

# Development of Combined Seam Tracking and Process Monitoring for Laser Welding

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Light emitting diode (LED)-based process zone illumination and coaxial imaging using a matching narrow bandpass filter give images of a sufficient quality to be used in a novel seam tracking and process monitoring laser welding tool. Features of the image can be determined every 10 ms. Variations in the features imaged (area, aspect ratio and centre position), along with changes in the noise levels of photodiode-monitored process emissions, allow for the detection of welding process defects, including contamination of the cover slide, joint gaps, incorrect settings of beam focus or gas shielding flow rate, and loss of full penetration on loss of power or an unexpected increase in material thickness.

*Keywords: Laser welding, titanium alloy, nickel alloy, light emitting diode (LED), photodiode, seam tracking, defects, aerospace*

## 1 INTRODUCTION

As a low distortion and high performance means of joining, laser welding can offer significant advantages when manufacturing high value, safety critical applications (see Figure 1). Narrow process tolerances, however, can make it a challenge to maintain weld quality. Failure to monitor and control part preparation and cleanliness, part placement, seam location and fit-up, and the parameters of the process itself can all result in weld defects.

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FIGURE 1

Example photograph of a complex aerospace structure incorporating laser welds (Courtesy of GKN Aerospace).

In this paper we report on work completed by TWI with Swedish partners Permanova Lasersystem AB, Bit Addict and GKN Aerospace Engine Systems. This work has developed and evaluated the performance of a novel seam tracking system. This system is also capable of multi-sensor process monitoring and thus fault recognition. Use of such systems will help ultimately to reduce the post-weld inspection burden on laser welded structures in the aerospace industry.

## 2 WORK CARRIED OUT

The use of data from a variety of different sensors during laser welding, i.e. multi-sensing solutions, is fast becoming widely recognised as the way forwards for commercial monitoring and thus control of laser welding. Adding one or more cameras to that suite of sensors is particularly attractive. A camera can be relatively compact, low-cost, and gives a direct, coaxial (if required) and often readily understandable view of the process with less inferences about defects needing to be made. The most affordable cameras, however, are normally saturated by the intense visible process light which is emitted when the focused laser beam interacts with the material during keyhole welding. One common step to take when faced with this problem involves wavelength or temporal filtering. But this filtering cuts down on the useful information that can be extracted from the camera images. A second alternative is to also use narrow bandpass filtering, but then re-illuminate the interaction zone with an intense light source of a matching emission. Secondary lasers have been used for this but a more affordable illumination option has been investigated in this work, that of using high intensity light emitting diodes (LEDs).

A standard 100 fps complementary metal-oxide-semiconductor (CMOS) camera, sensitive to visible light but with a matching bandpass filter, was then

fitted coaxially to the head of a Yb:fibre laser (YLS-10000; IPG Photonics Corporation) set up for welding, as shown in Figure 2. Figure 3 shows three camera images which are typical examples obtained with appropriate LED illumination settings and exposure times. With this hardware in place, image analysis software was then developed by Bit Addict. As Figure 3 shows the seam location can be resolved in such images. Analysis in this area of each image could successfully detect the seam. The co-ordinates of its location can then be fed to a side-to-side actuator, fitted between the welding head and its



FIGURE 2

Photograph of the laser welding head with built-in LED illumination developed by Permanova.

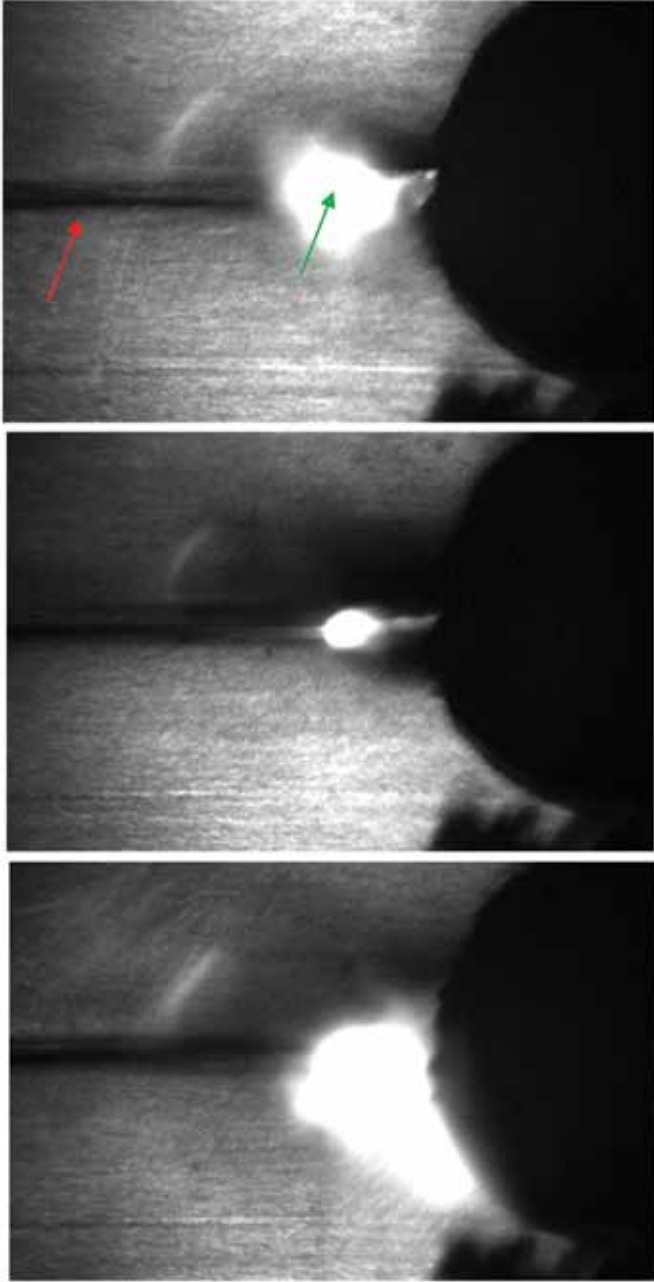


FIGURE 3  
Three camera images showing seam location (red arrow) and features of the laser beam-material interaction (green arrow).

manipulating robot. With such an arrangement in place, seams can then satisfactorily be tracked in real time.

This work concentrated more on using the camera images as a source of process monitoring data. Additional image analysis routines were developed to extract the area, aspect ratio (or circularity) and centre co-ordinates (in  $x$  and  $y$ ) of the bright pixels associated with the point where the beam impinges on the material being welded. Additional areas of bright pixels, arising for example from the ejection of spatter droplets from the keyhole during welding, could also be detected and quantified by this software. Software to monitor and control these algorithms was also developed by Bit Addict, including options to monitor and record data coming in from other process sensors, as well as optics temperature and/or scattered light readings. In the work reported here, the other process sensors used alongside the camera were photodiodes monitoring the intensity of any back-reflected  $1\ \mu\text{m}$  wavelength laser radiation, as well as any visible process light itself. This monitoring software could run in near real-time on an industrial personal computer (PC) (with analysis results coming back every 10 ms). Figure 4 shows an example of some of the software screens.

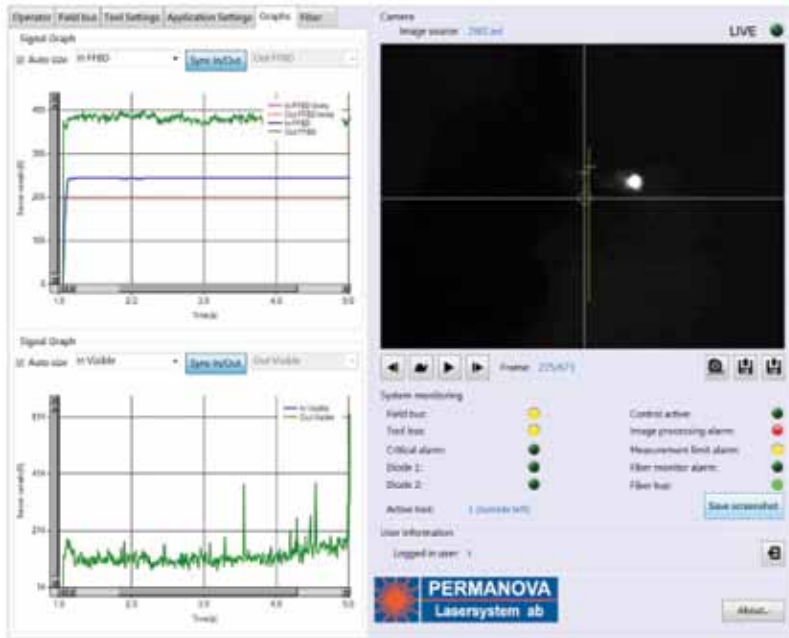


FIGURE 4

Laser weld monitoring software: laser beam intensity at both input and output ends of fibre (top left), process light (bottom left), example of coaxial camera image (top right) and system status (bottom right).

An iterative series of butt welding trials were then carried by TWI using this equipment on aerospace grade titanium and nickel alloys of thicknesses industrially relevant to GKN Aerospace. These trials helped to develop understanding around relationships between monitored signals and changes in welding process behaviour.

A number of different changes were deliberately introduced during welding, including using intentionally contaminated cover slides, welding over unacceptably wide joint gaps, welding with the wrong choice of focus position, welding with incorrect gas shielding settings, welding with incorrect laser beam power settings leading to loss of weld penetration and welding with incorrect choice of material thickness also leading to loss of weld penetration. In this manner, these trials experimentally identified which signals could most usefully be developed to automatically alert the equipment operator to certain changes in the welding process, and thus certain weld defects.

### 3 PRELIMINARY RESULTS

As Figures 5 to 8 show, a number of changes in the equipment, work-pieces or process parameters led to easily visible changes in the camera



FIGURE 5  
Example reference image.



FIGURE 6  
Image with contaminated cover slide.

images. Figure 5 shows a typical reference image from an acceptable weld.

Figure 6 shows the effect on such images with the occasional scattering of process light that can be seen when the cover slide begins to become contaminated. Figure 7 shows the process light that can be scattered down an unacceptably wide joint gap, then being detected by the coaxial camera. With a change in beam focus position, a change in the size of the camera image is also apparent, as shown in Figure 8.

A change in gas shielding settings was one of the few things investigated that, although affecting weld quality, did not bring about an easily visible change in the camera images. Instead, the significant increase in the levels of process light associated with a reduction in gas coverage of the processing zone were more readily detected using a photodiode, as shown in Figure 9, which plots emitted process light intensity with time.

More subtle variations could be picked up in the size, shape and stability of the image on loss of penetration, either resulting from a deliberately introduced reduction in laser beam power or from an intentional change in work-piece thickness, as can be seen from Figure 10.



FIGURE 7  
Image of unacceptably wide joint gap.



FIGURE 8  
Increase in image size with change in beam focus.



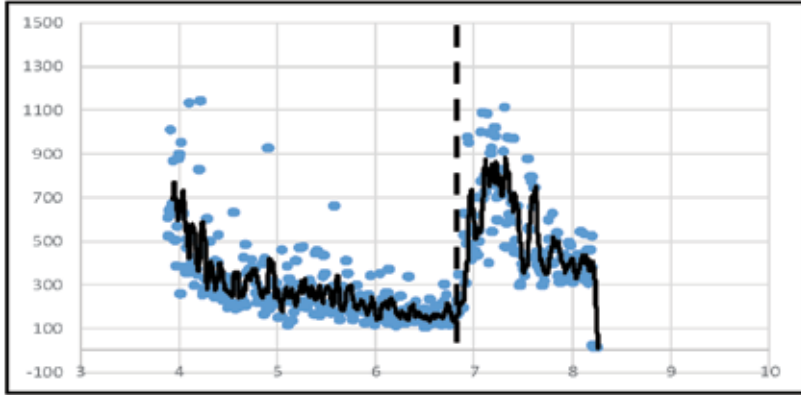


FIGURE 9  
Spike in-process light emitted on loss of gas shielding.

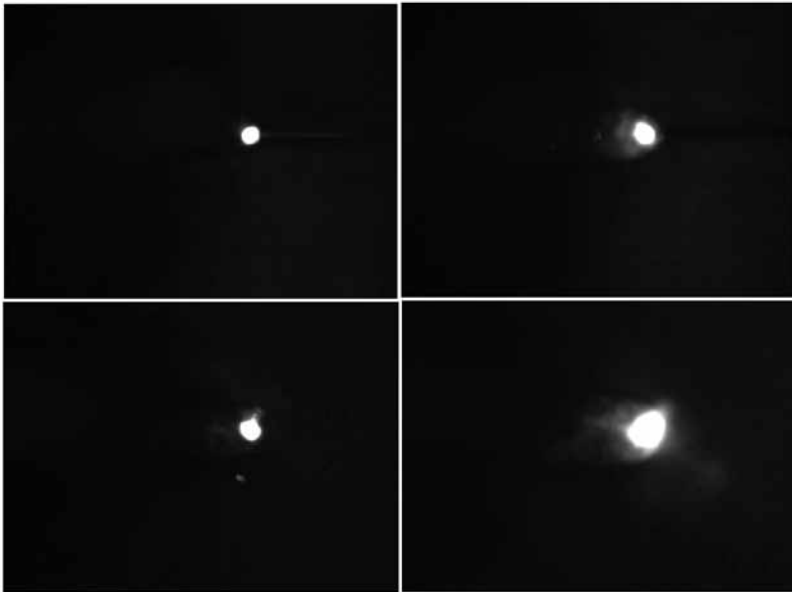


FIGURE 10  
Change in image on loss of penetration with either a power change (top left and top right) or material thickness change (bottom left and bottom right).

#### 4 FURTHER ANALYSIS RESULTS

As shown above, the preliminary findings of the work were that the coaxial imaging approach used could detect cover slide contamination, unaccept-

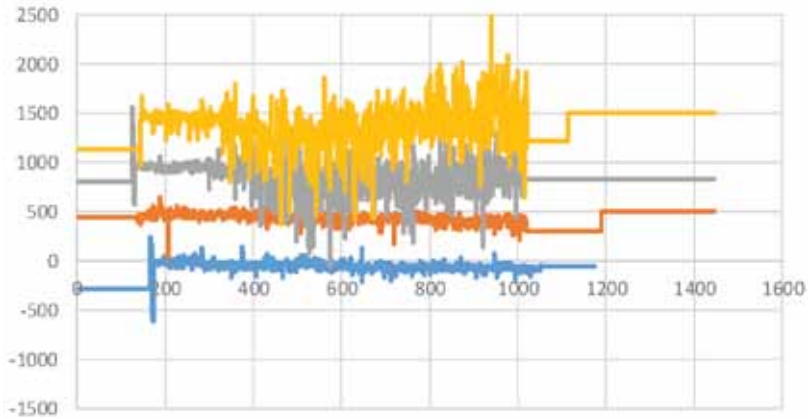


FIGURE 11

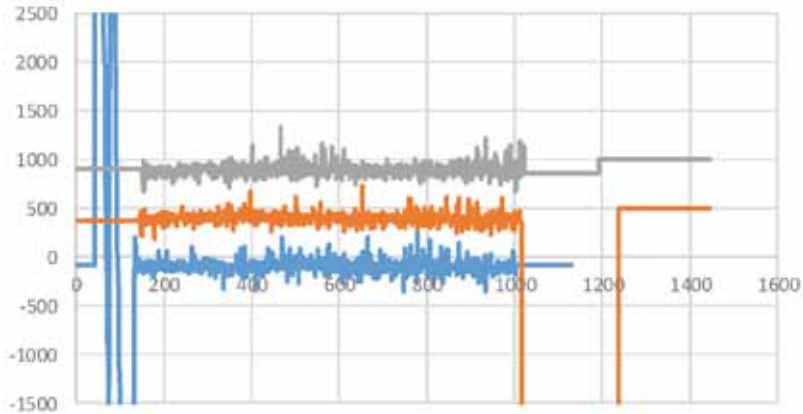
Change in x co-ordinate of image centre over the course of four welds with increasing cover slide contamination (bottom trace to top).

ably large joint gaps, incorrect beam focus settings or the loss of complete weld penetration arising from a loss of power or an unexpected increase in material thickness. Complementary photodiode monitoring of backscattered visible process light also detected when the weld pool gas shielding was set incorrectly. Further work then took place to determine which of these changes could be automatically detected, principally by using image analysis.

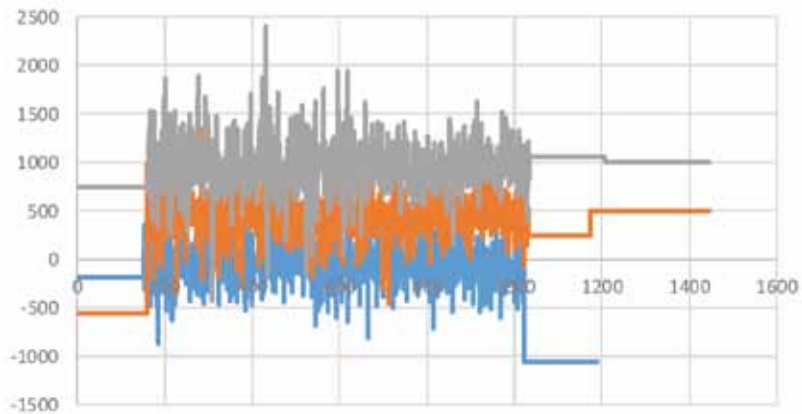
Figure 11 shows how the value of the x co-ordinate of the image centre became less stable with increasing cover slide contamination. This was presumably due to a gradual reduction in laser power arriving at the work surface and a corresponding reduction in process stability. Figure 12 shows how monitoring of this same parameter can also pick up changes in beam focus position resulting in process instabilities leading to variations in bead width or spatter. A similar result is achieved in this case when monitoring the aspect ratio of the image, which becomes more elliptical, and less stable, when using a non-optimum focus setting.

Figure 9 showed how a shut off in gas shielding could be detected using a photodiode monitoring process light. Figure 13 shows similar results, showing how the noise of this photodiode signal increased when using non-optimum gas shielding levels. Figure 13 shows what happens when using inadequate gas shielding, but the same increase in photodiode signal noise level was also seen when using an excessive gas shielding flow rate.

Figure 14 confirms the detection of the reduction in the positional stability of the image on loss of penetration. Corresponding increases were also seen in the value, and noise level, of the aspect ratio of that same image.



(a)



(b)

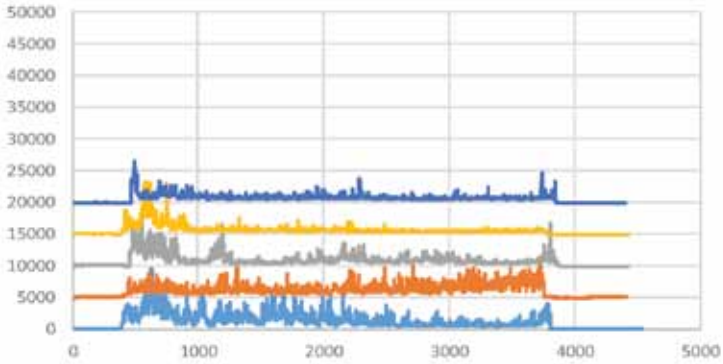
FIGURE 12

Plots of x co-ordinate of image centre for three experiments with (a) optimum beam focus setting and (b) non-optimum.

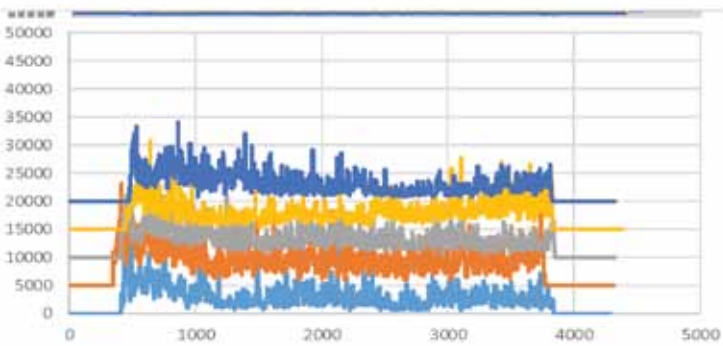
## 5 VALIDATION

As a final test case, using monitored changes in the process zone image to automatically detect weld defects, welding experiments were carried out on wedge-shaped coupons, of non-constant thickness. Back-scattered process light, image aspect ratio and image centre position were monitored and rolling average values compared against bounds set up in advance.

Monitoring of image aspect ratio proved the most successful at detecting whether full penetration was being achieved in a given coupon or not. A flag



(a)



(b)

FIGURE 13

Increase in process light noise between (a) five optimally shielded experiments and (b) five inadequately shielded.

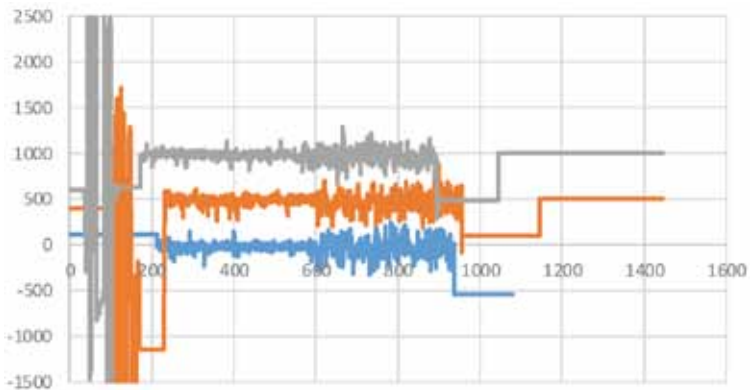


FIGURE 14

Increase in instability of x co-ordinate of image centre for three experiments welding over a step increase in material thickness, resulting in loss of full penetration.

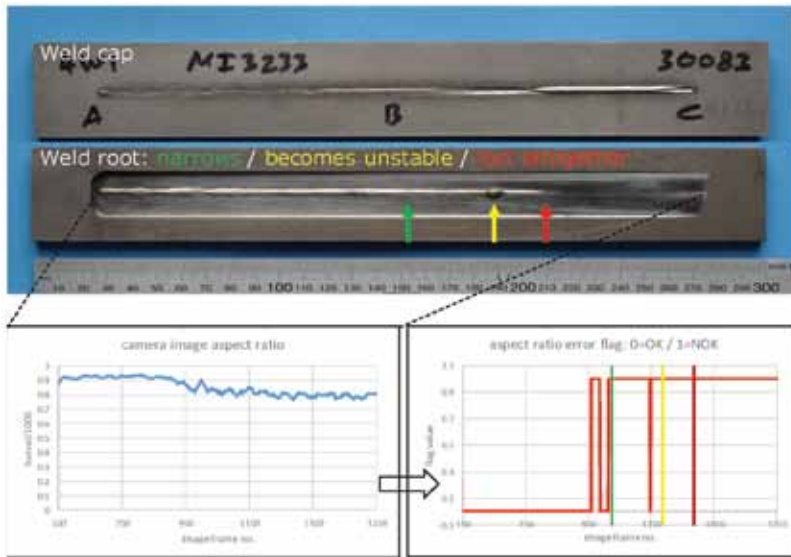


FIGURE 15

Welding of the wedge-shaped coupon (top) resulting in progressive root narrowing, instability and then loss of penetration. Corresponding reduction in image aspect ratio value and increase in its noise level (bottom left). Associated flag behaviour (continuous red line), compared to the behaviour of the weld root (vertical green, yellow and red lines in bottom right).

variable was set to trigger (by changing from 0 to 1) when the aspect ratio fell below the pre-set lower bound value. Figure 15 shows the result from one such experiment, showing that the flag variable already triggers just prior to the weld root starting to narrow, and remains consistently high (at 1) thereafter as penetration becomes unstable and is then lost.

Figure 16 compares this first trigger point along the length of the weld with these same three changes in weld root behaviour for five experiments. This indicates good reproducibility in using this method as a means of detecting loss of penetration.

## 6 CONCLUSIONS

A novel seam tracking and process monitoring laser welding tool has been developed in this work. Through a combination of light emitting diode (LED)-based process zone illumination, and coaxial imaging using a matching narrow bandpass filter, images of a sufficient quality can be achieved for both of these in-process functions. Features of the image, including its area, aspect ratio and centre position can be determined every 10 ms. Variations in one or more of these features, along with changes in the values and noise

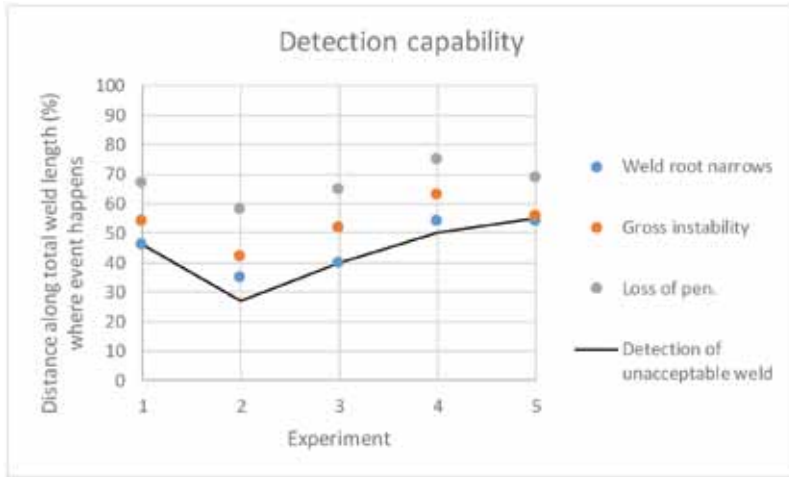


FIGURE 16

Comparison of flag trigger distance along five coupons with weld root narrowing, instability and then loss of penetration occurred in each.

levels of photodiode-monitored process emissions, have been seen to occur when a number of different welding process defects present themselves. These include contamination of the cover slide, joint gaps, incorrect settings of beam focus or gas shielding flow rate, and loss of full penetration on loss of power or an unexpected increase in material thickness.

With the then correct set up by the user of bounds for one or more of these values, this new tool shows promise in the automatic detection of a range of key scenarios which otherwise, if going unnoticed, would lead to significant lengths of defective weld.

The development of such tools in the future will lead to a reduction in the occurrence of defective welds, as well as potentially then reducing requirements on post-weld non-destructive testing (NDT), especially in critical components. These are both steps forward in promoting the uptake of laser welding and helping to reduce its operational costs.

## ACKNOWLEDGMENT

The authors would like to thank the European Commission Framework 7 'LASHARE' project (Grant No. 609046) for supporting this work.