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Monitoring undercut, blowouts and root sagging during laser beam welding

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Abstract

Using a 14 kW CO2-laser, 12mm thick cold-formed steel S420MC has been welded to a machined shaft pivot made of 25CrMo4 steel as part of a truck rear axel. A photodiode-based, on-line process monitoring system has been applied for detecting defects. However, the occurrence of certain defects, namely undercut, blowouts and root sagging is often not detectable from the sensor signal. The time dependent signal is collected from emissions from the melt pool surface as well as from the plasma plume. Based on the evaluation of high speed images, an explanation of the potential and limitations of detection of these defects has been generated. Although preliminary conclusions have been drawn, uncertainties regarding emissivity and the keyhole and plasma radiation characteristics require further studies.

Keywords: laser welding, defect, monitoring, blowout, undercut, root sagging

1 Introduction

Laser beam welding enables deep, narrow welds at high speed to be produced. This ability also sets high demands on the materials being welded and also on the joint preparation as the operating window is narrower than for arc-welding.

Today photodiode monitoring techniques are used by several companies as a fail/pass system that can reduce the need for expensive post-production inspection. Although the system can distinguish between different defects in many cases [1, 2] it is seldom used that way because it sets higher demands on the people using it and also the company have to set aside time to learn the system.

Many researchers have tried different types of sensors [3, 4, 5] to detect defects. Some have also tried to use different types of sensors simultaneously [6], which is called sensor fusion. This approach, of using several types of sensors, is manageable in a laboratory environment but when moving out to the shop floor there is a demand for ruggedness and reliability, and here only photodiodes have demonstrated those qualities. Ruggedness and reliability are the main advantages that the photodiode has over other techniques for monitoring weld quality. The biggest disadvantage to the photodiode is that it lacks the spatial resolution that is possible with a camera.

The camera together with photodiode sensors enables the user to better understand the correlations between defects and signals [7]. In this paper we have used high-speed imaging together with photodiodes to try to explain the signal response to specific defects.

2 Method

The welding experiments were mainly executed in an industrial application but cross sections and microscopy has been carried out at the university. The welding experiments have been performed during full production and therefore the results are used as production test results when compared to results gained from the laboratory tests that are performed on flat test pieces and in a laboratory environment. As the tests were performed the data from the sensor and the camera were saved for evaluation. The complete rear axel assemblies were scrapped and test pieces were cut out for cross sectioning and microscopy. The weld on the rear axis is approximately 470mm long and 12mm deep.

The experimental equipment used in the

laboratory test is shown in **Fig.1.** It consists of three photodiode detectors (5), High speed camera (4) and its illumination (3). The photodiode used in the industrial setup is only the plasma type in the 400-600nm range. The camera and illumination used was the same as in the laboratory setup. The camera is a Redlake HS-X3 high speed camera, synchronized with the photodiode signals. The photodiodes have different characteristics; the plasma sensor P has a band pass filter for 400–600 nm, the back reflection sensor R is tuned to the laser wavelength 1064nm (in the case of Nd:YAG) and the temperature sensor T is band-passed between 1100 and 1800 nm. The weld pool was illuminated with a pulsed diode laser (500W during 250 ns at 4 kHz) at 810 nm wavelength. The (specular and diffuse) reflected light was detected by the high speed camera through a narrow band pass filter at 810±2 nm. The optics for the camera was changed depending on the size of the monitored area and what is possible depending on the setup, e.g. the space inside the machine. **Fig. 2**. shows the setup for laser welding in the laboratory, the laser source optics are on the left, where we can change between 6kW CO_2, 3kW Nd:YAG and a 15kW Fiber laser. The laser illumination is in the middle and the high speed camera to the right in the picture.

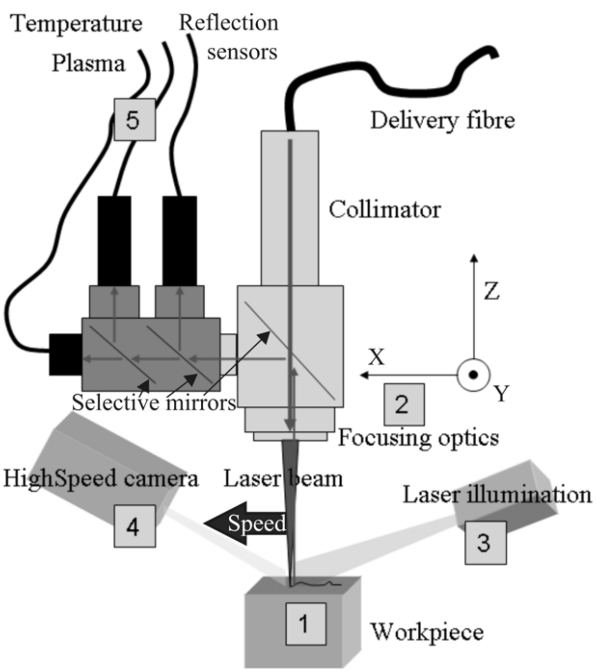

Fig. 1. *Experimental equipment used in laboratory*

For the industrial tests a 14kW CO_2 laser placed in the production line of the manufacturer was used. This machine welds rear axis components in 12mm S420MC steel and 25CrMo4.

For the company where the tests have been performed the most likely defects are undercut, blowout and incomplete penetration. During the tests only undercut and blowout defects have been found.

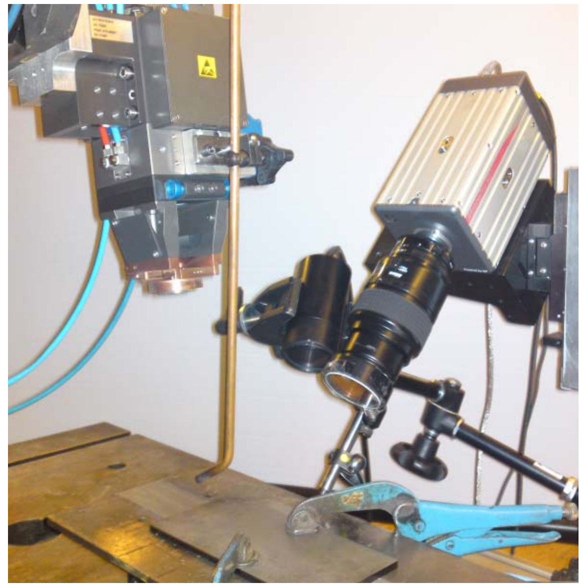

Fig. 2. *Photo of the laser optics, illumination and camera used in laboratory tests*

The instruments that are mounted before the tests are the camera and illumination. The welding system already has a photodiode sensor this was used to get information about the plasma level around the keyhole during welding. This setup gives approximately the same conditions in the laboratory and the industrial case.

In **Tab. 1**. the different type of defects that might occur during laser welding of metals is represented, it is an adapted version of the Swedish standard SS-EN ISO 13919-1 [8]. This table explains each defect and a probable cause of it. It was used in the experiments to classify weld defects.

Tab. 1. *Different types of defects occurring during laser welding*

Defect	Explanation
Cracks	Hot crack in the fusion zone or cold in HAZ
Porosity and gas pores	Voids in the material Spherical = gas bubbles Irregular = impurities
Incomplete penetration	Not deep enough penetration
Linear misalignment	The two parts centerlines do not coincide
Undercut Root sagging	Lack of material in upper weldzone Too much material in lower weldzone
Reinforcement Root concavity	Too much material in upper weldzone Not enough material in lower weldzone
Blowout	Crater formation on top surface

3 Results

The information from the industrial monitoring system is used as a quality assessment tool. The data fluctuates due to different phenomena such as keyhole collapse as shown in **Fig. 3**, also, impurities left over from cleaning and handling of the part affects the signal. In **Fig. 3** a sequence of pictures is shown depicting the formation of an undercut defect. There is a transition from a stable (**a**) situation to a disturbance of the keyhole (**b, c**), After this disturbance it seems that the keyhole is closed or much smaller (**c, d, e**). In (**f, g, h**) the keyhole is restored and the melt pool is calm again.

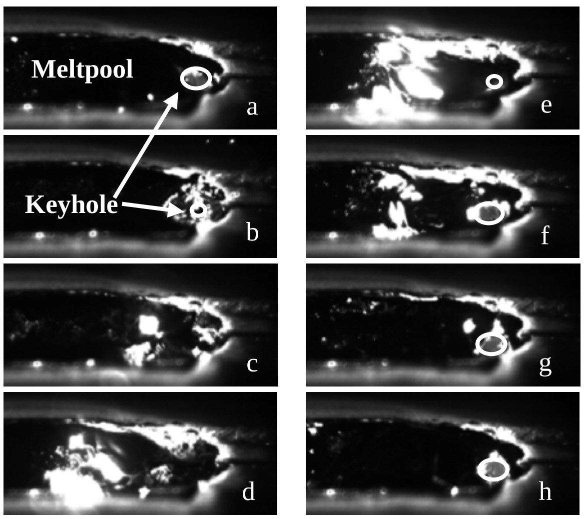

Fig. 1: *(a-h) Undercut defect formation*

Fig. 4 shows how a blowout is formed. It starts from a stable keyhole and meltpool in **Fig. 4a**. In (**b, c**, **d)** a hump is formed that travels away (**e**) from the keyhole and the meltpool seems to smooth out, but the keyhole is still irregular. Photo **(e)** shows a slightly larger keyhole and in (**f**) there is suddenly a blowout that is too small for the monitoring system to detect. In **(g)** the keyhole is larger for approximately 1/1000s. After this the keyhole and meltpool surface return to normal (**h**).

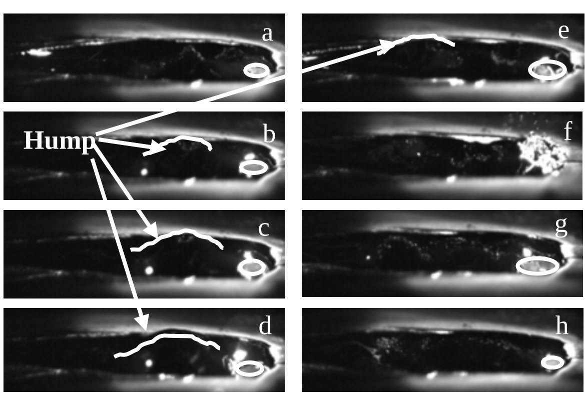

Fig. 4: *(a-h) Blowout defect formation*

Different types of signal appearances from the monitoring system are shown in **Figs. 5-9**. Because of the insecurity that the company feels about the system the boundaries (tolerance band) of the system is set to an cautiously high value (lines above and below the signal).

Fig. 5, shows a normal welding situation giving a weld that is approved. A top surface photo of this welding situation is presented in **Fig. 10a.**

In **Fig. 6** the system has detected a blowout. This defect is clearly visible for the naked eye and is in most cases easy to detect by the monitoring equipment. Smaller blowouts are not possible to detect with today's setting of the boundaries as seen in **Fig. 7.** and **Fig. 10c**. (according to the standard used, the size of this defect is acceptable).

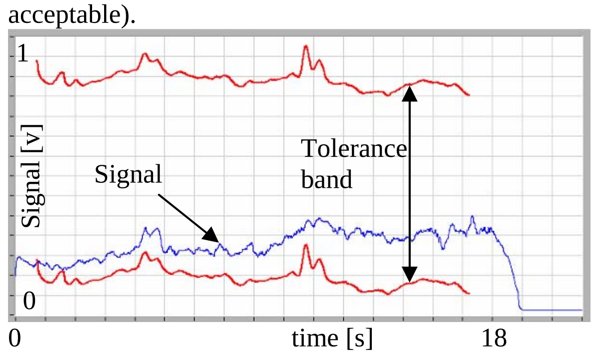

Fig. 5. *Showing a typical output from an industrial plasma monitoring system (length of weld on the X-axis and signal from sensor on the Y-axis).*

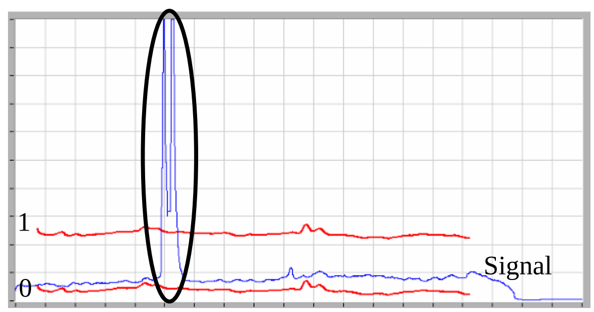

Fig. 6*. Blowout detection, Large Y-axis value due to higher output from sensor*

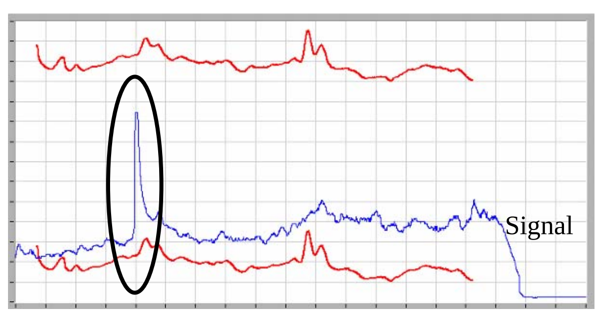

Fig. 7*. No detection, small blowout , not detected later*

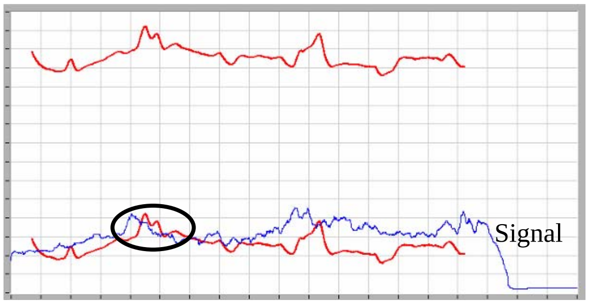

***Fig. 8**. Undercut detection*

Undercut detection is also a minor problem if the size of the defect is big enough as in **Fig. 8**. It shows a signal that is well below the set lower limit of the monitoring system for approximately 2 seconds of the complete weld cycle of almost 20 seconds. A cross section of the weld is shown in **Fig. 9a** where the top surface (**Fig. 10b)** has an undercut defect and at the same time the opposite side experiences root sagging. Undercut is normally seen together with root sagging but in a few cases there is root sagging without any undercut **Fig. 9b**. If there is a root sagging only, it cannot be detected by the on-line monitoring system. Another problem with the root sagging is also seen in **Fig. 9a** where a pore is present, this is common and is removed by grinding and manual welding. **Fig. 10** correlates the post welding top surface to the HSI during welding, it shows how the three cases are represented with two different methods of imaging.

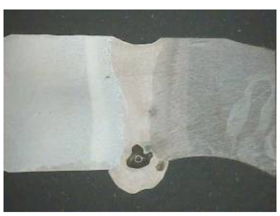

***Fig. 9 (a):** Cross section with undercut and root sagging*

***Fig. 9 (b):** Cross section no undercut with root sagging*

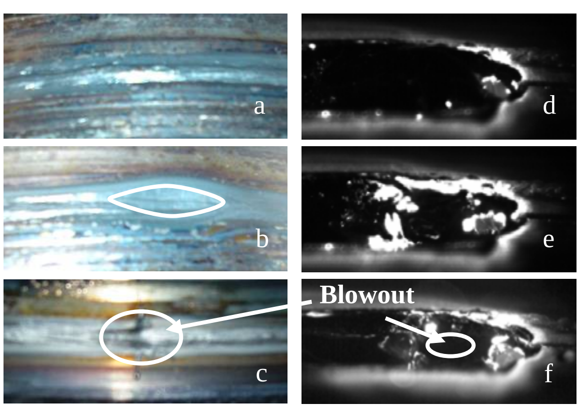

***Fig. 10 (a, b, c)**: Surface photos of normal, undercut and blowout situation, **(d, e, f):** HSI same situations*

As the company is so insecure of the functionality of the monitoring equipment they have installed ultrasonic equipment that tests all welds. If there is any error that the online monitoring misses, as in **Fig. 11** the ultrasonic equipment has a high probability of successful detection. **Fig. 11** shows a signal that is below approved limits for a short time but long enough to produce a defect. The type of defect is a small undercut, but is big enough to require rework.

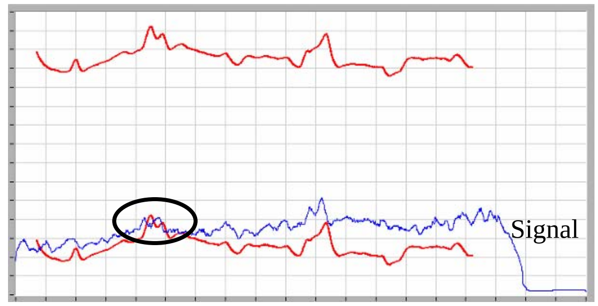

***Fig. 11.** No detection with photodiode, but during the ultrasonic testing*

The ultrasonic sensor has problems with small superficial defects but has no problems with undercuts or root sagging.

4 Discussion

One main problem when using photodiodes for measurements of the melt pool surface temperature is that the emissivity will change during welding. The change depends partly on melt pool surface oxidation but also on other factors. This change will make quantitative measurements of temperature very difficult [7] because if the emissivity changes the temperature that the sensor will give false readings.

For measurements between 400-600nm or in the plasma/metal vapour area the emissivity changes have no influence on the measurements as we are not interested in the quantitative value. The emissivity of the plasma can be calculated if it is needed, as shown by Cristoferetti et al [9].

Ultrasonic testing is a time consuming operation that can be avoided if the on-line monitoring equipment can be trusted. For undercut defects it is difficult to set the limits as the defect formation is sensitive to the joint preparation which makes the signal level deviate, but the blowouts have quite big signal values even for small defects so it is possible to detect them by decreasing the tolerance band.

Fig. 12 is a simplification of the HSI and shows how the keyhole changes in diameter in two different ways. With this fact at hand it is evident that the amount of plasma from the keyhole will change. By measuring the diameter and the amount of time for these two phenomenon an explanation of the signal behaviour can be found;

For the blowout defect the keyhole is wider during 1/1000 second giving a short burst of energy to the sensor, the short burst is clearly seen in **Fig. 6-7**. In the case of undercut defects the keyhole becomes smaller and the amount of time the keyhole is smaller is 1 order of magnitude longer. The signals longer detection of a smaller amount of plasma is seen in **Fig. 8** and **Fig. 11**. The signals are, in both cases, smoothed by the software which therefore doesn't show a true signal, but these two defect types can clearly be distinguished from each other.

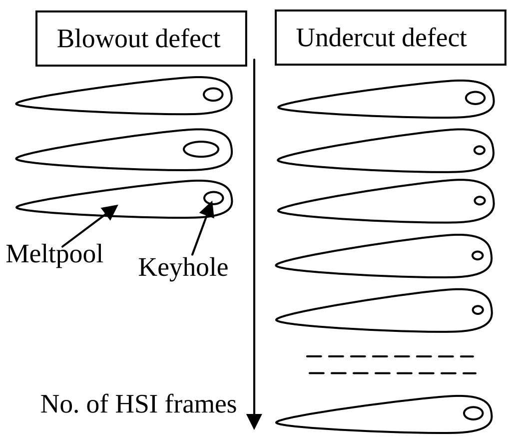

Fig 12. *Explanation of signal correlation to keyhole behaviour*

The main problem that has to be addressed is that the limits of the monitoring system have to be set tighter around the signal so that the defects can be detected. Future work will involve attempts to stabilise the process by having control over, amongst many parameters, the quality of the edge preparation and pollution level of the welded surfaces. This stabilisation will allow monitoring limits to be set at narrower values.

5 Conclusions

For this work the following conclusions can be drawn:

- Undercut and blowout defects can be detected better with the online monitoring system with a more stable process
- Stable processes has the effect that the quality level increase
- Undercuts are quite slow forming but has a low impact on the signal value
- A root sagging defect are often a consequence of an undercut defect
- Plasma vapour changes characteristics depending on keyhole diameter
- A blowout defect is preceded with a hump formation with this setup of the process
- The speed at which a blowout is formed is extremely high and can be missed if the monitoring system is to slow

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