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Correlation between camera image and photodiode signal during laser welding

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Abstract

Photodiodes are often used to monitor weld quality. This solution has the advantage of simplicity and low cost, but it may be more difficult to interpret the measured data. Moreover, measurement with multiple photodiodes indicates dependency of the measured intensity on the photodiode position. The purpose of this study is to better understand the data measured during the laser welding process. Therefore we explore which part of the high-speed camera image best corresponds to photodiode intensity during welding. Regions of interest including weld pool and vapour plume are selected from camera images. The regions are compared with the photodiode using correlation coefficient. Subsequently, the task is generalized, and the photodiode is compared directly with each pixel of the camera. This creates a map describing which parts of the image most closely correspond to the photodiode signal. In addition, the results are also viewed in relation to back-reflected laser radiation.

Keywords: laser welding; photodiode; high-speed camera; correlation; monitoring

1. Introduction

Laser welding process monitoring can be implemented in different ways. One of the possible ways is to use a photodiode for capturing the light emitted from the welded area and, based on the measured intensity, decide on the quality of the weld. Such a solution has an advantage in simplicity and low cost, but it faces many challenges.

Using only one photodiode may not be sufficient. When measuring with multiple photodiodes we obtain from each a slightly different signal, therefore we could gather additional information about the process. In order to identify whether there is a systematic problem in measuring system or the property of welding process itself, we decided to conduct more experiments. For reliable interpretation we must have a precise idea of what phenomena the photodiodes detect. Afterwards the detection system can be modified to avoid unwanted signals and improve reliably of monitoring.

The main method of comparing measured data is correlation analysis. Several authors have already been correlated photodetectors with image data. In contrast with the Watanabe et al. 1999, we do not use the additional illumination and only light we detect is the light emitted by the process. A number of authors, for example Eriksson et al., 2009, compared vapour plume with photodiode sensors operating at different wavelength. Brock et al., 2013, show that shape of metal vapours is dependent on process parameters and is not symmetrical. These findings are important for the interpretation of results.

2. Methods

A fiber laser IPG YLS-2000 was used together with welding head Precitec YW30 to produce the laser beam with 0.4 mm spot diameter with Rayleigh length approximately 7.5 mm. The laser parameters were varied to cover both the transition and penetration welding modes. The conductive welding mode is hard to observe for photodiode and camera settings used. The laser power was 0.5, 1, 1.5 and 2 kW, the welding speed 20 mm.s^{-1}, focal position was on the material surface and Argon was used for shielding. Base materials tested were stainless steel 1.4301 and carbon steel 1.0038.

The first experiment examined the effect of photodiode position on measured intensity. Two photodiodes were attached to the welding head, Fig. 1. The horizontal angle between photodiodes varied in the range from almost 0 degrees to 180 degrees. Photodiodes (Hamamatsu S1336-BQ) covered with protective window were placed in housing limiting the viewing angle to 10.5 degrees, which at a given distance from weld represents an ellipse with major axis of 14 mm and covers almost the entire welding process. The signal from the photodiode went through the converter and the amplifier to NI data acquisition device (DAQ) device and was sampled at 40 kHz.

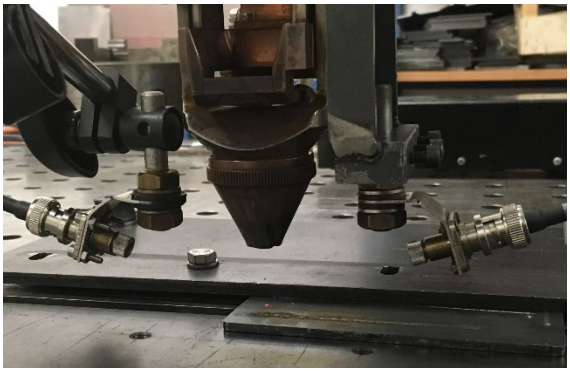

Fig. 1. Welding head with photodiodes, angle 180˚

In order to have a better insight into the process, the second experiment was conducted. We compared photodiode measurement with high-speed camera X-Stream XS-3. In figure 2 we see the camera capturing welded area from as closest as the same angle as the photodiode did, approximately 10 degrees. The DAQ sampling frequency 10 kHz, was limited by the maximum frame rate of the camera 10,000 fps at the lowest reasonable resolution. Camera exposure time was 30 µs. In front of the camera was installed ND filter and protective window. In addition, the back-reflected laser radiation returning to the laser was recorded as well.

Camera images were divided into individual regions of interest (ROI), including the weld pool area, the lower and upper part of the vapour plume, and the whole image. The overall intensity of the regions of interest was evaluated and compared with the photodiode intensity and the back-reflected laser radiation.

Further, the method was generalized so that every pixel was compared with a photodetector. In this way a detailed map was created.

We were looking for changes in the image intensity that most closely corresponds with the changes detected by the photodetector, therefore correlation technique was used. Due to the fact that the assumptions of the Pearson correlation coefficient are not assured we have to use a non-parametric method such as Spearman rank correlation. Spearman's coefficient is, in contrast to the Pearson correlation coefficient, more general. Instead of the degree of linear dependence, it measures the degree of monotonic dependence (Hauke et al., 2011).

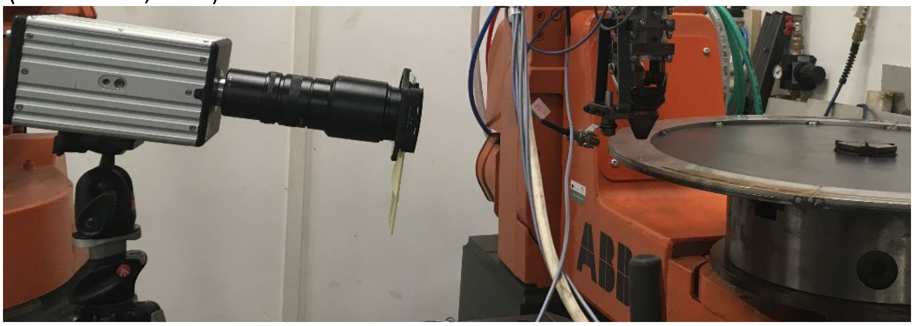

Fig. 2. Setup with high-speed camera and photodiode detector

3. Results

Evaluation of experiment with two photodiodes in figure 3 shows that the correlation between photodiodes decreases with increasing angle. Previous experiments with flashing LED as well defined light source instead of tempestuous welding process has shown, that correlation coefficient remained constant with value 0.8 independently on the angle.

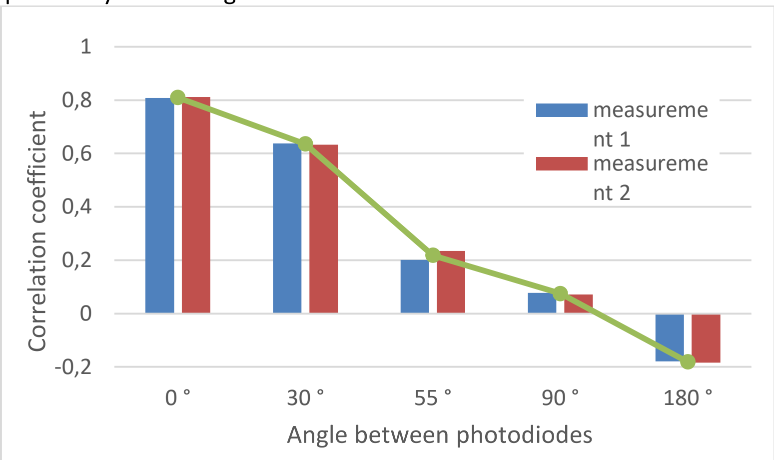

Fig. 3. Correlation between photodiodes

Furthermore, the aim was to specify the areas in welding process that have the greatest contribution to the intensity changes measured by photodiode and thus the greatest influence on resulting correlation coefficient. Identifying those areas may explain the results of measurements with two photodiodes.

Using high-speed camera and photodiode we found that the most correlated region is the weld pool region, colored red on figure 4a. The greatest refinement is achieved on pixel level. Figure 4b shows camera pixel correlation with photodiode. Clearly, the photodiode mostly correlates with weld pool. Applies that the higher the laser power, the greater the weld pool. Also the metal fumes and their reflection from a metal sheet. The weld does not carry any information in terms of this method. P-value is smaller than significance level 0.05, thus correlations are considered significant.

There can still be an issue with alignment and other properties of both detectors, the camera and the photodiode. Therefore the camera chip can be considered as an ideal photodiode with exact same alignment, timing and spectral sensitivity. There is such an ideal map in figure 7c.

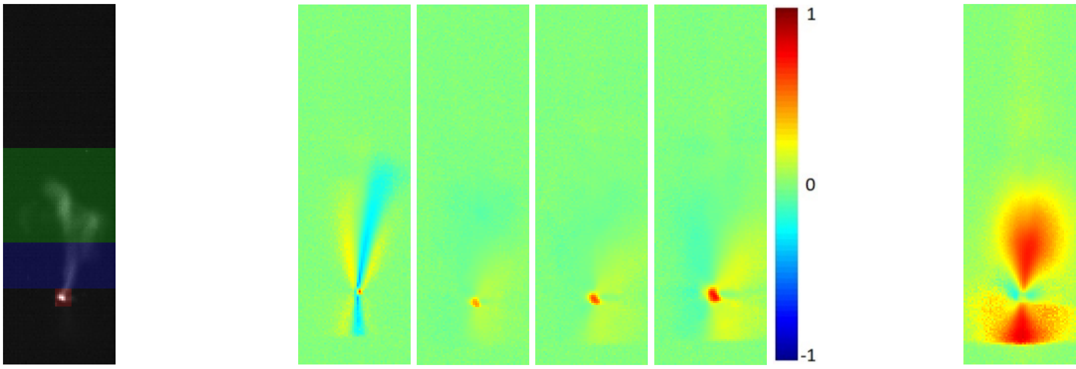

Fig. 4. (a) Camera image with ROIs; (b) Pixel correlation with photodiode for laser power 500, 1000, 1500 a 2000 W; (c) Pixel correlation with virtual photodiode

4. Discussion

From the results presented above, we conclude that the welding process appears to the photodiode slightly different, based on the direction we are observing. An over sensitivity to photodiode positioning relative to the welding area can be excluded by experiment with LED simulating welding process. Thus the decreasing correlation originates from the process.

From a time-spatial point of view, there is the strongest correlation is in weld pool. It is the area with the highest intensity. On the other hand, the high pixel values do not assure a strong correlation, the similar changes do. A possible explanation can be found in high-speed video recordings. The intensity changes are induced by the movement of molten metal. When an upward wave is formed, it shades the bright area of the weld pool and keyhole. Then both photodiode and camera detect lower intensity. At the same time from the opposite side of weld pool, we would observe the identical molten metal wave brighter, and vice versa. Which is in agreement with the first experiment.

However, figure 4c shows different results. There are possible explanations. Firstly, the sum of intensities of weld pool pixels is smaller than the sum of intensities of vapour plume and its reflection. Thus sum of all intensities is more similar to the plume. The metal vapours become with decreasing exposure time less visible and the camera has longer exposure time than photodiode. So it is possible that photodiode does not detect metal fumes at all. Secondly, the spectral sensitivities of both detectors are different. The camera has a sensitivity peak around 500 nm while the photodiode 950 nm. Spectral aspect was not taken into account in this experiment and should be taken into consideration for further investigation. The wide band photodiode without filters may be insufficient for separating radiation of the vapour plume, weld pool, and eventually reflected or scattered laser radiation is added to the measured signal.

No correlation between back-reflected laser radiation and camera image was found for penetrating laser welding mode.

5. Conclusion

Correlation between two photodiodes is decreasing with increasing horizontal angular distance. We found, by comparing photodiode intensity to camera image, that both signals best correlates in weld pool area. Based on both findings and high-speed video we conclude that photodiode in this setup detects large oscillation of weld pool near keyhole.

Acknowledgements

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