BASIC STUDY OF PHOTODIODE SIGNALS FROM LASER WELDING EMISSIONS

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Abstract

Photodiodes are commonly used to monitor laser welding as a cheap, rugged, online method to get an indication of changes in the process, particularly the occurrence of defects. However, the correlations between the signal characteristics and the process are usually empirical and not fully understood. In this basic study we try to obtain a better understanding of the generation of the signals from the laser welding process. By synchronising high speed imaging with photodiode signals in three wavelength spectra, we attempt to identify the contributions from different geometrical domains and temporal events, particularly from the weld pool surface, the keyhole opening and the escaping metal vapour flow. It is particularly valuable to study dynamic behaviour during pulsed laser welding. A quantitative estimation is difficult, but , with the help of high speed photography and modelling, clear correlations between different dynamic events and signal changes can be identified.

Keywords: laser, welding, monitoring, photodiode

1 Introduction

Laser welding is an important joining method in the industry today and, as the demand on product performance increases, the demand for online monitoring is also increasing. A common method for process monitoring of laser welding is to use photodiodes. This is the method that we investigate here in some depth, to try to correlate defects in the weld with the behaviour of the photodiode signal. If we can explain were the origins of the signals are, we hope to increase the monitoring capabilities and the robustness of laser welding in the industry.

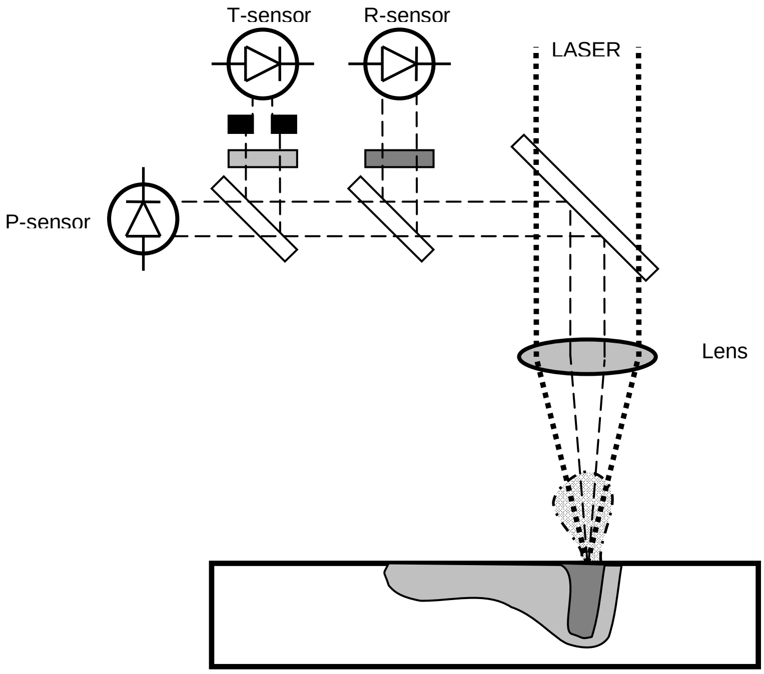

Fig. 1 *Standard concept of photodiode monitoring system.*

The photodiode setup in **Fig.1** is a common concept for commercial systems sold for online monitoring of laser beam welding.[1] The three sensors detect light in different wavelengths. T-sensor 1100-1800nm, R-sensor 1064nm and P-sensor 400-600nm. Also the T-sensor has an aperture to reduce the observed area. The idea for the T-sensor is to observe the hot liquid melt pool behind the keyhole, and thereby give a signal correlated to the surface of the weld.

Coaxial monitoring makes the alignment easy and insensitive to welding direction. Overall the design is rugged and easily implemented in industry. But until now the number of implemented online monitoring systems is low compared with the number of laser welding systems. One reason for this is the lack of reliability of the monitoring systems. There is no guarantee that the online monitoring will detect all faults.

2 **Method**

We start here with a description of the origin of the signal from the photodiode sensors. Then an evaluation of the error detection method used in a commercial online monitoring system. The rest of the paper focuses on experimental results that show the correlation between a significant change in signal value and a pertubation at the source of the signal. With examination of the melt pool size during pulsed welding. And the dynamic behaviour of the plume correlated to the sensors.

2.1 Signal origins

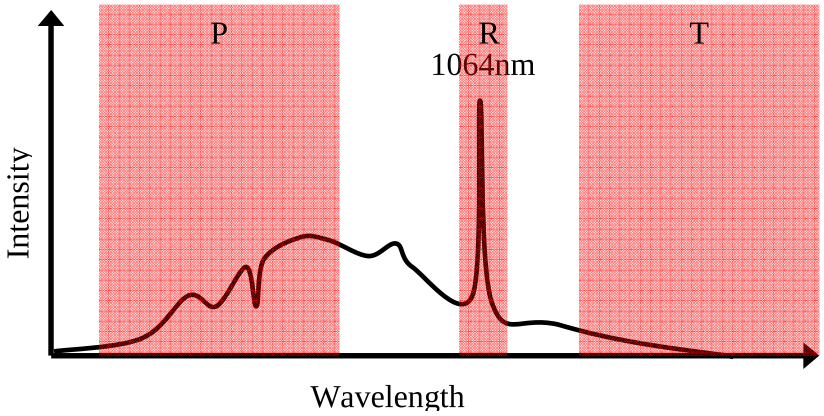

Fig.2 *Typical intensity distribution of the electromagnetic signal from Nd:YAG welding, and the wavelength range of the three sensors.*

The total emission from Nd:YAG welding[2] of metal is a wide spectrum of heat emissions according to Planck's law. Some small spikes from plasma radiation can be present [3] but the contribution of a narrow spike to a wide spectrum is insignificant. A large spike of 1064nm from the laser is always present.

Increasing the temperature of an object will increase the energy of the emitted light. And the peak emission will occur at shorter wavelength as described by Wien's displacement law. The total amount of emitted light also depends of the emission factor and the size of the object.

Previously it has been shown that there is a linear correlation between the T-sensor signal and welding depth [4][5]. Changing the welding speed changes both welding depth and melt pool size, and this changes the T-signal. Thus one origin to the T-sensor signal is the meltpool and the surrounding hot surface. But the T-signal is not only affected by the penetration depth. If the linear dependency [5] is extrapolated towards zero penetration there is still a large amount of T-signal present. This indicates that something more is contributing to the signal value. This must be the keyhole and the ejected plume of metal vapour and particles.

The R-sensor detects the reflected laser light from the surface. But the complexity of the reflections from keyhole welding is very high and to analytically describe the change in reflection is beyond the scope of this paper.

The P-sensor is mostly affected by the keyhole and the plume above, but some signal does appear to be from the surface.

2.2 Online monitoring

To evaluate the fault detection by photodiode systems, a commercial system has been investigated. We chose the Precitec LWM system with 4 analogue channels. This leaves an extra channel that can be utilized to monitor the laser power, besides the three photodiodes. The system is based on a DSP-board and has 8 bit resolution. The maximum sampling rate is 20 kHz. After initially acquiring some strange signals we realized that there is no antialiasing filter in the A/D-conversion circuit. This means that the measurements are more or less distorted by folding according to the Shannon-Nyquist sampling theorem.

2.3 Threshold

In the LWM system the monitoring is a comparison to a reference signal, acquired previously. The monitoring is basically a threshold value of the distance from the reference signal. To avoid false alarms from spikes in the signal, a minimum time above the threshold can be implemented. To reduce the noise level in the signal a digital low pass filter can be added.

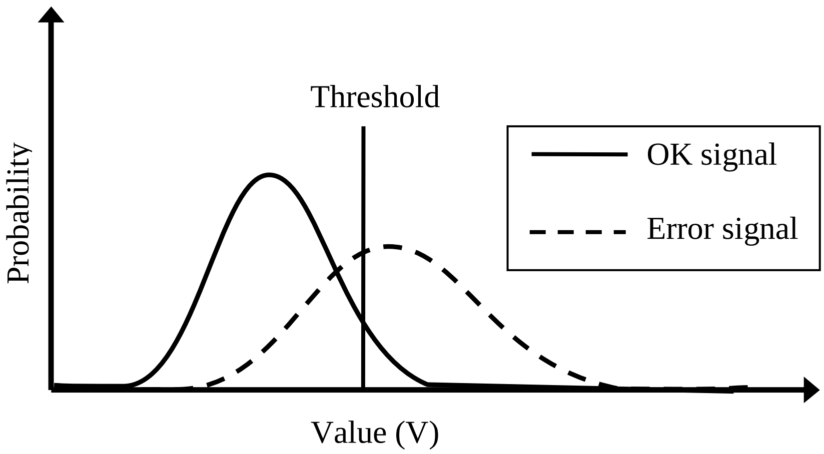

Fig.3 *Example of Probability Density Functions*

To set the correct threshold value is not easy, too high a value and no errors will be detected, too low a threshold value and lots of false alarms will lower the trustworthiness of the system and error warnings will be ignored. A chart of the probability density functions for signals from good and bad welds can help when choosing the threshold value. But it is always a compromise between good error detection and low false alarm count.

The optimal threshold value depends on the cost of an action. The cost of a false alarm or a dismissed error has to be taken into account.[6] The probability of dismissed error (P_D) is the error signal below the threshold. The probability of false alarms is the OK signal above the threshold. The optimal threshold is found by minimizing the total cost C in **eq (1)**

$$C = P_D * C_D + P_{FA} * C_{FA} \qquad (1)$$

Experimental results show that the variance of the signal tends to be larger for bad welds. But in many cases the mean value changes only a little, thus setting the threshold becomes more difficult.

By adding a low pass filter the variance in the signal is decreased. A smaller variance makes it easier to distinguish different mean values, but then only long lasting errors can be detected. The time span of an error can be very short. At 12m/min welding speed, a 1mm movement takes only 5ms. This means that a cut-off frequency of 50Hz in a low pass filter limits the detectable fault to about 4mm.

The difficulty of setting a fixed optimal threshold is not unique for laser weld monitoring. Many methods are available with dynamic adaptive thresholds[7]. Often the signal is filtered by Kalman filter, and more or less advanced error detection is implemented in the filter. None of these modern error detection algorithms is implemented in the LWM-system investigated. In the LWM-system the operator is manually to set a maximum deviation from a previously recorded "OK"-signal.

2.4 A/D-conversion and aliasing

Analogue to Digital conversion is done by freezing an analogue signal value and then converting the value to a digital value. To correctly mimic the original signal, the number of digital samples must be high enough in a given time frame. In **Fig 4** the blue signal is the analogue value. The green signal is sampled with sufficiently high frequency to give the correct image of the signal. The red signal has too long sampling intervals and misses important signal changes. Also false peaks are created in the red signal.

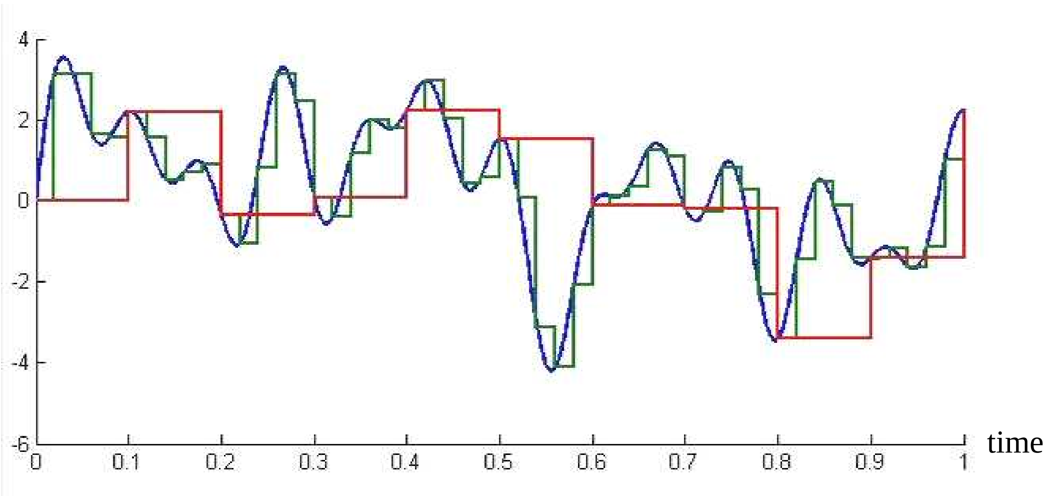

Fig.4 *Example of different sampling frequency of a signal.*

This is called aliasing and by the Nyquist-Shannon theorem a signal can be correctly recreated only if the sampling frequency is more than twice the highest frequency in the original signal. If a fixed sampling frequency is used, an antialiasing filter must be used to avoid aliasing. In the Precitec LWM system no such filter exists. This will distort the signal and reduce the usability of the system. As the maximum sampling frequency in the LWM is 20 kHz and the frequencies measured during laser welding have been well above 10 kHz [8] aliasing will distort the signal.

3 Pulsed welding: signal response and imaging

To investigate the source of the signal from the T-sensor we set up a simple experiment. A bead on plate weld in steel, utilizing quasi-CW Nd:YAG welding (pulsing with 50% duty cycle and 10ms pulses) was produced. The welding was monitored by the photodiode system and a high speed video was created. Filming at 10000fps and photodiode measuring at the max sampling rate of 20000Hz, we have tried to correlate the events in the video to signal changes.

With a powerful Cavitar laser illumination synchronized to the Redlake camera exposure, a clear image of the weld pool is achieved. The monochromatic light also eliminates the chromatic aberration. In front of the camera a band pass filter of 810nm is placed, to block all other light than the illumination light.

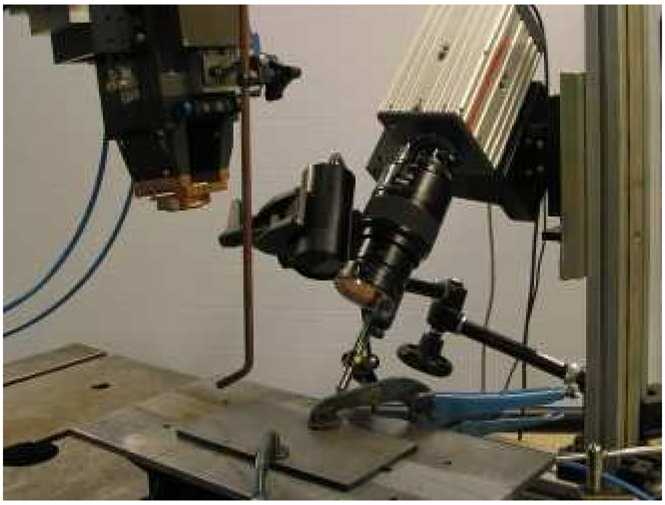

Fig. 5 *Experiment overview*

The exposure time was adjusted to show the glowing plume above the keyhole, thereby enabling correlations to plume fluctuations.

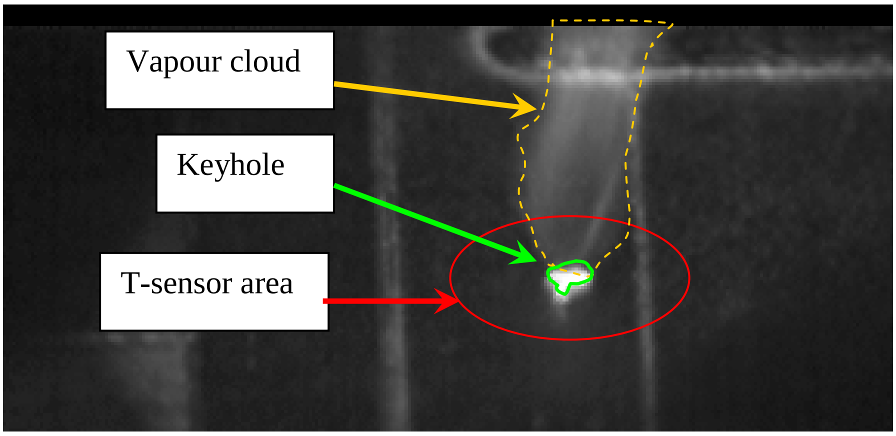

Fig.6 *Image extracted from high speed video*

On top of every frame an old weld seam is visible and two lines indicating the starting point. **Fig.6**

3.1 Studying T-sensor

During the OFF period of the laser, the keyhole collapses. This means that the sensors show the emission from the melt pool and the heated surrounding material. During the ON period a keyhole quickly builds up and a plume is ejected from the keyhole. The cloud has an almost stochastic behaviour visible in both video and diode signal. The keyhole is more stable but rapid fluctuations do appear from time to time. By comparing the diode signal value during ON period with OFF period, a value of the contribution from the blackbody emissions of the solid and melt surfaces can be estimated.

In the start up of the weld (**Fig 7 a-b**) the melt pool is small and the heat conducted to the surrounding metal is low. The signal value during the OFF period is close to zero, in all three sensors, but a small signal is visible in the T-sensor.

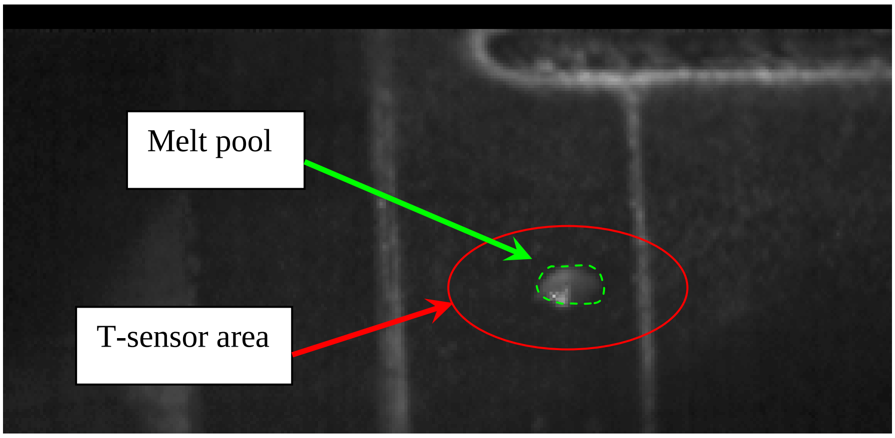

Fig.7a *Image during OFF period at the beginning of the weld*

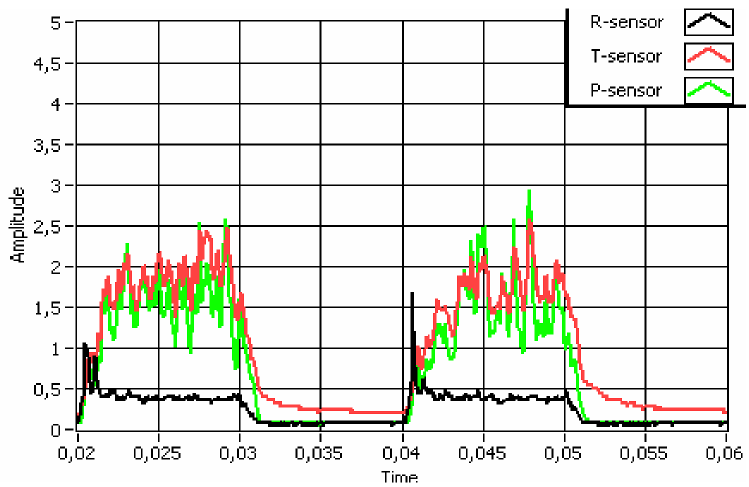

Fig.7b *Signal value at the beginning of the weld*

After some distance of welding a steady state is reached and the size of the melt pool is constant. The larger melt pool and the heat conducted to surrounding material increases the T-sensor signal during the OFF periods **Fig 8 a-b**.

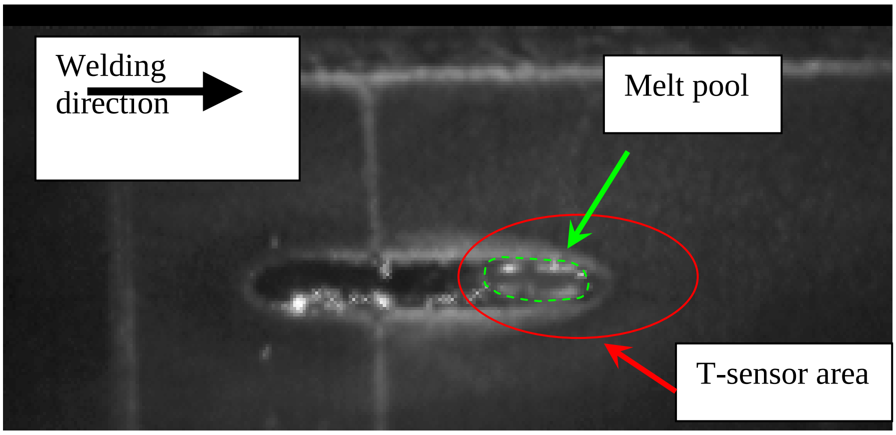

Fig.8a *Image during OFF period in the centre of the weld*

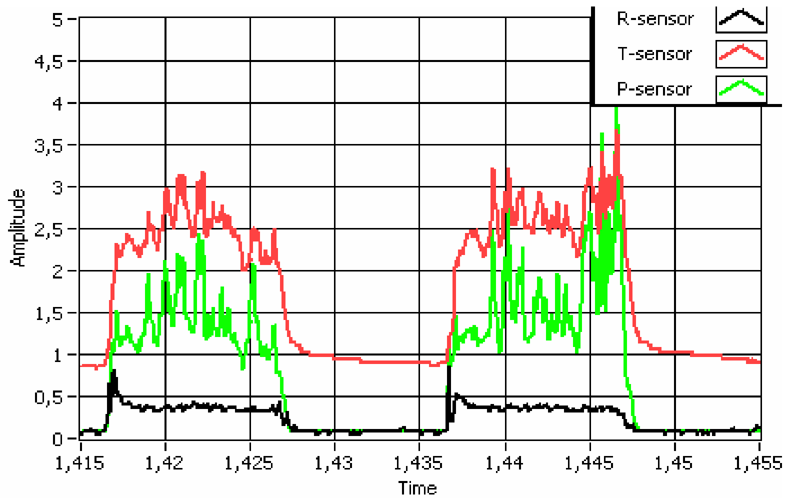

Fig.8b *Signal value in the centre of the weld*

In this particular welding case approximately 1/3 of the total T-signal comes from the molten and solid metal. 2/3 comes from keyhole and plume. The increase of the T-signal from a small melt pool to a large melt pool is less during ON period then during OFF period. By assuming that the emissions from keyhole and plume are constant and independent of melt pool length, the contribution of the surface must be changing. There are two possible explanations. Photo diodes can be biased by a reversed voltage to give a linear response otherwise they give a logarithmic response. A logarithmic response will give a higher increase to low signals then high signals. Whether or not the T-sensor is working in a linear or logarithmic mode is unknown. The other explanation is that the plume is shielding the emissions from the surface. Both explanations indicate that the contribution from the surface is less then 1/3 of the T-signal during the ON period.

3.2 Fluctuation in the plume

The rapid and large fluctuations in both the T-sensor and the P-sensor during the ON period of the welding are almost exactly synchronised. When compared with the high speed images, the same fluctuations can be observed in the vapour cloud. In the 5 frames in **Fig. 9** the frame number and acquisition time is visible on top of the frame. In **Fig.9 a-e** it can be seen that from time 2,2637 to 2,3639 the cloud goes from full to nothing to full again within a time span of 0,2ms

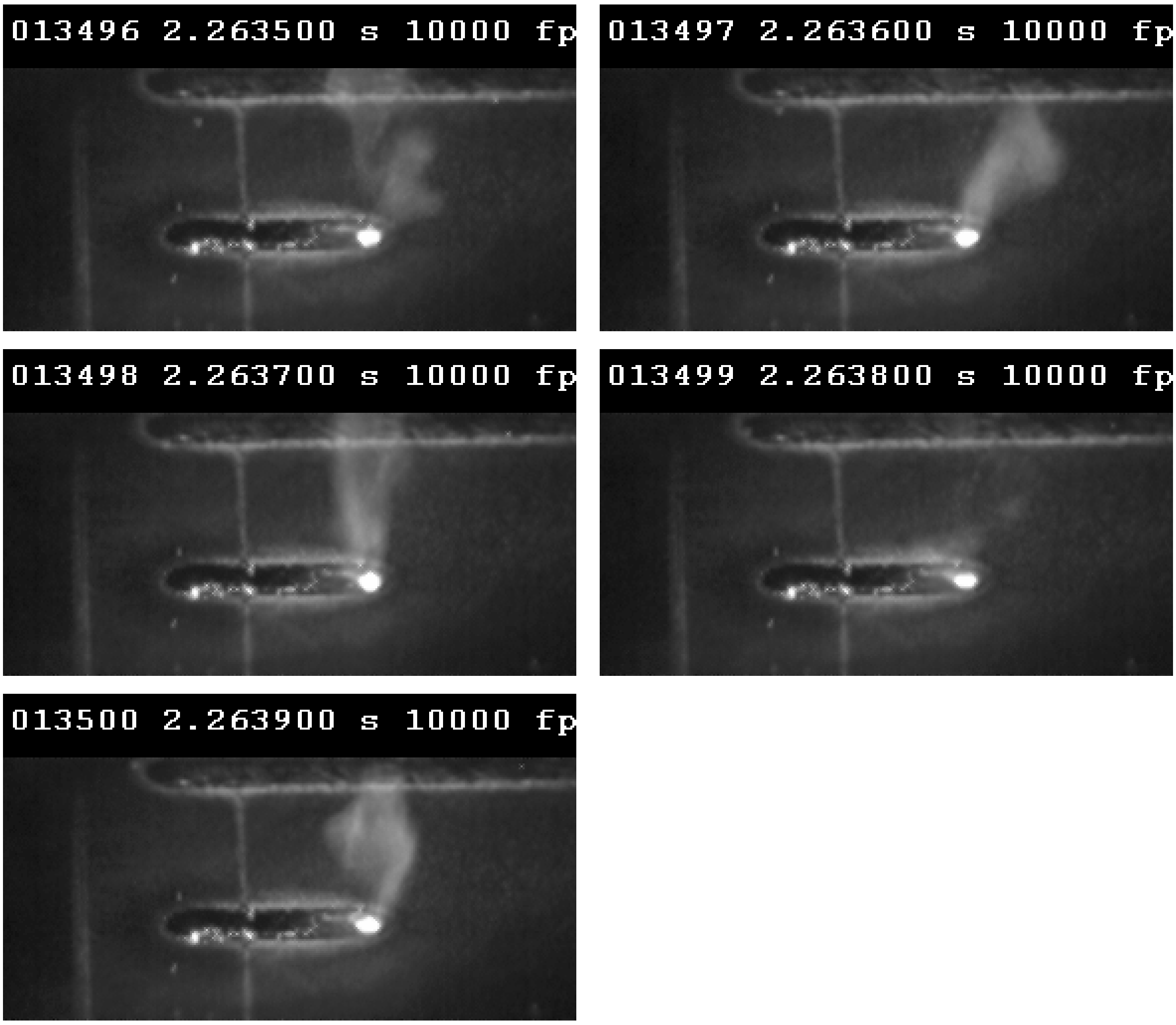

Fig. 9 a-e *Fluctuations of the plume*

The P-sensor signal has much larger fluctuations and no signal during OFF period. Therefore there is no contribution to the P-sensor from the surface, only a keyhole and vapour plume contribution.

3.3 Measuring plume intensity in video

A qualitative measurement of the video images is possible if the intensity change is extracted from the film. As the background is fairly constant it can be subtracted from the images and only the fluctuations are left. In **Fig.10** the plume and keyhole from frame nr 013496 **Fig.9a** are extracted from the video. As the intensity in the keyhole region is saturated in the camera, keyhole related measurements cannot be made from this video.

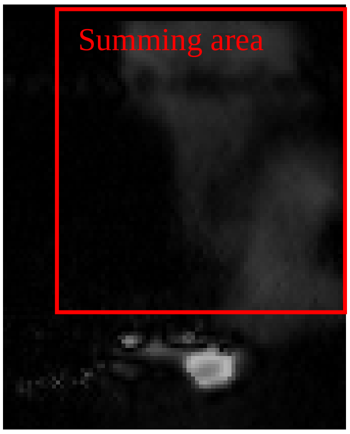

Fig.10 *Plume intensity extracted from Fig.9a*

By summing the intensity from every pixel in the plume, a qualitative measurement of the fluctuations is created. In this way the fluctuations over time can be correlated to fluctuations of the plume above the keyhole as seen in **Fig.11**. The small dots in the image intensity curve are individual frames in the video.

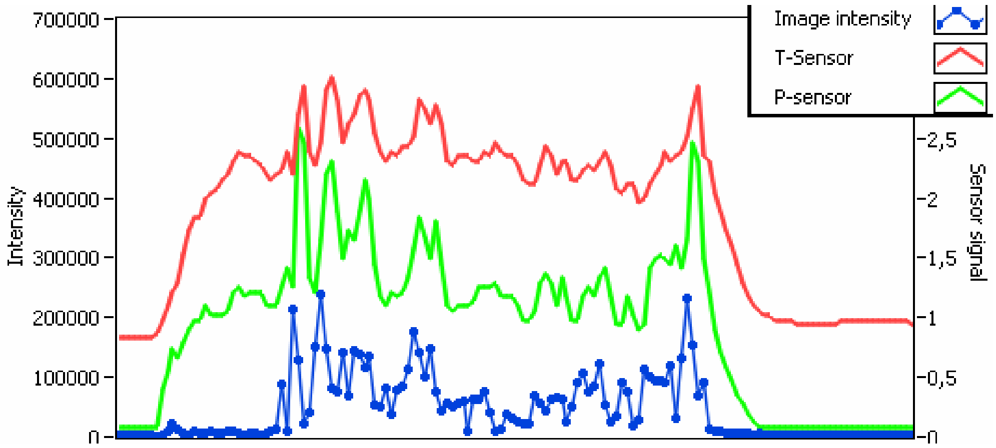

Fig.11 *Calculated image intensity from video and P-sensor/T-sensor*

Fig.11 shows that the rapid fluctuations in the T-signal and P-signal are created by the plume ejected from the keyhole.

By scaling and subtracting the plume intensity from the P-sensor signal, the contribution from the keyhole can be calculated. Then, if the P-sensor signal is scaled and subtracted from the T-sensor signal, the surface contribution could be calculated. Unfortunately, the lack of an antialiasing filter in the hardware makes this impossible. The folding distortion from the high frequencies of the fluctuating vapour cloud creates a lot of noise in the signal. And as there is a small time difference between the sampling of different channels the noise is different for all channels.

3.4 Identification of the plume radiation characteristics

One major question is; Is the plume above the keyhole creating light or merely reflecting the light from the keyhole? To test this a shadowing rod was inserted in the plume. In the experiment an overlap weld in Zinc coated 0.8 mm plates was carried out. The rod was placed normal to the camera view as shown in **Fig.12**.

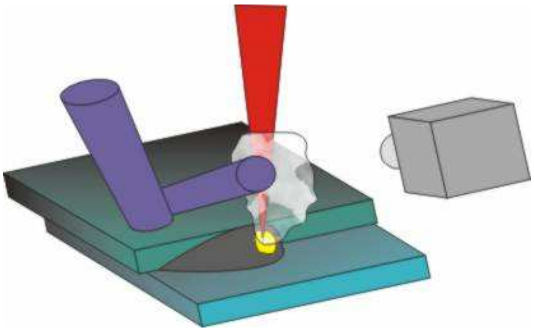

Fig.12 *Experiment setup*

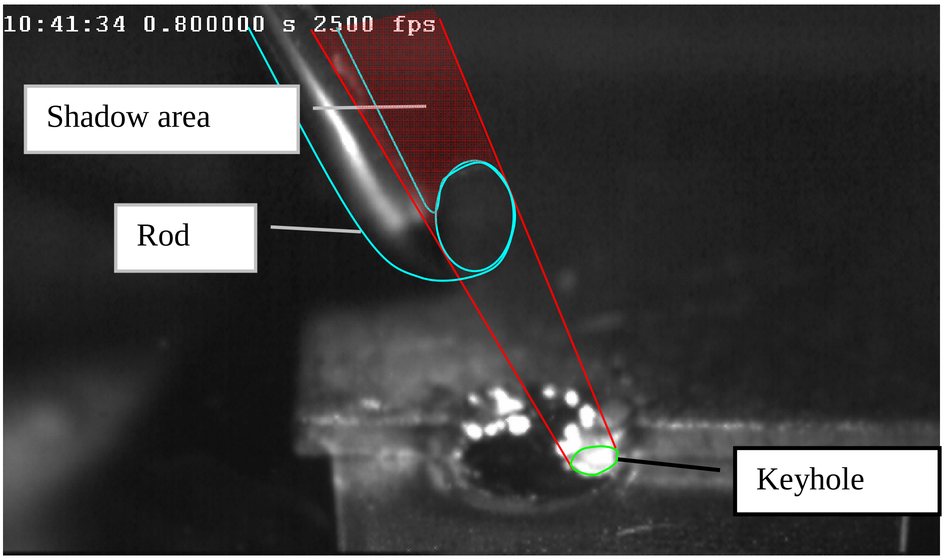

Fig.13 *Illuminated frame during welding*

In **Fig.13** the Cavitar has illuminated the exposure with a 1µs long illumination time. The exposure time of the camera is also 1µs. The illumination light is very focused thus creating glare in the reflecting melt pool.

By using a double exposure mode in the high speed camera one image illuminated by the Cavitar laser and one image without illumination can be captured almost simultaneously.

In the image without illumination the exposure time is longer and the light from the keyhole is saturating the camera. The rod is obviously deflecting the plume ejected by the keyhole, as any fast flowing media is deflected by an object. But sometimes turbulent flow makes the plume reach the area behind the rod.

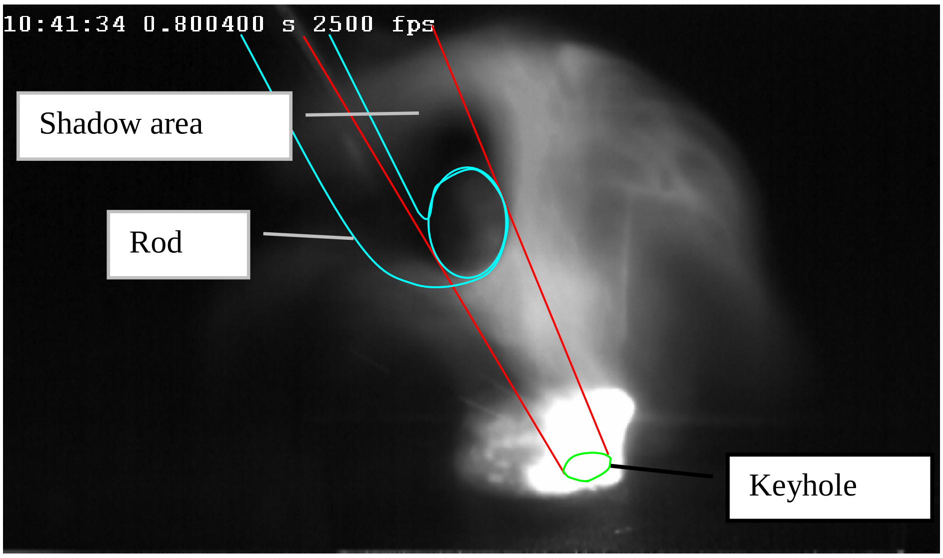

Fig.14 *Nonilluminated frame during welding.*

In **Fig. 14** it is clearly visible that the plume is glowing also in the area shadowed by the rod where no light from the keyhole can reach the plume. This means that the plume is emitting light in sufficient intensity to be registered by the camera through the 810nm band pass filter.

Fig. 15 *Frame during weld in zinc coated overlap weld with long melt pool.*

Later during the weld the melt pool is elongated and the emissions from the surface at 810nm are visible.(**Fig. 15**) The difference in emission factor between solid and liquid metal is clear. The length of the melt pool is approximately 8mm.

In **Fig 16** the average intensity over 900 frames is calculated to remove the fluctuations in the plume. Here it is easier to estimate the contributions from different parts to the sensors. The 810nm filter in front of the camera doesn't change the blackbody radiation relationship. Thus the intensity in the images gives a representation of the intensities contributing to the P-sensor and T-sensor signals.

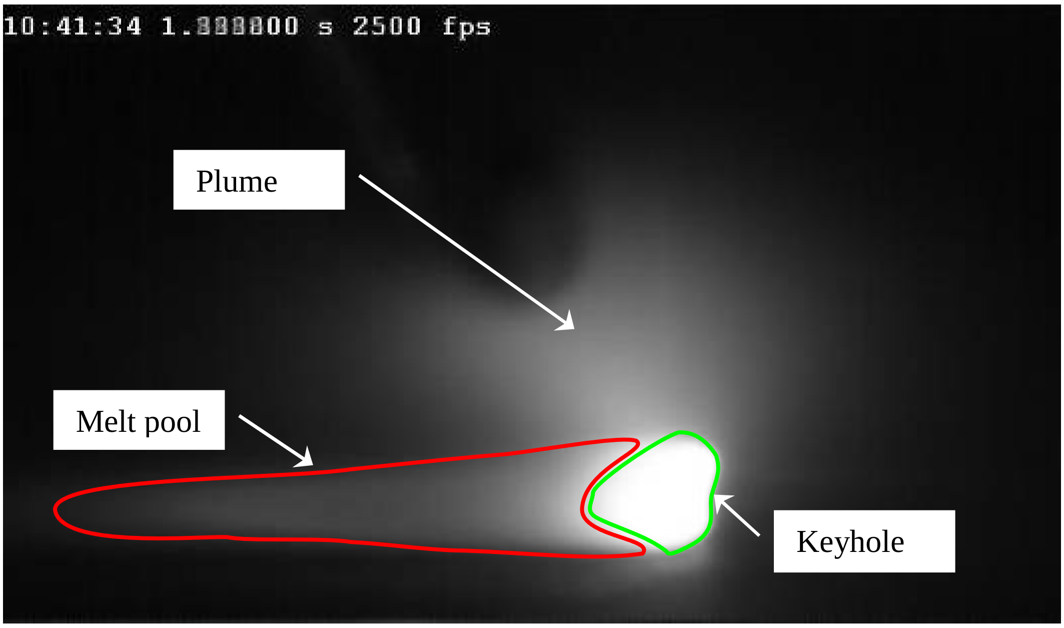

Fig.16 *Average intensity of 900 frames*

4 Conclusions

Photodiodes used to monitor laser beam welding have the potential to warn if the welding process change. This investigation of the Precitec LWM system has led to the following conclusions.

The R-sensor with a sharp narrow band pass filter in 1064nm is directly related to the surface geometry of the area where the laser beam interacts with the material. But keyhole welding has a very complex geometry of molten metal, and a generic explanation of signal changes is almost impossible. In the conduction welding mode there is a higher possibility of explaining the signal behaviour. Any welding case going from a stable welding condition to an unstable situation will most certainly lead to a change of the sensor signal behaviour in some way.

The T-sensor and P-sensor both have a broad band pass filter. This makes them sensitive to blackbody radiation. Even though no real blackbodies exist in reality, all materials will emit radiation at more or less all wavelengths when heated. During laser welding there are three main radiators; the melt pool and the heated surrounded metal, the keyhole and finally the ejected plume above the keyhole.

The contribution from the three parts to the T and P sensor will differ depending on the different center wavelength of the sensors. This is because of the Wien's displacement law.

The strong fluctuations in the plume will reduce the possibility to detect short lived fluctuations in the melt pool and keyhole, making the monitoring capability from the P-sensor and T-sensor less valuable.

The aliasing occurring in the LWM system due to the lack of an antialiasing filter will distort the signals and reduce the possibility to detect errors.

During pulsed laser welding of steel, 30% of the signal to the T-sensor came from the surface 70% from the keyhole and plume. In the P-sensor signal ~50% came from keyhole and 50% from the plume.

The rapid fluctuation in T-sensor and P-sensor are correlated. And both were correlated to the intensity of the plume extracted from high speed images.

The absence of a shadow from the wire shows that light is emitted from the plume.

4 Acknowledgment

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5 References

[1] Kessler, B., **Online quality control in high power laser welding,** Precitec KG

[2] B.J. Aalderink, R.G.K.M. Aarts, J.B.Jonker and j.Meijer, **Weld Plume Emissions During Nd:YAG Laser Welding,** Third International WLT-conference on Lasers in Manufacturing, 2005, Munich, p.413–417

[3].Lacroix, D and Jeandel, G., **Spectroscopic characterization of laser-induced plasma created during welding with a pulsed Nd:YAG laser,** Journal of Applied Physics 81 (1997), p.6599

[4] Norman, P., Engström, H. and Kaplan, A. F. H., **Theoretical analysis of photodiode monitoring of laser welding defects by imaging combined with modelling**, Journal of Physics D, Applied Physics 41 (2008), p.195502

[5] Sanders, P. G., Leong, K. H., Keske, J. S., Kornecki, G., **Real-time monitoring of laser beam welding using infrared weld emissions,** Journal of Laser Applications 10, (1998), p.205-211

[6] Batchelor, D B. and Sampson, C E., **A Minimum Cost Thresholding Strategy,** Proceedings of the IEEE, (April 1973), p.510- 512

[7] Mal´tsev, A.A.and. Silaev, A. M, **Optimal detection of discontinues change of signal parameter in discrete time,** Radiofizika Vol. 35, (Nov-Dec 1991), p. 938–951

[8] Hongping, Gu and Duley, W. W., **Resonant acoustic emission during laser welding of metals,** Journal of Physics D, Applied Physics 29 (1996), p. 550–555.