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[INVITED] Evaluation of process observation features for laser metal welding ☆

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ABSTRACT

In the present study we show how fast the fluid dynamics change when changing the laser power for different feed rates during laser metal welding. By the use of two high-speed cameras and a data acquisition system we conclude how fast we have to image the process to measure the fluid dynamics with a very high certainty. Our experiments show that not all process features which can be measured during laser welding do represent the process behavior similarly well. Despite the good visibility of the vapor plume the monitoring of its movement is less suitable as an input signal for a closed-loop control. The features measured inside the keyhole show a good correlation with changes of process parameters. Due to its low noise, the area of the keyhole opening is well suited as an input signal for a closed-loop control of the process.

1. Introduction

The monitoring and control of laser material processes is in the scope of science and research for almost 30 years. One important requirement of a process control system is the ability to monitor and control the process in real-time. Due to the very dynamic process behavior, high sample rates are needed to satisfy this requirement. However, closed-loop control systems with control frequencies well above 1 kHz are not generally necessary for the control of the laser welding process, since different process features do behave differently with respect to their fluctuations or the delay time after changes of process parameters.

Another important feature of a control system is the reliability. For a desired controlling frequency f_{con} a monitoring frequency f_{mon} is needed. For a reliable monitoring of a process feature f_{mon} has to be well above f_{con} ($f_{mon} = X \cdot f_{con}$). The value of X depends on the fluctuation of the monitored process feature. For features with small deviations, when using constant process parameters, using only ten measurement values might be enough to assure that the measurement does really represent the process behavior. However, some process features might have a higher dynamic and thus a larger amount of noise [18]. Therefore, a monitoring frequency which is several magnitudes above the controlling frequency might be needed for a reliable measurement value. Furthermore, from an industrial point of view the sample rate should be chosen as low as possible to have an inexpensive and reliable control system.

Summarizing, there is always a need for balancing costs and frame rate of a specific monitoring system. Hence, there is the question: how fast is fast enough? Furthermore, the melt and gas dynamics inside the keyhole might have a certain delay time when changing laser power and feed rate. This delay is a limiting factor for controlling the process. Hence, it has to be known. For a long time it was not possible to measure these small delays. Nowadays, high-speed cameras are capable of imaging these changes in a sufficient time resolution.

2. State-of-the-art

The first approaches for the monitoring of laser material processing have been done over 30 years ago by the use of photodiodes and microphones [14]. The monitoring of the process radiation was thereafter enhanced by evaluating spectral information from the vapor plume [6]. These approaches are beneficial for monitoring the highly dynamic laser welding process since a real-time evaluation of the photodiode signals can be done easily. Therefore, photodiode-based measurement systems are available on the market and are still a topic of research [12]. Nevertheless, these approaches lag the possibility to have the whole picture of the process and the adjustment of the measurement system is

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prone to errors, since photodiodes do have a very limited field of view. Furthermore, the process radiation is only an indirect measure of the real process dynamics. A direct camera-based observation of the interaction zone between the laser beam and the material does not suffer from these drawbacks since the whole process and its surrounding are imaged and the sensor system is easily adjustable. With the rise of high-speed cameras in the 1990s first attempts could be made to directly image the interaction zone in laser welding [22]. Nevertheless, these approaches have been limited in their significance due to the low magnification which prevents the analysis of fluid dynamics inside the keyhole. Another drawback of this technique is the large amount of data which hampers a real-time processing of the monitoring data. An approach which tackles these issues is the use of cellular neural network cameras which have an image processing unit inside the camera for every single pixel. The use of these cameras enabled a real-time monitoring of the fusion state in laser metal welding [1]. For the monitoring of process characteristics which do not change rapidly within a couple of milliseconds, like the temperature distribution in the work piece, a real-time monitoring can be realized more easily and thus be better applied in an industrial environment [7].

However, for an accurate imaging of the fluid dynamic in laser welding, which is the determining factor for seam quality, high spatial and temporal resolution is needed [3]. Since today, no real-time monitoring camera-based device can achieve these resolutions which are in the range between 100 and 300 kHz. Therefore, in the industrial application of process monitoring technique, there is always a trade-off between the processing speed and the accuracy of a specific sensor system. Moreover, the fastest monitoring system cannot control the process in real-time if there are delays in the actuator unit due to mechanical or electronic limitations (e. g. the inertia when increasing the feed rate). Therefore, in most of the cases changing the laser power is used for influencing the process, independent from the monitoring technique. This might be the measurement of the electron temperature [17], the position of the vapor plume [5] or the measurement of the keyhole depth via white light interferometry [4].

Summarizing, there is a lack of real-time control systems which do guarantee a defect-free weld. However, it might not be necessary for all applications to control the process with the highest spatial and temporal resolution available. If process characteristics do not change instantaneously when changing feed rate or laser power, a lower control frequency can be sufficient for controlling the process. In contrast, some process characteristics might seem to be measurable quite easily, but can be inconsistent in their appearance, so that their measurement might lead easily to errors when using a low frame rate. Therefore, a detailed analysis of the dynamic of the process features, as shown in the present paper, is needed.

3. Experimental setup

To determine how fast a process has to be imaged to measure the fluid dynamics with a high certainty we use two synchronized high-speed cameras (*VisionResearch Phantom v1210*) working with a frame rate of 240 kHz when using an image size of 128 x 128 pixel (see Fig. 1(a)). A band-pass filter in front of the cameras prevents reflections of the laser light saturating the images. Since the size of the process features is in the range of some hundred micrometers we use a magnification objective (factor 3) from *Navitar* to obtain a detailed view at a working distance of approximately 200 mm. The high spatial and temporal resolution of this setup allows for the complete imaging of the process dynamics as the process features are not expected to change within 4.17 µs (when using a frame rate of 240 kHz). Therefore, it enables us to measure the effect of changing process parameters on the process features and to conclude what is the maximal useful speed of a control system. For material processing we use a *TruDisk 4002* Yb:YAG laser (wavelength 1030 nm, maximum output power 4 kW) coupled to a focusing optic (BEO D70, focal length 200 mm, spot size 600 µm, beam profile top hat).

We apply this setup to weld into a stainless steel plate (X6CrNiTi18-10) of 5 mm thickness. Due to the thickness of the steel plate we avoid any influences of full penetration of the material. For moving the metal sheets with high accuracy we use a system of linear stages (*Aerotech PRO280LM*). Due to the high temporal and spatial resolution of our imaging setup we are able to resolve velocities inside the keyhole of up to several tens of meters per second with certainty, which is necessary for measuring the dynamics of the weld process.

During our experiments we vary laser power and feed rate, since those two parameters are the most widely used parameters to influence the laser welding process in the application of closed-loop control systems. By changing the laser power step-wise for different feed rates the influence on the process behavior can be obtained. The lowest laser power we used was 1500 W. This ensures to have a stable keyhole for all welds and avoids the influence of the transition from heat conduction to deep penetration welding. The feed rate was varied between 2 and 10 m min^{-1}. In every experiment we change either the laser power or the feed

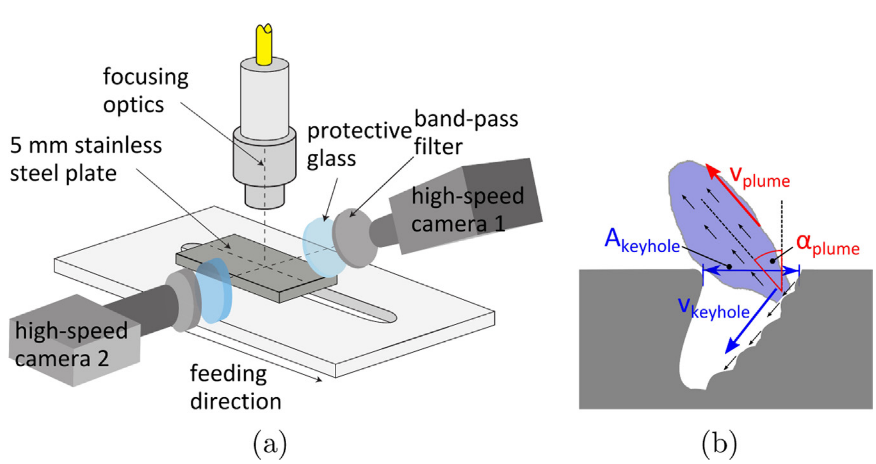

Fig. 1. Setup for measuring the keyhole opening area $A_{keyhole}$, the velocity of the melt at the keyhole front wall $v_{keyhole}$ (both imaged with camera 1), the vapor plume velocity v_{plume} and inclination angle α_{plume} (camera 2); inclination of camera 1: 55°, inclination of camera 2: 0°.