# A STUDY ON WELD POOL MONITORING IN PULSED LASER EDGE WELDING

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**ABSTRACT**

Edge welding of thin sheets is very difficult because of the fit-up problem and small weld area. In laser welding, joint fit-up and penetration are critical for sound weld quality, which can be monitored by appropriate methods. Among the various monitoring systems, visual monitoring method is attractive because various kinds of weld pool information can be extracted directly.

In this study, a vision sensor was adopted for the weld pool monitoring in pulsed Nd:YAG laser edge welding to monitor whether the penetration is enough and the joint fit-up is within the requirement. Pulsed Nd:YAG laser provides a series of periodic laser pulses, while the shape and brightness of the weld pool change temporally even in one pulse duration. The shutter-triggered and non-interlaced CCD camera was used to acquire a temporally changed weld pool image at the moment representing the weld status well. The information for quality monitoring can be extracted from the monitored weld pool image by an image processing algorithm. Weld pool image contains not only the information about the joint fit-up, but the penetration. The information about the joint fit-up can be extracted from the weld pool shape, and that about a penetration from the brightness. Weld pool parameters that represent the characteristics of the weld pool were selected based on the geometrical appearance and brightness profile. In order to achieve accurate prediction of the weld penetration, which is non-linear model, neural network with the selected weld pool parameters was applied.

**KEYWORDS**

Weld pool monitoring, Vision sensor, Laser welding, Edge joint, Neural Network

## 1. Introduction

Pulsed Nd:YAG lasers are appropriate for particular industrial applications requiring precision seam welding of small mechanical and electromechanical components[1,2]. In laser welding, as other welding processes, monitoring and prediction of weld penetration has been an important point for sound weld quality. Acoustic, light and visual signals can be extracted by various monitoring methods. Among the various monitoring methods, visual monitoring method by using a vision sensor is preferred because the direct information of the weld pool can be extracted. Various studies have been conducted on weld pool monitoring in laser welding by using the vision sensor systems[3-7]. These systems are generally equipped with a high-speed camera and auxiliary light source such as Ar laser or frequency-doubled Nd:YAG laser illuminating the weld pool. In this study, a vision sensor which needs no auxiliary light source was applied to weld pool monitoring in pulsed Nd:YAG laser edge welding[8].

Pulsed Nd:YAG laser provides a series of periodic laser pulses, while the shape and brightness of the weld pool change temporally even in one pulse duration. Basically, weld pool increases in size and becomes brighter temporally. Also, brightness profile of the weld pool changes according to the laser pulse width and energy. Therefore, the weld pool image has the different shape and brightness according to the image acquisition moment. The shutter triggering moment of the CCD camera was carefully selected for obtaining the relatively clear and consistent weld pool image, because the acquired weld pool images have the temporal characteristics which represent the status of weld pool. Weld pool image has the information about weld penetration. That information can be extracted by the size and brightness characteristics of the weld pool. However, this relationship between the weld pool and penetration is non-linear. Neural network was applied to relate the weld pool characteristics to the penetration. The weld pool parameters as the input in neural network were carefully selected based on the shape and brightness characteristics. Finally, neural network was applied to test of weld pool penetration monitoring and prediction.

**2. Edge Joint and Monitoring System**

Edge joint has characteristics according to joint fit-up and geometry as shown in Figure 1. Weld pool penetration has relationship not only with welding conditions – beam width, energy and pulse rate – but also joint geometry – gap, misalignment and thickness change. In order to relate the penetration to the welding conditions and joint geometry, weld pool monitoring system is essential. The system for weld pool monitoring consists of a 2-axis stage, Nd:YAG laser focusing optics, CCD camera, narrow bandpass filter, synchronization circuit and PC(with an image processing board and pulse generator). Figure 2 shows a system architecture. Pulsed laser seam welding consists of multiple periodical pulses. The start of each pulse is detected in the synchronization circuit when the pulsed Nd:YAG laser is radiated. The shutter of the CCD camera is opened with a specific time delay from the laser pulse start, in order to acquire the clear weld pool image. The vision sensor consists of a CCD camera, macro lens and narrow bandpass filter, and has a 2.6mm×2.0mm field of view and 3μm resolution. A narrow bandpass filter with a bandwidth of 805nm to 815nm was used to extract the light from the weld pool.

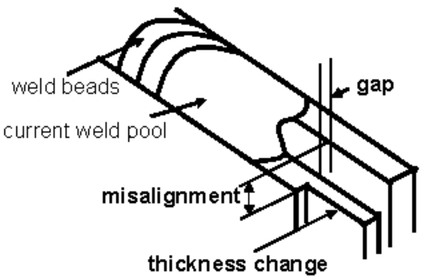



**Fig. 1** Photograph of the system

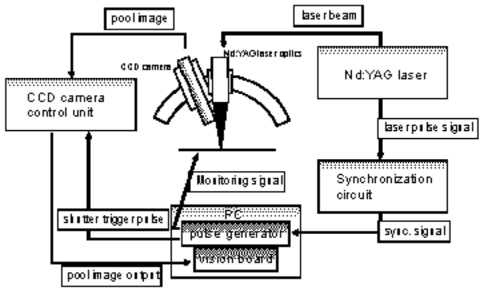



**Fig. 2** Overall system architecture

The shutter speed of the CCD camera was selected to be 1/30000s because of the short pulse duration in test welding. One-pulse-trigger mode was adopted to acquire the weld pool image with a specific time delay from the laser pulse start, where the shutter of the CCD camera was opened after the pulse generator counts the fixed number predetermined for the time delay as shown in Figure 3. In order to find the moment for a clear and meaningful weld pool image, image acquisition test was performed in bead on plate welding as shown in Figure 4. Figure 4(a) shows the temporal weld pool images from 0.4ms to 1.8ms when the beam width is 1.8ms. The size of weld pool increases and brightness profile severely changes. Weld pool width and gray level sum rapidly change in the early stage. Otherwise, they become steady at the latter stage as shown in Figure 4(b).

Temporal behavior of the weld pool in edge joint is shown in Figure 5. As in the bead on plate welding, the shape, size and brightness profile temporally change. At the early stage, the reflected area appears at the front boundary because the previous weld bead reflects the light from current weld pool as in Figure 5(b). At the latter stage, the current weld pool becomes bigger and brighter. Therefore, the weld pool image for monitoring was acquired at the latter stage.

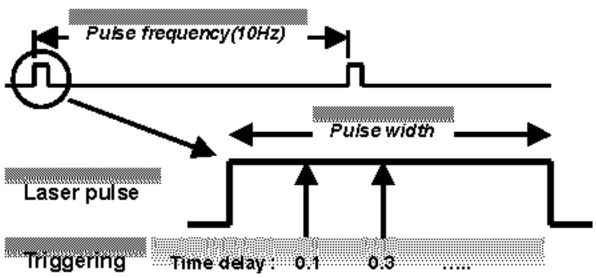
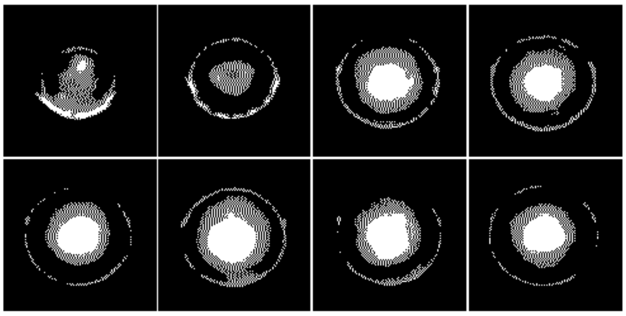
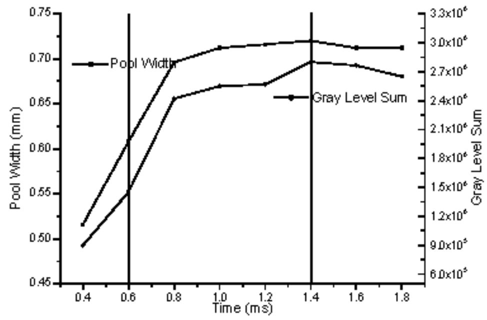



**Fig. 3** Image acquisition with a specific time delay

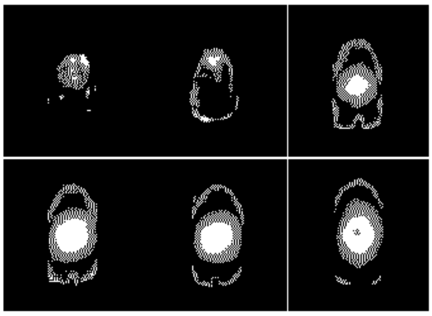


(a) Temporal weld pool images

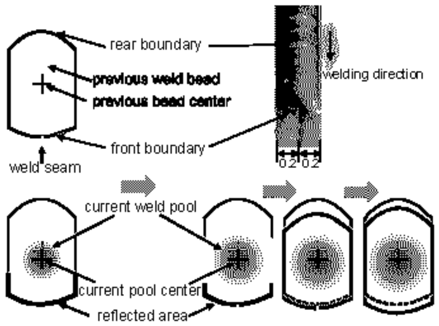



(b) Pool size and gray level sum

**Fig. 4** Temporal behavior in bead on plate welding



(a) Temporal weld pool images

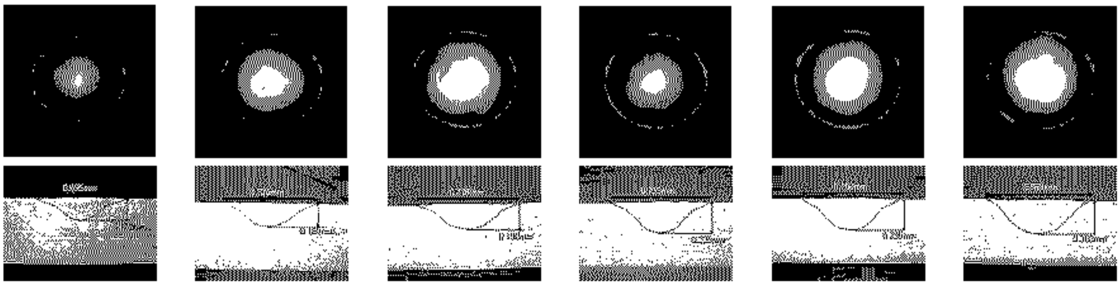



(b) Weld pool shape

**Fig. 5** Temporal behavior in edge joint

**3. Weld Pool and Penetration**

In order to find the relationship between the weld pool image and penetration, welding test was performed in bead on plate welding. Figure 6 shows the weld pool images and penetrations. As shown in Figure 6, weld pool image has characteristics such as size and brightness profile according to the beam width and energy. Weld pool parameters should be carefully selected, in order to be used as the input parameters for prediction of penetration. Many other studies have applied the neural network to the penetration monitoring in arc welding[9-11]. Usually, the geometrical characteristics, such as pool width, length, area and rear angles, have been used as parameters. Otherwise, in this study, the brightness profile as well as the geometrical appearance was considered as the weld pool parameter.



1. 1ms, 0.7J    1.1ms, 0.8J    1.1ms, 1.0J    1.6ms, 1.2J    1.6ms, 1.4J    1.6ms, 1.6J

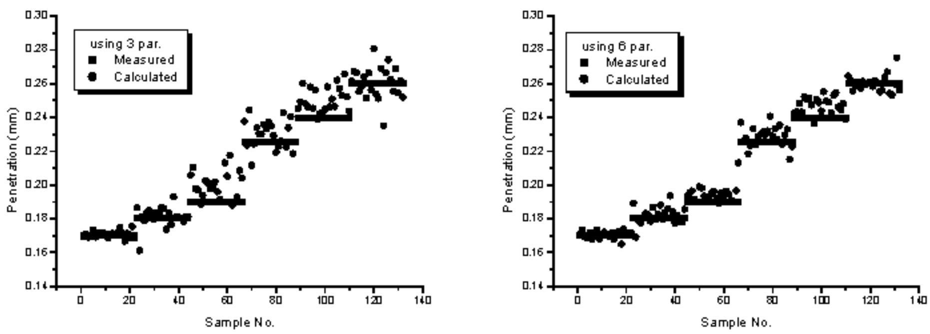
**Fig. 6** Weld pool image and penetration

Major three types of weld pool parameters are pool size, distinctively bright region and brightness profile. Among them, pool size and bright region belong to the geometrical parameters. In this study, pool length($L$), effective area($A_{eff.}$) – number of pixel whose gray level is brighter than 150 value, and average gray level($G_{ave.}$) in that area were selected as the geometrical parameters. As shown in Figure 6, the bright region of the weld pool is ring-shape with a dark central region or a gaussian shape. In addition to the shape, the rate of brightness change can be considered as a parameter. The shape and brightness change can be extracted from the intensity distribution along the weld pool centerline. However, this 1D information may cause an inaccurate result because the shape and location of the bright region is irregular and unstable. Therefore, 2D information of the bright region will be more reasonable parameter. At first, the more distinctive area in the bright region($A_b$) – the rim of the ring-shaped area – was selected, which is the number of pixel whose gray level is brighter than $G_{ave.}$. Secondly, the ratio between $G_{ave.}$ and $A_b$ - $R_a$ – was selected. Finally, in order to represent the rate of brightness change, the ratio between ($G_{ave.}$ –150) and $R_{eff.}$ – S – was selected, in which $R_{eff.}$ is the effective radius of the irregular bright region as follows:

$$R_{eff.} = \sqrt{\frac{A_{eff.}}{\pi}} \tag{1}$$

**4. Application of Neural Network**

The back propagation neural network was used to test the possibility of the selected weld pool parameters. The number of samples was 54 and 2 hidden layers were used. Test was performed by the generally used geometrical parameters – L, $A_{eff.}$ and $G_{ave.}$. And then, the brightness characteristics - $A_b$, $R_a$, and $S$ – were included. Figure 7 shows the test results that represent the possibility of the proposed parameters.




(a) Using 3 parameters (b) Using 6 parameters

**Fig.** 7 Test of weld pool penetration prediction

Inaccurate prediction was resulted because of the insufficient parameter selection in Figure 7(a). The improvement of accuracy was significant by using the six proposed parameters. This improvement was achieved by the more accurate description of the weld pool image.

As in the bead on plate welding, the same parameters and method would be applied to the edge joint.

**5. Conclusion**

The shape and brightness profile of weld pool image change temporally even during one laser pulse. The monitored weld pool image has the relationship with the weld penetration. In order to find that relationship, weld pool parameters – geometrical appearance and brightness profile – were selected. The back propagation neural network was used to test the possibility of the selected weld pool parameters. As a result of the test, the proposed parameters including the information of the brightness profile resulted in the improvement of prediction because of the more accurate description of the weld pool image. This method and the selected parameters could be applied to an edge joint. Test for the possibility of the proposed parameters in an edge joint with a gap, misalignment and thickness change will be needed.

**Acknowledgements**

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