clockwise direction. The acceleration of the drives is reduced to achieve long acceleration paths where the time of the cutting tear cold be easier determined. During these cuts the voltage signals from the sensor of both Si and InGaAs diode are recorded and plotted over time as shown in figure 3. It is worthwhile to mention that the signal voltage trend of complete cuts as shown in figure 3 (top) stays constant independent of the chosen process parameters. The piercing in the top right of figure 2 is depicted in the voltage signal as a peak in second 0.4. After the piercing a waiting period of 1.2 seconds follows. During this period the piercing hole widens up which is expressed by the slow falling hill of the InGaAs diode because more and more metal is melt and blown out of the hole. Due to the increasing hole diameter less metal is in the laser irradiated area and therefore the amount of melt and thermal radiation decreases. At second 1.6 the drive start to accelerate

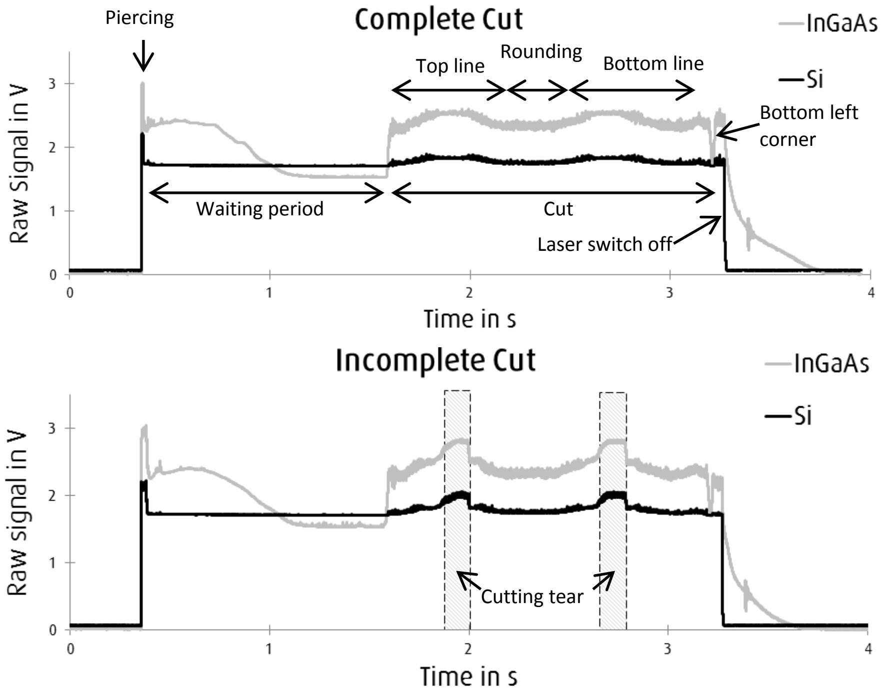

Figure 3: Raw voltage signal of a complete cut (top) and incomplete cut (bottom). The areas of cutting tears are marked with dashed rectangles.

and begin to cut the top line of the geometry which is indicated by an increase and fluctuation of both diode´s voltages. To cut the top line at first die drives accelerate, then hold the velocity and after that decelerate before the rounding which is in the sensor signal expressed by an increase, hold and decrease of both diode´s voltage. The same behavior is observed for the bottom line. During the rounding the absolute value of the velocity stays constant and only the direction alters. The sensor signals of both diodes stay constant when cutting the rounding which highlights the cutting direction independent sensor signal. When the bottom left corner is cut the drives have to decelerate drastically which is expressed in a negative peak in the InGaAs diode´s signal. When the laser is switched of at second 3.3 the voltage of the Si diode drops immediately while the InGaAs diode reveals a slower decrease. This behavior is attributed to the cooling of the process area after laser switch of and the emission peak shifts towards longer wavelength (Wien´s law).

The comparison between the signals of the complete (top) and incomplete (bottom) cut in figure 3 show at first glance no major differences. This general behavior during incomplete cuts is also observed for a series of cuts with the same parameter combination as well as for other parameter combinations such as lower gas pressure or higher velocity. Noticeable is the wider peak at the piercing at the incomplete cut which is caused by a longer required piercing time due to the lower laser power. From the cutting tears observed in the bottom part of figure 2 the position and length is measured and from the movement profile of the drives taking into account the acceleration and deceleration paths the time of the cutting tear is calculated. These time slots are marked with dashed rectangles allowing an identification of a possible cutting tear indicator. During the cutting tears the voltage of both diodes reveals immediately increases and falls down at the end of the cutting tear but this effect is difficult to evaluate because this increase also appears during acceleration. Therefore a more complex cutting tear calculation is required.

3.2. Cutting tear calculation

A reliably cutting tear detection method is found in the comparison between the fluctuation ranges of both Si and InGaAs diode´s signals. Therefore, the fluctuation range for both diodes is calculated in two steps. The first step is a digital two element high pass filter according to equation 1 calculating the difference between two successive measuring values $\mathrm{x_i}$ and $\mathrm{x_{i-1}}$. The symbol i indicates the consecutively number of the measurement value and y indicates the filters signal.

$$y_i = x_i - x_{i-1} \tag{1}$$

After that the fluctuation range from 50 successive values is calculated from the high pass filtered signal with formula 2 which is also used to calculate the standard error. Thereby $\bar{\mathrm{x}}$ is the arithmetic mean of the last 50 values. This fluctuation range calculation at the same time removes extreme values.

$$y_i = \frac{1}{49}\sum_{i=1}^{50}(x_{-i} - \bar{x})^2 \tag{2}$$

The minimum time delay caused by the sample rate is 2 samples for the high pass filter and 50 samples for the fluctuation range which results for 20 kHz sample rate in a time delay of 2.6 ms. Please note that the calculation time is not included because when using a well optimized digital signal processor the calculation delay is quite low. At the chosen velocity of 100 mm/s the drives travel in 2.6 ms is 0.26 mm which is in the range of the beam diameter, highlighting the fast possible response time of the sensor system.

A cutting tear is indicated when the fluctuation range of Si diode exceeds the fluctuation range of the InGaAs diode. To achieve a digital value indicating a cutting tear CT equation 3 is used.

$$CT = if[fr(Si) > (cf * fr(InGaAs))] \quad (3)$$

In this formula if is the logical operator which is 1 when the greater than constraint in the squared bracket is true and 0 in case of a false constraint. Further $fr(Si)$ indicates the prior calculated fluctuation range signal of the Si diode and $fr(InGaAs)$ is the fluctuation range signal of the InGaAs diode. Finally, cf is a correction factor for fine tuning to achieve high cutting tear detection rates and a low number of false reports. In a series of 193 cuts in stainless steel and mild steel with 83 of them include a cutting tear a correction factor of 0.85 is determined to achieve a high detection rate of 96.4 % and no false reports.

3.3. Exemplarily demonstration

To demonstrate the function of the calculation, exemplarily the algorithm is applied on the signals shown in figure 3 for both the complete and incomplete cut. For the complete cut without cutting tear the fluctuation range is calculated for both diodes signals and depicted in figure 4. Distinctive points in the course are the peaks at second 0.4 which is the piercing and the increase of the fluctuation range of both diodes at second 1.6 marking the acceleration of the drives and start of the cut. Further at second 3.3, a decrease of the fluctuation range for both diodes mark the laser switch off. It is noticeable that during the whole cut between second 1.6 and 3.3 the fluctuation range of the InGaAs diode is always higher as compared to the Si diode, which is not the case for cutting tears. This effect is also observed for cuts without cutting tear with other parameter combinations.

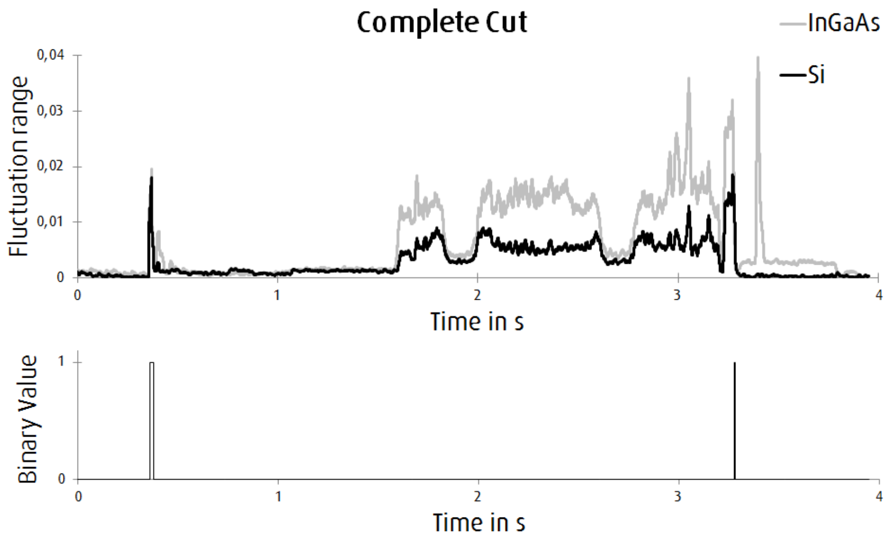

Figure 4: Fluctuation range (top) and binary cutting tear value (bottom) of a complete cut.

Applying formula 3 on the signal in figure 4 top, the result is depicted in the bottom signal of figure 4. The binary value indicating a cutting tear is 0 over the complete time except on second 0.4 indicating the piercing and second 3.3 indicating the laser switch off at the end of cut. Both the piercing and the end of cut can be valued as a cutting tear and show the high sensitivity of the sensor and evaluation system.

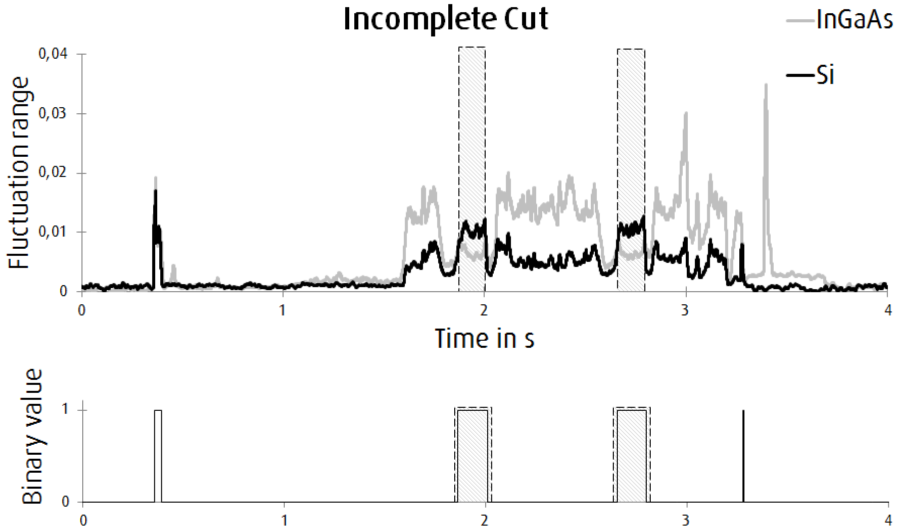

Figure 5: Fluctuation range (top) and binary cutting tear value (bottom) of an incomplete cut. The areas of cutting tears are marked with dashed rectangles.

Similar to the complete cut, the fluctuation range of the incomplete cut from figure 3 bottom is calculated and depicted in figure 5 (top). Also the peak at the piercing at second 0.4, the voltage increase at the acceleration of the drives at second 1.6 and the voltage drop at the laser switch off (second 3.3) can be clearly seen. In contrast to the complete cut, in the signal of the incomplete cut a period with a fluctuation range of the Si diodes exceeding the fluctuation range of the InGaAs diode is observed. This exceed of the Si diode as compared to the InGaAs diode is exactly in time slots of the cutting tears marked with dashed rectangles between second 1.9 and 2.0 as well as between second 2.7 and 2.8. Hence, this effect can be well used to identify cutting tears in the signal. The binary value is calculated according to equation 3 and depicted in the bottom part of figure 5. The binary value indicates a cutting tear firstly at the piercing (second 0.4) with the signal shows up longer compared to the complete cut which is caused by the longer piercing duration due to the lower laser power. The second and third high signals indicate the cutting tear on the straight lines because of the too high feed rate for the chosen laser power. At second 3.3 the last indicated cutting tear is caused by the laser switch off at the end of the cut. Thus, the cutting tears are successfully detected which demonstrates the function of the sensor system.

3.4. Detection error rate

The identification of cutting tears described above is a threshold detection based method which is usually evaluated statistically by their error behavior. The first type of error is the type I error or alpha error which expresses in our case that a cutting tear occur which is not detected by the sensor system. The other error type is the error type II or beta error which describes a cutting tear signal during a complete cut. To evaluate these two error types in a statistic significant volume a series of 193 cuts is performed with 83 of them a cutting tear is activated willfully. The cuts are performed in both stainless steel and mild steel in different material thicknesses. The cutting tears are activated by increasing the feed rate or reducing the laser power until the track energy is too low for a complete cut. Further used methods are defocussing of the laser, reducing the gas pressure or increasing the workpiece thickness during the cut. From the 83 cutting tears, the sensor system detected 80 which results in a low alpha error of 3.6 % (96.4 % detection rate). In the 110 complete cuts no error is reported resulting in 0 % beta error. This impressive high detection rate and suitability of the algorithm for different thicknesses and steel types highlight its potential to detect cutting tears in industrial application.

4. Conclusion

In this paper, we report on an optical sensor, which is mounted between collimator and cutting head, for cutting tear detection at a 4 kW fiber laser machine. The sandwich photodiode consisting of an InGaAs and a silicon diode collects the optical emission from the process zone during the laser cutting and digitized the radiation with a sampling rate of 20 kHz. Additionally, we demonstrate an evaluation system for identifying cutting tears. For this demonstration, two exemplary cuts were selected, one with a cutting tear and one without a cutting tear in 2 mm stainless steel. For cutting tear detection the signal of both photodiodes are first high pass filtered, afterwards the fluctuation range is calculated. We discover that during a cutting tear the fluctuation range of the Si diode exceeds the fluctuation of the InGaAs diode, multiplied with a correction factor. The piercing process, the laser switch on and switch off, waiting period and distinctive cut geometries are clearly resolved in the signals. With an alpha error of 3.6 %, a beta error of 0 % and a delay distance of 0.26 mm which is within the range of the beam diameter, a high detection rate are achieved with a short delay time for both stainless and mild steel. The possibility of an integration of the sensor into existing laser machines, highlight the potential for cutting tear detection in industrial applications.

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