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Burr formation detector for fiber laser cutting based on a photodiode sensor system

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ABSTRACT

We report a unique sensor system based on a InGaAs photodiode to detect the formation of burr during near infrared fiber laser cutting. The sensor approach encompasses the measurement of the thermal radiation form the process zone, optical filtering, digitalized sampling at 20 kHz, digital filtering using an elliptical band-pass filter 12th order and calculation of the standard deviation. We find a linear correlation between the deduced sensor signal and the generated burr height with this functionality being experimentally confirmed for laser cutting of mild and stainless steel of different thicknesses. The underlying mechanism of this transducer concept is attributed to the melt flow dynamics inside the cut kerf.

1. Introduction

Automated unmanned laser cutting is one of the major trends in high volume laser material processing of metals. To facilitate such operation while maintaining high cutting quality, online quality monitoring is indispensable as to control cutting parameters, such as, e.g., laser power, feed rate, gas pressure and focus position, respectively. In addition, varying material properties or soiled optics may disturb the cutting result, e.g. burr formation or an incomplete cut [1], in turn, necessitating extensive rework or loss material and production time.

Whereas for laser welding, online monitoring systems are well established in industry [2–4], sensor solutions for laser cutting are rarely in practical use, especially for near infrared (NIR) lasers. However, several scientific studies addressed burr detection and cut interruptions during laser cutting [5–7]. For instance, Sichani et al. [8,9] determine roughness, striation angle and burr formation during laser cutting with a 6 kW CO_2 laser using a NIR camera sampling with 40 Hz. Wen et al. [10] monitor laser cutting with a CO_2 laser observing the spark trajectories beneath the cut metal sheets and correlate this to the cutting quality. Kek and Grum [11] monitor the acoustic emission during laser cutting and deduce burr formation by evaluating the measured acoustic bursts.

Yet, none of the named systems are industrially established and most of the present systems in industrial use are developed for CO_2 laser application, only, being based on the detection of the UV plasma emission and IR thermal radiation. The ongoing trend to fiber and disk lasers imposes an imperative need for monitoring systems for NIR laser [12–16]. In this spectral range, however, detection of thermal radiation is hampered by the primary laser radiation spectrally coinciding with the maximum of the thermal radiation. Against this background, in this contribution, we present a new infrared-photodiode-based burr formation detection sensor and algorithm for fiber laser based cutting applications. The sensor is evaluated with respect to typical application conditions with the characteristic signatures of the sensor being identified for cutting mild and stainless steel in the thickness range of up to 3 mm. This in turn facilitates the successful detection of burr formation.

2. Materials and methods

The used sensor unit is designed to be installed between the collimator and the cutting head as shown in Fig. 1. The sensor detects the thermal radiation emitted from the process zone by the molten front in the cut kerf of the workpiece with an InGaAs photodiode. During a complete cut, the temperature in the process zone is higher than the melting point of the specimen on hand, typically for metal sheet cutting resulting in a maximum wavelength between 1000 nm and 2000 nm according to the Planck's law. The emerging thermal process radiation propagates in all directions form the melt and partly through the nozzle into the cutting head, in which it is collimated and guided to the sensor system. As the optical aperture of the sensor is larger than the primary laser beam,

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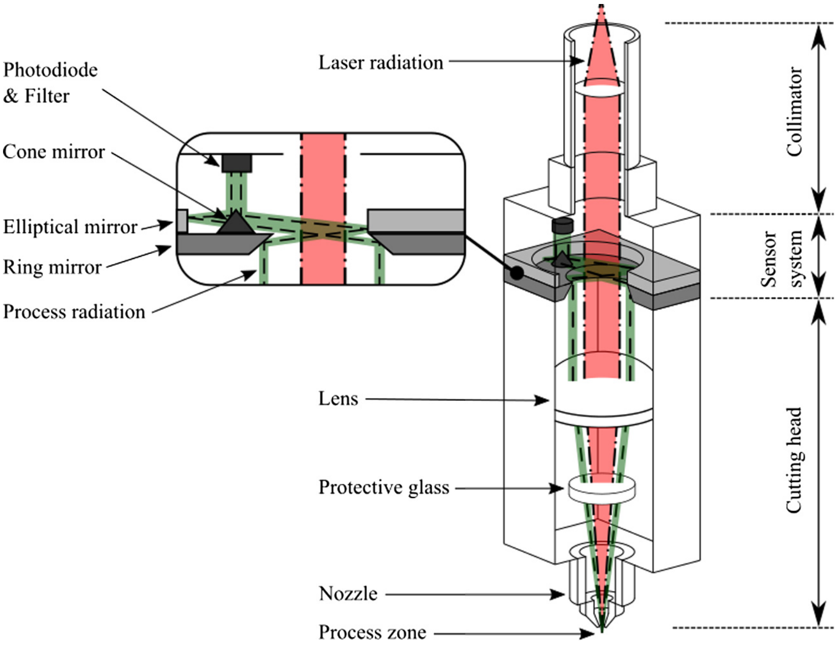

Fig. 1. Design of the sensor system.

the latter is not affected in its propagation. Both the secondary thermal process radiation and the reflected primary laser radiation spread in the sensor system and is guided by the ring mirror onto an elliptical mirror, with one of its focal points being identical with the center point of the ring mirror. In the second focal point of the elliptical mirror a reflecting cone is placed which guides the radiation upwards to the InGaAs photodiode [5]. In front of this diode, a sophisticated multi-level filter is placed with a stopband between 700 nm and 1220 nm to remove the scattered and reflected primary laser radiation, which is orders of magnitude higher than the thermal radiation. The bandwidth of the filter is specifically selected as to allow the sensor to be used also for direct diode laser applications. The diode current is digitalized with a sample rate of 20 kHz for a subsequent signal evaluation by a digital signal processor or PC.

In our study, we employed a continuous wave 4 kW multimode fiber laser (IPG Photonics) to demonstrate the online burr detection system. The laser with a $M^2 < 8.5$, a beam parameter product of 2.9 mm × mrad and a fiber core diameter of 100 µm emits at a wavelength of 1070 nm. The cutting head is moved with a 3D linear stage across the workpiece.

3. Results and discussion

To illustrate the raw data measurement of the sensor system, the result of an exemplarily chosen cut is shown in Fig. 2(a). In our study, a rectangle of $5 \times 37.5\ \text{mm}^2$ with 2 adjacent corners rounded to a semicircle is cut, allowing to exemplify acceleration along straight lines and reduced velocities within the rounding of the rectangular. The rise and fluctuation of the signal after 0.3 s is associated with the beginning of the cut. The semicircle, after the first long straight line of the rectangle, can be correlated with a reduced signal value of the diode caused by the lower velocity of the drives at second 1.0. The sharp 90° turn of the laser drives, after the second straight line of the rectangle, leads to a negative peak of the diode current just at second 2.0. The laser turns off after 2.1 s, leading to a slow decrease of the InGaAs signal value, caused by the cooling process of the workpiece, i.e. a decrease of the thermal radiation. This distinctive signal behavior of the thermal process radiation occurs generally, regardless of the employed process parameters for a complete cut in steel.

To highlight the detection of burr formation, the signals of 3 cuts with different amount of burr (no, little, significant burr formation) are compared in Fig. 2. For all three cuts, 3 mm thick mild steel is cut at 3.1 kW laser power and a velocity of 75 mm/s. For the cut without burr, a working distance of 1 mm and a gas pressure of 12 bar (Nitrogen) is chosen. To enforce burr formation, the nozzle to work piece distance is increased to 3 mm, to gain an unfavorable gas stream in the kerf. Subsequently, the gas pressure is reduced to 8 bar to force an even higher formation of burr. As depicted in the upper diagrams of Fig. 2, the formation of burr is accompanied by stronger noise in the measured signal. To determine the formation of burr, we investigate the noise ratio in a specific high frequency band. To obtain the pure noise component, the measured InGaAs signal is filtered with a digital band-pass filter, which results in a signal fluctuating around the zero-point. The used band-pass filter is an elliptical-filter 12th order with a lower passband frequency of 7.1 kHz, a higher passband frequency of 7.9 kHz, a passband ripple of 6 dB, a stopband attenuation of 30 dB and a sample frequency of 20 kHz. The filtered signals are depicted in the second row of Fig. 2.

To determine the fluctuation of the filtered signal, the standard deviation (SD) in 5 ms time intervals is subsequently calculated and depicted in the third row of Fig. 2. To gain a linear correlation to the burr height, the peak-to-peak value of SD is subsequently calculated for a window width of 1500 samples in an interval of 1000 values. The mean of this peak-to-peak value is marked in the SD diagrams by Ø signs and indicated by vertical bars. Apparently, the peak-to-peak value of SD increases with a larger amount of burr formation.

To show the versatility of the detection system we apply the algorithm to laser cutting of 1 mm mild steel, 3 mm mild steel and 1.5 mm stainless steel, respectively. From the measured diode currents, the signal width of SD is calculated with the above described algorithm for all cuts. Fig. 3 details further information of the calculated SD width as a function of the measured burr height (left part of Fig. 3) for varying laser powers (a), process velocities (b), process gas pressure (c) and nozzle to surface dis-