ON-LINE MONITORING AND PROCESS CONTROL IN SELECTIVE LASER MELTING AND LASER CUTTING

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Abstract

Real-time or on-line process monitoring and control is almost a 'conditio sine qua non' for many physical or chemical machining processes or so-called non-traditional or non-conventional machining. The augmented need for real-time monitoring and control in those processes, as compared to conventional (i.e. mechanical) machining, is due to the large number of process variables and disturbance factors characterizing physical and chemical processes, and to the physical or chemical nature of the process itself that is less deterministic or more variable than mechanical processes. This is why on-line monitoring and control has been developed in the past for several laser processes like laser welding and cladding. The present paper focuses on two other laser machining processes: i.e. the laser cutting and Selective Laser Melting. The paper discusses typical hardware (mainly optics) used for monitoring laser processes and gives some monitoring application examples. It also shows how such monitoring systems can be applied for adaptive feed-back control and demonstrates the performance of such control systems in improving the laser process robustness and productivity, as well as the resulting part quality.

Keywords: selective laser melting, laser cutting, process control

1 Introduction

Non-conventional electro-physical machining processes, like electro-discharge machining (EDM) or laser machining, are difficult to control [16]. This is partly due to the fact that those processes are not as deterministic as conventional machining processes, like turning and milling.

In conventional metal cutting, material removal rate (MRR) is fully determined by three parameters (cutting speed v_c, feed rate f and depth of cut a_p):

$$MRR = a_p \cdot f \cdot v_c \qquad \text{(all units e.g. in mm and sec)} \qquad (1)$$

In most non-conventional processes, feed rate for instance does not determine MRR in a direct (proportional) way. Increasing feed rate in EDM will not necessarily increase MRR: on the contrary, the reduced gap between tool and workpiece might yield more bad discharges (arc and short-circuit discharges) that lower the MRR and might finally result in a crash of the tool against the workpiece, forcing the process to be stopped [16]. Similarly, increasing the feed rate in laser cutting might result in a total collapse of the process: above a certain feed rate, the cut will be lost (i.e. the provided laser power will no longer be sufficient to produce a full penetration cut through the workpiece) [7].

The complex, non-deterministic, sometimes even erratic behaviour of electro-physical processes calls for more complex control systems than in conventional machining. Working at fixed settings (e.g. constant feed rate) is mostly not possible and may require complex process monitoring and feed-back control. E.g., consider the control of the depth of cut in laser caving (also called laser ablation, erosion or milling): there is no deterministic way to control or predict the depth of cut and ingenious depth measuring systems and feed-back control were to be adopted [2, 11, 25, 30].

Process control in electro-physical machining is complicated by the fact that there are more process input parameters (settings) influencing the process outputs (MRR, surface roughness, etc.) than in conventional machining. Where conventional machining is basically controlled by three settings (v_c, f and a_p), the removal rate or surface roughness in laser machining might depend on ten or more parameters like: laser power, laser mode (continuous mode of or pulsed), type of pulse (rise time, profile, etc.), pulse frequency, duty cycle, spot size, feed rate (scanning velocity of spot), stand-off distance, focal distance, assist gas pressure or flow, (preheating) temperature, absorptivity, etc. Most of those parameters may be controlled to some extend (e.g. using variable beam expenders to control the spot size, or applying carbon black to enhance absorptivity), but in many cases it may be difficult to control all those 'input' parameters and many of those are characterised by high variability and noise.

Another element that adds to the complexity of proper process control in electro-physical or laser machining is the fact that process monitoring itself is often more difficult than conventional machining: no accessibility to the machining location, no visibility.

In summary: process control in electro-physical or laser machining is hampered by:

- Non-deterministic character of the processes (i.e. unpredictability)
- No models readily available for modelling relation between input parameters (settings) and output parameters (e.g. MRR, surface roughness)
- More input parameters than in conventional processes; high interaction between some parameters
- More process disturbance: erratic behaviour, lack of control on some input parameters, process noise
- Difficulty to monitor and measure process output on-line.

Hence, it might not be surprising that process monitoring and control attracted a lot of attention in electro-physical machining processes. Adaptive control systems have been developed for most non-conventional machining processes [16, 18]. Quite some research has been devoted to searching for appropriate control algorithms: ACC (Adaptive Control

Constraint), ACO (Adaptive Control Optimisation) [16], expert systems, fuzzy logic, neural networks, etc. [18].

After a brief survey of some earlier monitoring and control systems developed for laser machining processes, this paper will focus on research done at the University of Leuven (K.U.Leuven, Belgium), with respect to monitoring and control of two specific laser processes, i.e. laser cutting and selective laser melting (SLM).

2 Monitoring in laser processes

Monitoring of laser machining processes is, as for most electro-physical processes, not easy, as it is mostly impossible to measure on-line the direct process objectives (i.e. process outputs like productivity or MRR, surface or sub-surface quality like roughness, absence of burning marks, etc.). Therefore, the aimed outputs will have to be assessed by monitoring other process dependent output variables, often called sensing signals. The best sensing signals for monitoring are often those that are most directly linked to the basic nature of the process: e.g. forces in mechanical machining, electric signals (voltages, current, pulse shape, RF-signals) in Electro-Discharge Machining, or electromagnetic radiation in laser machining. Those signals may often contain a lot of process information and are anyhow readily available as part of the processes. The main problem is to find appropriate sensors for measuring those intrinsic process signals.

Electromagnetic radiation from the processing zone might hence yield suitable process information for monitoring laser machining processes, as long as the radiation sensors do not merely detect back radiation from the incoupled laser beam itself. In many cases the process may irradiate in a broad frequency spectrum (UV to IR), even though the radiation frequency spectrum may vary with the process conditions: measuring the change in spectrum might on its own be a way to monitor laser processes [7, 28, 29]. Monitoring laser radiation may therefore be done in the UV range [4, 7, 28], the visible range [7, 9, 14, 15, 19, 6] or the IR range (near IR or far IR) [3, 4, 7, 20, 28, 1, 6]. The type of radiation that is observed will mainly depend on the process itself (This process radiation is the one to be used for monitoring), the material being processed (spectral emissivity), the type of laser used (However, avoid measuring at the wavelength of the own laser radiation), the type of sensor used (spectral sensitivity of sensor, see Figure 1 a), the optics used (filters, lenses, fibers, having each a characteristic spectral transmission, see Figure 1 b).

Various radiation sensors can be used for laser monitoring:

- Single sensor pyrometers [29]
- 2D pyrometer arrays [5, 10]
- Spectrometers [7, 28]
- Single sensor photodiodes [7, 20, 22]
- CCD cameras (photodiode arrays) [1, 5, 12, 26, 29]
- CMOS cameras [22, 27].

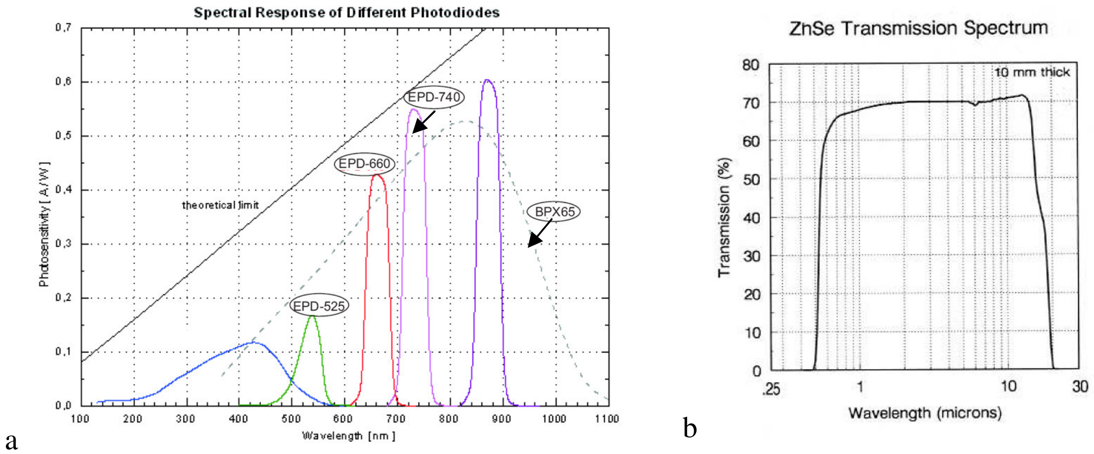

Figure 1 (a) spectral response of different photodiodes (b) ZnSe transmission spectrum

In each sensor type category, one may distinguish between single sensor devices and array devices (linear arrays or mostly 2D cameras). Single sensor devices are often considered as “integrative” sensors. Either they are focussed on a single small spot. However in monitoring applications the upfront optics often make the single sensor to observe a finite area of the emitting object or surface. Those sensors hence act as an integrating 2D sensor: it is like a 2D camera having a 2D pixel array, but where the output signal of the device is nothing else than the integration over all 2D pixel sensors. Such ‘integrative’ single sensor device just measures the total radiation emitted by a surface of a certain size (dependent of area of view). It indicates the total amount of captured radiation (i.e. size and intensity of the observed radiation area), but does not provide spatial information on the radiation as cameras do. The examples in the following sections will demonstrate that integrative sensors might be quite appropriate for laser process monitoring and control, even though no information is available on the spatial distribution of the radiation. In other applications, spatial or geometric information of the radiation zone might be crucial for proper process monitoring: e.g. for detecting melt pool balling effects in selective laser sintering (see Figure 6).

The fact that laser processes are mostly thermal processes[1], is a direct incentive to call on thermal or near IR imaging for monitoring and feed-back control in laser machining. Thermal imaging has already been applied for some laser machining processes, like **laser welding** [20] and **laser cladding** [3].

Sensors may be positioned off-axis to the primary laser beam (Figure 2 a). In this case, the sensor looks to the process from another direction and using other optics than the primary laser beam: laser beam and sensor have their own distinct optical path. Alternatively the laser beam and the radiation sensor may share part of their optical path closest to the processing

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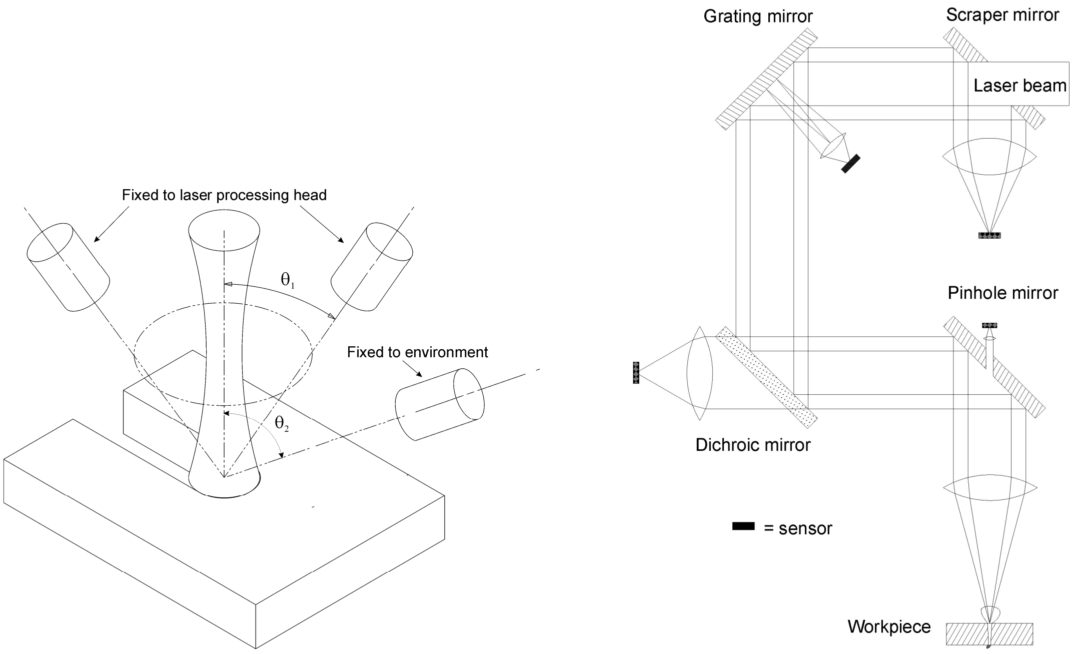
[1] Exception to this rule are e.g. stereolithography and some polymer marking processes that rather rely on photochemistry than thermal processing.

area [27]. This is called a collinear set-up: the laser beam and emitted radiation act along the same optical axis or ‘look’ to the process along the same direction or axis (Figure 2 b). The latter has the advantage that the sensor always looks at the processing spot from the same (axi - symmetric) position and follows the spot as the laser spot scans across the object being processed. Off-axis set-ups may also be mounted on the laser head, as to follow the movement of the laser spot with respect to the processed object, but it yields an asymmetric view that generally varies as the scan direction of the laser beam varies.



a. Off – axis

b. Collinear

Figure 2: Example of possible set-ups

Several researchers combine more than one radiation sensor (single sensors or cameras; collinear and off axis) in a single set-up. [20, 27] describes a system for monitoring laser welding with 3 photodiodes and 1 CCD camera. The photodiodes and cameras are made to measure in different spectral range (see Figure 1a) [7, 8, 22, 23, 29].

De Keuster applies a configuration as shown in Figure 3 for laser cutting. It consists of 3 off-axis photodiodes, integrated in a disk-shaped holder. The sensors are equally divided along the 360^o outline of the disk in order to compensate for the intrinsic direction dependence of the off-axis set-up. Next to these photodiodes, another large-area photodiode has been integrated in the experimental platform according to a perfectly collinear configuration. In order to separate the process-induced radiation from the laser radiation, a dichroic mirror has been installed in the optical path. Using this set-up, the applicability of different types of photodiodes (with different spectral sensitivities) for on-line quality monitoring and control of laser cutting has been investigated. Next to the optical sensors, an acoustic microphone has also been integrated in the experimental set-up.

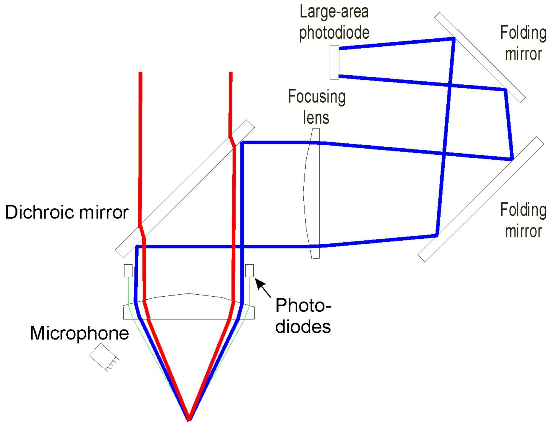


Figure 3: Schematic outline of the monitoring system, developed for laser cutting

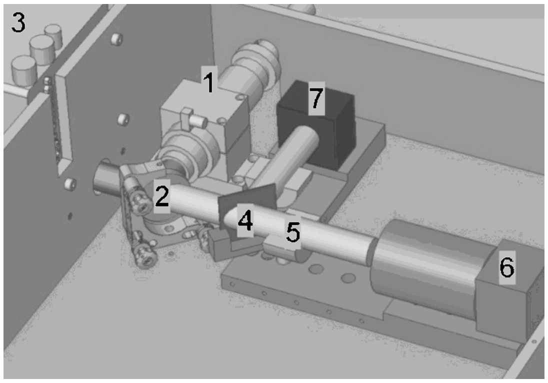


Figure 4: Schematic outline of the coaxial monitoring system for SLM, 1: fiber laser output, 2: 45 degree mirror, 3: laser scanner, 4: beam splitter, 5: optical filters, 6: CMOS camera, 7: photodiode module.

In order to monitor and control the Selective Laser Melting process, Mercelis et al. developed a coaxial optical system. Since the optical path of the laser and the optical path of the sensor system are combined by a semi-reflective mirror, the sensors keep track of the melt pool, regardless of the scanner movement. A photodiode module and a high speed camera were integrated in the system (Figure 4). A beam-splitter divides the melt pool radiation over the photodiode and the high speed camera. A planar photodiode with a large active area is used, to ensure that all melt pool radiation is captured. This way, the photodiode measures variations in the mean melt pool temperature as well as variations in the melt pool dimensions (the latter being more dominant than the former in SLM). Since the high scan speeds of the SLM process necessitate high speed imaging, a high speed CMOS camera was used, allowing very high frame rates, by reading out only part of the chip.

The photodiode output and the images frames are recorded simultaneously in order to correlate the photodiode output signal with the geometric melt pool characteristics.

3 Monitoring and control of laser cutting

From the integrated sensors (acoustic microphone and photodiodes), a near-IR Si with peak sensitivity around 810 nm (i.e. similar to BPX65 in Figure 1 a) photodiode proved to be well suitable for on-line quality monitoring during laser flame cutting of thick mild steel plates. For fusion cutting of stainless steel, a photodiode that is more sensitive in the UV spectral range proved to improve the monitoring capabilities with respect to plasma formation.

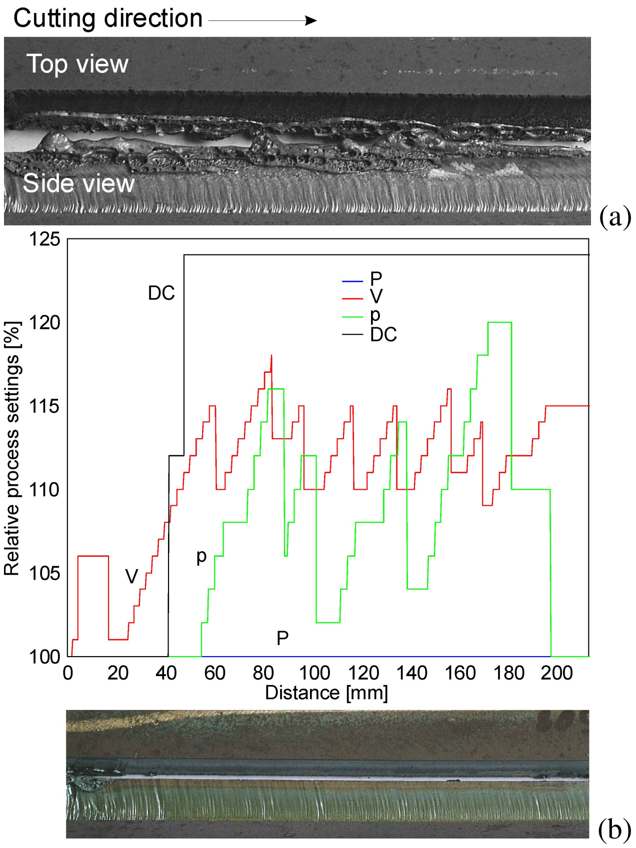


Figure 5: Cutting of a preheated ST52-3 15 mm sample with the control and optimization system inactive (a) respectively active (b)

Thanks to the good signal-to-noise ratio of the IR photodiode signals, signal parameters could be identified that show good correlation with the different cut quality characteristics. The mean value of the photodiode signal proved to correlate well to the drag of the striations and the risk of dross attachment. The standard deviation provides essential information about the roughness of the cut edge and the occurrence of burning defects. Based on these two signal parameters, the cut quality can be assessed.

This cut quality information is then used to control and optimise the process: taking the actual process status and corresponding cut quality into account the settings for different process control parameters are adapted in order to always guarantee well-optimised process conditions. As process control parameters, the laser power (P), cutting velocity (V), assist gas pressure (p) and duty cycle (DC) have been withheld during the research (see Figure 5). The actual control and optimisation is realised using a rule-based expert strategy: this strategy consists of clear, physically interpretable rules that are based on both heuristic (operator) and theoretical knowledge about the laser cutting process.

The performance of the developed control and optimisation system proved to be satisfactory: the quality, robustness and productivity could be raised significantly. To illustrate this, Figure 5 shows the performance of the control and optimisation system during the cutting of a preheated ST52-3 plate of 15 mm. At the top, the cut quality is shown for a workpiece, cut without the control and optimisation system active. It is clear that, without control, the preheating effect has a detrimental impact on the process status: full penetration hardly achieved, increased drag of striations, severe dross formation, high edge roughness, large cut width. At the bottom, the improvement realised by the control and optimisation system is illustrated. Both the evolution of the process control parameters[2] and the resulting quality are shown. Although initially some bad cut quality can be observed, the quality of the rest of the workpiece is relatively good. From productivity point of view, it can clearly be seen that the average cutting velocity has been increased by +/- 12%, relative to the recommended standard setting.

4 Monitoring and control in Selective Laser Melting

Selective Laser Melting is a layered manufacturing process in which successive layers of powder material are melted and consolidated to produce complex 3D parts. As compared to Selective Laser Sintering the laser fully melts the powder around the laser spot [17]. This leads to almost 100% densification of the powder, but may also yield melt pool instabilities due to the surface tension (so called Raleigh instabilities). Other kinds of melt pool instabilities occur when scanning 3D shapes. Variations in the local geometry of the part around the melt pool that is produced result in large variations of the (conductivity) border conditions. Examples of this kind of instabilities are the drastic change of the melt pool geometry at an overhanging plane, at sharp angles or at tiny features. At the edge of an overhanging plane for example, the conductive heat transport drastically changes, since the heat conductivity of the powder bed is much smaller than the corresponding solid material. In case of scanning such geometry with fixed parameters, these changes in the local conductivity result in large variations in the local melt pool geometry. These variations result in geometrical deviations and dross formation in the produced 3D parts. Another example is the phenomenon of balling, in which the melt pool breaks up and droplets of consolidated metal are formed on the scanned surface. The breaking up of the melt pool can be detected by the high–speed CMOS camera as shown by Figure 6. Notice that no balling occurs at low scan speed, while melt pool splitting is clearly observed at scan speed of 50 mm/s. In order to overcome these instabilities, a feedback control setup based on the coaxial optical system shown in Figure 4 has been developed [23, 21].

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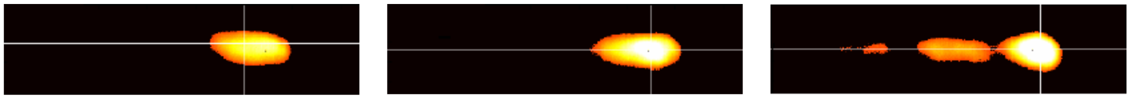
[2] Control parameter settings are given relative to standard settings as recommended by the machine's parameter data base. E.g. P = 100% means "standard recommend power settings"; V = 120% means 20% higher cutting velocitiy.



v = 6 mm/s v = 16 mm/s v = 50 mm/s

Figure 6: melt pool stability at different scan velocities

The sensing variable monitored in the case of selective laser melting is the total melt pool area. Experiments revealed that the output signal of the planar photodiode correlates well with the total melt pool area as detected by a 2D CMOS camera [22, 23]. The feedback signal in the control loop therefore is the output voltage of the planar photodiode. For every set of relevant process parameters, laser power, beam velocity and scan strategy, a steady state setpoint for the photodiode voltage can be determined experimentally. The purpose of the controller is to keep the output voltage of the planar photodiode as close as possible to the setpoint voltage. A constant melt pool area will avoid balling and dross formation and lead to better overall quality of the produced part.

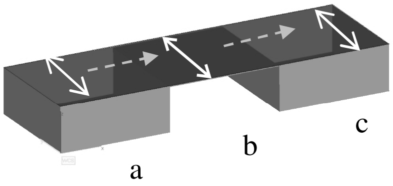


Figure 7: Definition of parallel scanning for a horizontal overhang plane.

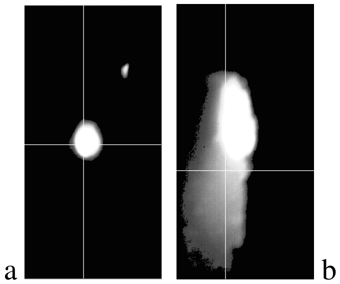


Figure 8: Typical melt pool
a) Scanning on solid substrate
b) Scanning on powder substrate (overhang)

In order to stabilize the melt pool during the process, the laser power that is applied to the powder material is controlled in real-time, during the scanning of the geometry. The use of the scanning velocity as control parameter is not possible in the current setup because the scanner software does not allow adjustment of the velocity within one scan vector. Since the control of the laser power level is independent of the scanner motion, the laser power can be adjusted even during the scanning of a single vector. The high-speed camera was used to record melt pool images during the execution of the different tests, in order to validate the performance of the feedback controller. A National Instruments DAQ device (6024E) was used to sample the diode output voltage and to generate the control signal for the laser source.

An example of changing border conditions is the scanning of overhanging surfaces. If an overhang plane is scanned ’parallel’ to the overhang border line, like in Figure 7, the scanning will move from a zone with underlying solid material (zone a) to a zone with underlying powder material (zone b), having a much smaller effective heat conductivity.

If the laser power and the scanning speed are kept constant during scanning of this geometry, the melt pool will enlarge drastically when passing the overhang zone: compare Figure 8 a and b. At the same time, the laser beam will penetrate too deep into the powder bed. This results in the formation of dross material that solidifies at the bottom of the overhang (Figure 11 a).

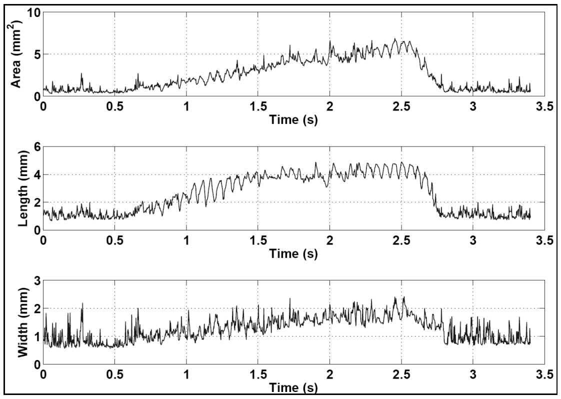


Figure 9: Melt pool geometric characteristics during parallel scanning of the overhang plane.

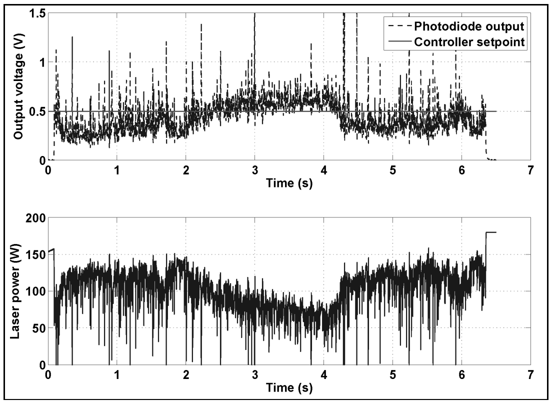


Figure 10: diode output voltage and laser power in case of PI feedback controlled perpendicular scanning of an overhang plane

Figure 9 shows the melt pool's geometric characteristics (melt pool area, length and width) as obtained from the camera images taken during the fixed parameter scanning of the overhang. It can be seen that melt pool area and melt pool length enlarge significantly in the overhang area (zone b in Figure 7), while the melt pool width remains more or less constant. When feedback control is applied, the rise in the diode signal at the passage of the overhang is counteracted by lowering the laser power, thus reducing the fluctuations in melt pool size. A setpoint of 0.5V is used for the diode output signal, corresponding to the diode signal on the non-overhang zones in case of fixed laser power. Many different settings were tested for P and PI controllers. Figure 10 shows the measured photodiode voltage and the controlled laser power in case of PI feedback control, which proved to give the best performance.

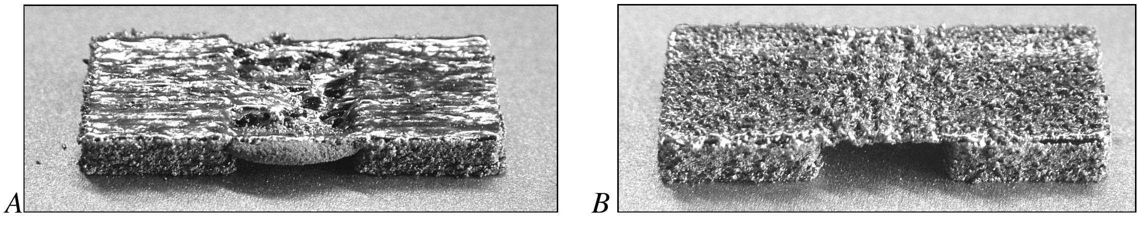
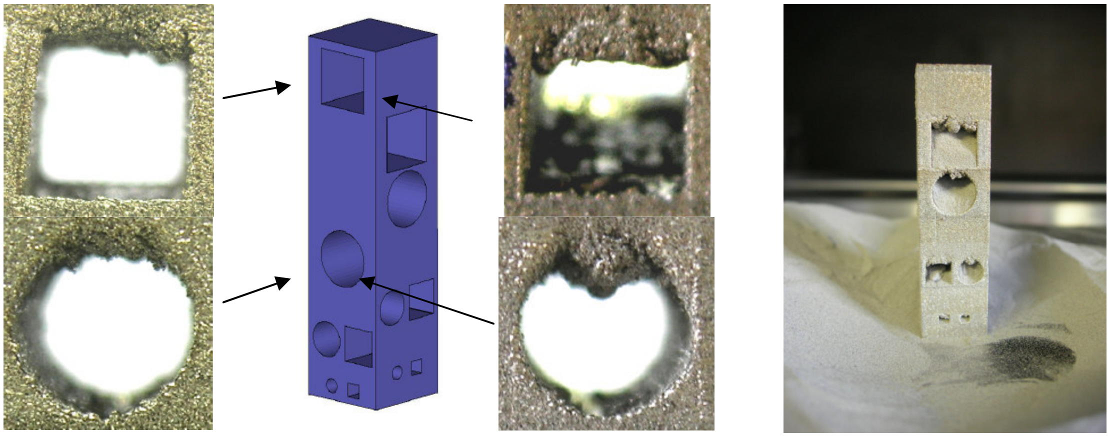


Figure 11: Resulting overhang geometry in case of scanning at (A) fixed laser power versus (B) feedback control.

A comparison of the resulting geometries is shown in Figure 11. In case of using fixed laser power, a lot of dross is present in the overhang zone, due to the fact that the large melt pool is attracted mainly by capillary forces in the underlying powder bed. It is clear that the dross is much less in case of feedback control, since the melt pool size was much less in the overhang zone than in the case of fixed parameters.



With control *Part design* *Without control* *Without control*

Figure 12: comparison of scanning overhang structures with and without feedback

In order to evaluate the current real-life performance of the photodiode-based feedback system, a benchmark part was designed, including a number of different overhang geometries: straight and circular overhang geometries with a length, respectively diameter of 2, 5 and 8mm, in X as well as in Y direction (i.e. parallel and perpendicular to the scanning direction). Since large overhang lengths or diameters result in a worse part quality, the largest overhangs were placed at the top of the part, while the small overhangs are placed at the bottom. This benchmark part was built twice from stainless steel powder; once using fixed scanning parameter, and once using feedback control (PI) of the laser power. Figure 12 shows the benchmark design and the resulting parts. It is clear that using feedback control a much better quality of the overhang structures (i.e. downfacing surfaces) has been achieved, with much less dross formation. Notice also the improved quality of the upfacing surface when using feedback control.

5 Conclusions

This paper illustrated the application of process monitoring and the use of feedback control in laser processes, with special attention for laser cutting and selective laser melting. It has been demonstrated that on-line monitoring the electromagnetic radiation emitted by the process area around the laser spot is an effective way to assess the process performance and quality. It allows detecting process deterioration like the occurrence of dross, striations, balling, surface roughness degradation, loss of cut, etc. While the process emits radiation in a large spectrum (from UV to IR), the best results are obtained when monitoring the near IR or thermal radiation, since the described laser processes are mainly thermal driven processes. Monitoring this radiation can be done using different types of sensors: single point sensors, 2D sensor arrays (e.g. CCD or CMOS camera's) or integrating sensors (e.g. large area photodiodes) positioned collinearly or off-axis to the optical path of the laser beam. The best results are obtained with a collinear set-up since the image is not influenced by the movement and direction of motion of the laser beam. Collinear set-ups, however, require more complex optics to separate the primary laser radiation from the emitted process radiation.

In the second part of the paper, such monitoring systems were applied for real-time control of laser cutting and selective laser melting. It has been demonstrated that in most cases an integrative sensor (i.e. large area photodiode) already provides sufficient information for feedback control. Different control strategies have been used: simple proportional or proportional-intregrative feedback in selective laser melting, and a knowledge-based or rule-based controller in case of laser cutting. Dependent on the application, different laser process parameters are regulated: laser power, scan speed, laser duty cycle and/or assist gas pressure. In both cases (cutting and melting), it turned out that those control systems were quite effective in improving the robustness of the process: the system was able to keep the process under control, avoiding common process degeneration like loss of cut in cutting, or bad surface roughness in SLM that prohibits the deposition of a next powder layer or causes a part to collapse. Moreover, the part quality is improved significantly as well in laser cutting (avoidance of excessive dross, striations, roughness and burning defects, while guaranteeing cut straightness by maintaining a constant cut width), as in SLM (less balling, less porosity, less dross, smoother up and down facing surfaces or overhangs). Finally, in laser cutting, the control system was even able to increase the cutting speed (up to 20%) at increased process robustness and quality. No proof was given so far that feedback control may also allow to speed up the SLM process, but it is expected that the improved process robustness will allow to do so.

On-line process monitoring and real-time process control are anyhow very effective means to control and improves laser processes that by nature are less deterministic and controllable than conventional mechanical manufacturing processes.

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