Visualization of laser back-reflection distribution during laser welding

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Abstract. There are several approaches to weld quality monitoring during laser welding. Reflected laser radiation carries partial information about the welding process. Fibre lasers has usually a built-in diode to detect excessive back-reflected laser radiation to protect the laser source from damage. Reflected laser radiation measured in the laser source is compared with reflected laser radiation measured in the welding head. Moreover, coaxial high-speed imaging with a narrow bandpass filter on laser wavelength is used to visualize the reflected laser radiation. The advantage of this solution is that no additional illumination is needed and the reflected laser intensity and spatial distribution can be obtained from the image. Keyhole inlet dimensions are measured and related to the laser power. The transition between laser welding modes is studied.

1. Introduction

Part of laser radiation is reflected during laser welding. High levels of reflections can lead to dangerous situations and damage. However lower levels of reflections may carry information about the condition of the welding process. Laser back reflection (BR) is a sum of reflections on optical elements of a processing head, reflection on the weld pool surface and keyhole walls, and scattering on metal droplets and microparticles above the weld pool.

Molten metal has greater reflectivity than non-molten metal and behaves like a mirror that reflects the laser beam. Movements of the free surface of the weld pool can focus, defocus, or deflect the beam, while the keyhole predominantly absorbs the beam. This article intends to investigate which areas of the weld pool reflect the most laser radiation during different welding modes. Such conclusions will help to interpret the effects of the individual components on one-dimensional photodiode measurements.

Photodiode-based monitoring systems are commonly used in industry due to the advantage of higher possible frame rates and robustness, but on the other hand, with such a simple tool you cannot obtain a comprehensive description of the process. Norman et al. found out that the signal is governed mainly by the weld pool size and liquid pool emissions [1]. The emissivity of the weld pool surface is strongly influenced by the oxidation state of the weld pool surface. You et al. measured emitted laser and visible radiation and compared them with the keyhole and plasma plume area, concluding that BR is sensitive to laser power and keyhole size [2]. The intensity of reflected laser radiation is also affected by focus position [3]. Eriksson et al. found out that variance of photodiode signals tends to be larger for bad welds while the mean value changes only a little [4]. This may cause problems with setting thresholds for weld quality classification and shows the challenges in finding principles for a universal monitoring system.
Stritt et al. investigated reflected laser radiation to distinguish between heat-conduction and deep-penetration mode during disc laser welding with modulated laser power [5]. The authors also observed higher and more variable BR during the heat-conduction mode compared with deep-penetration mode and noticed that the BR is higher during the keyhole formation than the BR corresponding to keyhole closure. However, no analyses have been made to determine whether the major source of BR is weld pool or keyhole.

Images of laser welding process are usually recorded by a side camera with additional illumination. Zhao et al. proposed a setup with coaxially mounted camera with a side lighting source [6]. Kaierle et al. tried a setup with a coaxially mounted NIR camera and standard CMOS camera with additional coaxial illumination and bandpass filter [7]. Near-infrared images were too saturated and thermal radiation was visible. In contrast to previous studies, replacing the illumination laser with the processing laser suggest since it is also a powerful source suitable for illumination.

The welding process is a source of a wide range of emitted radiation. The highest level of intensity is reached at the wavelength of the processing laser. A narrow bandpass filter tuned to the wavelength of the laser is necessary to ensure that only desired wavelength reaches detectors. Nevertheless, both the weld pool and laser emit in NIR spectrum. The contribution of laser and thermal radiation cannot be separated from the measured values. Fortunately, the weld pool radiation is an order of magnitude weaker than laser reflection and can be suppressed under the detection limit by neutral density filters. Such a solution should suppress the effect of thermal radiation and images carry an intensity value of BR in each pixel and therefore can be used for further measurement.

2. Experimental setup

The laser source IPG YLS-2000 with welding head Precitec YW30 with 100 mm focusing and 200 mm collimating lens were used. The feeding core diameter is 200 μm which theoretically results in a 400 μm beam waist diameter. The welding head is equipped with a beam splitter allowing coaxial observation of the process zone. Custom optics with InGaAs photodiode with amplifier and AOS Promon U750 camera were attached to the welding head.

Several bead-on-plate welds with different processing parameters were performed. Welding speed was 20 mm·s⁻¹ and laser focus position 1 mm under the surface of the 10 mm thick S355J2 carbon steel sheet. Different weld dimensions were obtained by laser power variation from 100 to 2000 W with an increment of 100 W. The beam waist diameter was checked by contactless profilometer BeamWatch. The beam parameters vary depending on the laser power, therefore measurements for two laser power values were made. The average diameter was 391 ± 26 μm for 1000 W and 446 ± 10 μm for laser power 2000 W. The diameter of the laser spot on the sheet surface, thus 1 mm above the focus position, for both laser power values was 410 μm for 1000 W, respectively 460 μm for 2000 W. To ensure the correct focal position, the sheet standoff distance was measured by a triangulation sensor prior the welding. The welds were shielded with an argon protective atmosphere.

2.1. Imaging optics

Back-reflected laser radiation is split inside the welding head. A part of the laser beam continues through the optical fibre to the built-in photodiode in the laser while a part of the beam is directed outwards. Standard coaxial camera optics were replaced with a modular system, figure1. The reflected laser beam passes through the gas nozzle of inner diameter 5.5 mm, welding head focusing lens and beam splitter, simple optics, bandpass filter on laser wavelength 1070±10 nm and neutral density filter with optical density OD = 3 to suppress the intensity. An aperture with a 4 mm diameter is mounted before a 50/50 beam splitter. The beam splitter divides the beam in half and the lens focuses the beam on both InGaAs photodiode and camera chip. The lenses have an AR coating to eliminate reflections and clear aperture of 25.4 mm. The optical path was covered during the welding.
3. Results
Both photodiodes built into the laser and the head were sampled at 100 kHz. The camera framerate was 3003 fps which is the fastest possible at a resolution of 144 x 140 pixels. The exposure time was 59 µs which is the limit of the camera to ensure a sharp image. The camera can be treated as a single photodiode by summing the intensities of all pixels. Figure 2 shows the reflected laser intensity detected of all three detectors: the photodiode built into the laser source, photodiode built into the welding head and sum of all pixels of coaxially mounted camera at 600 W laser power. The figure shows that all detectors have a similar pattern which indicates that the same phenomenon is measured. While photodiodes are suitable for industrial practice due to their simplicity, the camera allows for a more detailed spatial analysis of the back-reflected laser radiation.

![Figure 1. Optics for measuring the intensity and spatial distribution of reflected laser beam.](image)

![Figure 2. The intensity of reflected laser radiation measured with the built-in photodiode (phd) in laser, and coaxial photodiode and camera (cam) in welding head.](image)
Figure 3 shows the intensity distribution of BR of consecutive images at three different laser power values. The laser is reflected only from a small area and most of the image is black. Correct intensity measurements are disrupted by small, saturated areas. Those can be eliminated by using a filter with higher optical density but at the cost of reducing lower intensity reflections. Nevertheless, they are not an issue for the subsequent evaluation. The recorded events are faster than the frame rate of the camera because the changes between frames are too rapid and the frames do not show the gradual changes. Thus, a framerate of 3003 fps is not enough to fully capture the dynamics of the laser welding process.

Welding with laser power of 300 W melts the sheet without creating a keyhole. The unabsorbed laser beam is shaped and partially reflected back. On the other hand, the laser power of 600 W begins to form a keyhole. The keyhole is present from time to time, but not fully developed. The small circular grey area is an early stage of the keyhole. The saturated high-intensity reflection still occurs. The last pictures of figure 3 show that the laser power of 1500 W is enough to form a stable keyhole with part of the weld pool visible. The keyhole changes the shape and size of the inlet opening. It is possible to look inside the keyhole but the details are not visible and the depth cannot be estimated.

![Figure 3](image)

**Figure 3.** Consecutive images of reflected laser radiation for laser power 300, 600 and 1500 W.

It is quite challenging to determine what part of the welding process is present in the camera pictures. Laser irradiates a relatively small area, molten metal has smooth shapes and occasionally spatter occurs. This makes the images blurry and the surface of the weld pool does not always reflect the light upwards, making it difficult to determine the dimensions programmatically. To describe the process in a more statistical manner than a single measurement, averaged image from over 8000 images for each weld was calculated in figure 4.

The heat-conduction mode has the sharpest weld contour with a relatively uniform average intensity distribution except for the intermediate ring with lower intensity. On the other hand, the deep-penetratio
mode with a fully developed keyhole has the brightest spot in the centre and unsharp edges. Laser is absorbed inside deep and narrow keyhole by multiple reflections that is the reason why the keyhole is not much brighter compared to reflections from the free surface [8]. The bright area does not represent the weld pool, but the keyhole in this case. The transition mode is a combination of the previous two.

The images were calibrated to perform length measurements as well by capturing the scale. One pixel corresponds to 12.5 µm in the camera focal plane. By modifying the imaging system, better resolution can be achieved but in this case the frame rate was more important at the sacrifice of spatial resolution. Since laser spot diameter is 0.4 mm values are reasonable and will be discussed in more detail below.

**Figure 4.** Average distribution of reflected laser intensity during laser welding with power values from the left 300, 600 and 1500 W.

Weld fusion zone dimensions of metallographic cross-sections were also measured and plotted in figure 5. The excessive width deviations for higher laser power values are caused by humping and the fact that only one cross-section was made from each weld. The penetration depth is only needed to assess the welding mode as depth cannot be directly measured by the proposed setup. The transition between both welding modes is around the point where measured weld width and depth intersects. In this case, it is at the laser power of 650 W. Figure 6 shows estimated bright spot dimensions from averaged camera images. The threshold was set fixed for all welds based on the visible contours of the weld pool in the heat-conduction mode. The dimensions of the area are approximately 0.44 - 0.53 mm for laser power under 500 W. While for laser power higher than 1000 W it is between 0.4 - 0.44 mm. The zone between them has a prolonged shape and the estimated length and width differ significantly. On this basis, the transition mode can be detected. During the heat-conduction mode, the bright spot represents the weld pool and on the other hand, during deep-penetration welding keyhole is observed.

**Figure 5.** Weld dimensions measured on metallographic cross-sections.
Figure 6. Process area dimensions estimated from averaged camera images.

4. Discussion

The intensity of reflected laser in figure 2 detected by the photodiode and signal calculated from the camera seems to be very similar on a macro scale. Yet on closer look, there are small differences that may be caused by different chip size, sensitivity, and alignment. Also, light detected by the built-in photodiode passes through the fibre while part of the beam detected in the welding head is deflected before the fibre.

The laser beam has the highest intensity within its nominal diameter of 0.4 mm. The beam measurement made at 1000 and 2000 W shows that with increasing laser power the beam diameter is also slightly increased. Therefore, the largest irradiated area detectable by the camera depends on the laser power. But it is difficult to verify this statement since the metal sheet is molten at higher laser power values. The irradiated area for laser power under 500 W is roughly 0.86 mm which is greater than the weld pool size and the solid surface of the sheet is visible.

The transition between welding modes is detectable by both photodiodes. The figures are very similar, hence only intensity measured in the welding head is presented. Figure 7 shows the mean values and standard deviations of signal averaged over the length of the weld. The three welding modes are distinguishable based on a variation of BR signal. The zone below 500 W with the greatest variability corresponds with the heat-conduction mode. The zone above 1000 W with the lowest variability is deep-penetration laser welding and the zone between them with medium variability is transition mode. The results are consistent with Stritt et al. Excessive variability in low power laser welding is caused by the data not following a normal distribution. Two or more effects are mixed together. The camera captures only the keyhole area without the weld pool at higher laser power values. Therefore, BR signals follow the normal distribution so that assumptions for correct standard deviation estimation are met.

Image segmentation to distinguish the contributions of keyhole and weld pool should be done and is crucial for verifying the hypothesis of different contributions. One possibility is differentiating the regions based on a variation of intensity. The region with lower variance should be the keyhole and solid metal sheet. On the other hand, the weld bath should exhibit greater intensity variability as Stritt et al. noticed.
The common dividing line in defining the transition between laser welding modes is based on metallographic cross-sections. Asibu claims that heat-conduction welding mode typically results in a depth-to-width ratio of about 3:1 compared to about 10:1 or more for deep-penetration welding [9]. That is much more than in our case and thereby unusable. Another dividing line is the depth-to-width ratio lower than one for heat-conduction mode and greater than one for deep-penetration mode. Now compare at which laser power values the changes corresponding to the welding modes vary for different methods. The welding head photodiode indicates transition mode between 600 and 900 W and the observation of keyhole presence on images suggests the same values. A slight drawback is that detection of keyhole does not work on individual images at this stage but estimates the presence of a keyhole based on averaged values. The depth-to-width ratio equals one at 650 W according to the weld dimensions plot. The Depth-to-width ratio in figure 8 proposes that transition mode is shifted to lower laser powers between 400 and 700 W. Thus, all methods give similar results, but for a detailed comparison more measurements with finer power division would be needed. This was a simple verification that the coaxial camera imaging method does not give results that conflict with the other methods. Moreover, others [5] have shown, that capillary formation and closure is correlated with reflected laser radiation. There is the potential to monitor the keyhole presence during the welding process.

Figure 7. Reflected laser intensity measured by the photodiode in the welding head.
Further development should be directed towards the development of algorithms for segmenting the images capable of distinguishing between weld pool and keyhole. The biggest challenge here is that in heat-conduction mode only the size of the weld pool is visible, whereas in deep-penetration mode only the keyhole is visible and the weld pool remains dark. This existence of multiple welding modes especially transition mode complicates implementation of universal recognition algorithm and interpretation of results. However, it may be sufficient to focus only on the study of the one welding mode, namely the deep-penetration mode.

5. Conclusion

For general monitoring purposes, it should not matter if reflected laser intensity is measured by a built-in photodiode which is primarily used for laser protection or photodiode solution implemented in welding head. It was proved that the BR signal from both photodiodes is the same except for minor differences. The sum of pixel intensities from all the pixels of the coaxially mounted camera shows similar behaviour as the photodiodes. Therefore, the camera can be used instead of a photodiode. The greatest advantage is the ability to visualize detailed spatial distribution of reflected laser radiation during the laser welding process. It is possible to coaxially observe the reflections from the weld pool surface and interior of the keyhole during laser welding. The laser beam is predominantly focused by the convex shape of the weld pool during heat-conduction mode. On the other hand, a major part of the laser beam incident on the weld pool surface during deep-penetration mode is absorbed in the keyhole or reflected. The image is not negatively affected by the plasma plume.

No external lighting source synchronized with a camera is needed. The advantage of this solution is that the images can be used for intensity measurement. On the other hand, the disadvantage of this method is that only a small area approximately the size of the laser beam is visible.

Three welding modes can be distinguished based on back-reflected laser intensity variation. Although distinguishing the modes can be based on intensity alone, so photodiode appears sufficient, the camera allows to check the presence of keyhole. The coaxial images of reflected laser radiation have made it possible to understand from which regions the reflections originate. The images were averaged for an objective assessment. It is important to be aware that the method of averaging images emphasizes different objects – weld pool for heat-conduction mode and keyhole for deep-penetration welding mode. The thresholding method is not suitable because some areas of the process are not always visible and the reflections from the weld bath have a random character. Averaging the images solves the problems with randomness but average values differ only slightly, and it is problematic to find the correct threshold for transition and deep-penetration welding mode. More advanced algorithms should be used to take full advantage of this imaging technique.

It has been verified that the intensity of reflected laser radiation for heat-conduction mode is proportional to the weld pool size. The greater the weld pool size estimated from images, the higher the

Figure 8. The effect of laser power on depth-to-width ratio.
overall intensity detected by the camera or both photodiodes. The size of the measurable weld pool is limited by the size of the illuminated area at the laser spot size scale.

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