Estimation of Weld Pool Geometry and Cooling Rate in Laser Welding

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Abstract

The laser processing of materials has immense importance in design, development and fabrication of micro products in multidisciplinary fields. The real-time tracking and inspection of weld joints can be done by using wide range of sensors available to monitor weld quality. This paper aims to predict weld bead geometry from the images captured by high-speed camera without filters during laser welding of dissimilar metals. The high-speed Y4 camera having image grabbing capacity of 2000 fps is used to record the welding process of two different thick materials. A graphical user interface is developed to compute the weld pool area and images are processed by using MATLAB based image processing module. The effect of process parameters on heat affected zone hardness has been analyzed. The images captured by the high-speed camera and analytical methods are successfully used to predict weld pool geometry and cooling rates. The cooling rate and weld bead geometry obtained from experimental and analytical methods are compared and found in close agreement with each other.

Key words: Weld pool geometry, Laser welding, Image processing and Micro hardness

1. Introduction

The laser welding process is widely used in fabrication of micro systems. The precise control of process parameters is a primary requirement to attain desired weld quality. In this process, a high energy density laser beam is targeted on a weld joint surface by adjusting operating process parameters. The surface exposed to the laser source is subjected to high thermal energy which results in melting of surface and heat energy progress through the weld joint by thermal conduction, convection and diffusion. In real-time applications, the expected performance of the weld joint is based on the amount of heat consumed for melting the material.

The depth of penetration is a most important parameter to fulfill the criteria of expected performance of the weld joint. The model developed for predicting weld bead geometry should be computationally efficient and relate to the immeasurable parameter to easily measurable parameter. The phenomenon of formation of weld pool can be accurately tracked on real-time basis by using a wide range of reliable, high performance sensors such as Complementary Metal Oxide Semiconductor (CMOS), Charge-Coupled Devices (CCD), Infrared, Ultra violet and photodiodes.

Bertrand et. al. (2000) applied a bi-dimensional monochromatic and one spot multi-wavelength pyrometer to monitor surface temperature, variation in brightness and defects in Nd: YAG continuous laser welding. Emil (1972) proposed a simple method for predicting cooling rates from curves developed by conducting more than 300 bead-on-plate weld experiments on steel metals. Hang Yao (2004) tried to diagnose the geometry of the weld pool from a sequence of images captured by using digital image processing. De et. al. (2003) carried out theoretical and experimental investigations to examine the effect of laser power and time on the weld thermal cycle, weld metal microstructure and hardness. Poorhaydari et. al. (2003) adopted Rosenthal analytical methods for estimating the actual cooling rate in a weld section of thick and thin plates.

Zhang (2013) used the images of weld pool and keyhole captured during welding and processed them by using region growing and Canny algorithm. Neural networks are used to identify weld pool parameters in real time. Tadamalle et. al.(2013) characterized the weld joint and influence of laser power (P), Pulse Duration (PD) and welding speed (V) on weld bead geometry, duty cycle, pulse overlap. Harish kumar et. al. (2012), Kratzsch, et.al. (2000) and Abels et.al.(1999) carried out tests by using a high speed CCD, CMOS camera, Infrared
camera or array of sensors to measure plasma radiation in welding for predicting 2D spatial intensity distribution which allows to monitor weld bead geometry, seam defects, spatter, keyhole stability, weld pool dynamics, temperature distribution and laser weld quality. Ahmad et. al.(2012) modified the Scherrer equation to predict accurate value of grain size from different XRD peaks patterns.

In this paper, a graphical user interface is developed to estimate weld pool area from the images captured by using high speed camera without filters. These images are processed by using MATLAB image processing module to estimate the weld pool area, cooling rate and to predict the effect of process parameters on micro hardness. The welding of dissimilar material less than 1mm thickness. The advanced equipments and techniques are used to study the behavior of the weld joints.

2. Experimental Procedure
The laser welding of stainless steel and galvanized iron sheets has been carried out by using pulsed Nd:YAG laser welding machine, Trumpf make, TruLaser station 5004, designed to deliver maximum laser power of 4 kW. Argon gas is used at 7 lit/min to avoid distortion in material and spatters on the weld surface. The specimens of 150 mm x 60 mm are cut with the help of wire cut electron discharge machine from 0.5 mm and 0.7 mm thickness sheet plates.

The specimens are cleaned before welding by using 8 % NaOH and 20 % HNO₃ solution. The galvanized iron and stainless steel sheets are welded along the 60 mm side. The schematic diagram of laser welding process, fixture used for holding weld specimen and camera mounting to record the process is shown in Figure 1.

2.1 Recording of Welding Process
A high speed Y4 camera having an image grabbing capacity of 2000 fps is used for recording the welding process. The process parameters used during welding of two different thickness material is show in Table 1.

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>P (kW)</th>
<th>S (mm/s)</th>
<th>PD (ms)</th>
<th>Maximum Energy (J)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>4</td>
<td>2</td>
<td>3.41</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>5</td>
<td>1</td>
<td>1.15</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
<td>6</td>
<td>2.2</td>
<td>9.96</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The frames from recorded films are extracted by using pro motion software. The frames (F1-F12) captured for single pulse during experiment number 3 are shown in Figure 2. A Metatech make, Semi-automatic hardness testing machine (HXD-1000TM) with an objective lens of 400X is used to measure the hardness of weld zone. A diamond shape indenter is used to measure the hardness across the weld cross section parallel to the top surface under an applied load of 200 gm for 0.5 mm and 300 gm for 0.7 mm thick sheets.

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![Figure 1: Experimental setup](image1)

![Figure 2: Frames recorded by using high speed camera for single pulse during welding process](image2)
3. Prediction of Weld Pool Geometry

The weld pool provides information about welding process in terms of weld performance parameters. A human operator can acquire most of the information about the welding process by observing the weld pool geometry.

3.1 Image Processing Technique

A MATLAB based Graphical User Interface (GUI) is developed to compute weld pool parameters. The GUI facilitate to perform four functions namely manipulating images, loading image, processing of loaded images by receiving input from the user interface and display of desired output in terms of weld pool area or pixels. The Figure 3 shows GUI window developed for entering the data input and to display the output parameters in numeric form. The top portion of the window is equipped with two push buttons namely Load Image and Process.

The load image push button facilitate the image to be selected for analysis. The process pushbutton initiates the processing of the uploaded image by using image processing algorithms available in MATLAB software. Figure 4 shows the distorted images before gray scale threshold value of 200 whereas reduction in image area is observed after this value. The GUI allows to display the original image and the grayscale image based on the selection of Red Green Blue (RGB) components with the help of radio buttons and corresponding results are shown in the second column of the Figure 3.

The range of pixels to be cropped from the grayscale image is set in the program by default in order to extract the weld pool pixels properly. The cropped images are de-noised or smoothened by using Wiener filtering method proposed by Cao et al.(1995). This method is used since it reduces the noise in better way as compared to the other image filtering techniques. The default input values for threshold intensity level, contour width and conversion factor are set as 200, 10 and 0.0446 respectively. The threshold values are decided based on the images processing to get an appropriate size of weld pool. The GUI converts filtered image into an equivalent binary form. The input threshold intensity is used for setting demarcation between maximum and minimum grayscale level. The pixels having gray level higher than the threshold value is set to 255 whereas the pixel with gray level less than threshold value is set to 0.

The weld pool shape has been approximated with a combination of elliptical and parabolic shapes. The traces of weld pool boundary extracted from weld pool region is shown in third column of Figure 3. The actual ellipsoid and the protruding portion of the weld pool can be approximated by using the boundary pixels and by blending elliptic and parabolic curves. The output module in the GUI facilitates the display of different plot options and weld pool area parameters.

Figure 3: GUI to measure weld pool area and corresponding output display

Figure 4: Weld pool size obtained at different threshold values

Figure 5: GUI to determine conversion factor and pixel size
The plot type drop down menu in Figure 3 allows to select different plot types such as 2D contour filled, 2D contour lines, 3D contour, surface faceted and surface interp. The extreme end points of weld sample is measured in terms of coordinate points. A line joining these coordinate points is used to convert into pixels. The length and width of the weld pool is established by correlating weld pool dimensions with the estimated line length. A conversion factor is used to convert a pixel into area. The GUI shown in Figure 5 is used to determine weld pool dimensions by using the conversion factor. The output parameters module in Figure 3 shows the calculated quantities of weld pool area in terms of pixels as well as in millimeters.

2.2 Experimental Technique

The weld samples are cut in transverse direction for metallographic inspection as per ASTM E8 standards.

![Image](83x367 to 272x473)

Figure 6: Weld bead geometry cross section

The weld joint specimens are polished by using different grade polishing papers followed by electrolytic etching process to observe the structure of weld bead geometry. The samples prepared for metallographic inspection are shown in Figure 6(a) - Figure 6(c). The measurement of weld bead geometry in terms of bead width and depth of penetration is done by using a Metatech make, HITACHI model, Electron Microscope.

3.3 Analytical method

An equation proposed by Ikhwan et. al.(2012) is used to estimate the depth of penetration. This equation is derived in terms of sheet thickness and thermo mechanical properties of the material.

\[
DOP = \frac{(L - R L_{90})}{R t_{0} \rho L_{m}} + \epsilon (T_{m} - T_{o})
\]

where \( R \) is the resistivity (m K/W), \( P \) is the power supplied (W), \( t \) is the pulse duration (ms), \( r_{0} \) is a beam radius (mm), \( \rho \) is the density of the material (kg/mm³), \( L_{m} \) is the latent heat of melting (kJ/kg), \( c \) is the specific heat (J/kg K), \( T_{m} \) and \( T_{o} \) are the melting and ambient temperature (K) respectively.

4. Cooling Rate

In laser welding, the cooling occurs from evaporation temperature to the solidus temperature of weld pool. The cooling rate is computed based on the time required from heat input to melt the material to the molten weld pool disappearance by neglecting all types of temperature losses. The variation of weld pool size obtained from individual frames captured at different time intervals is shown in Figure 2. The time required for recording the frames during heating and cooling of a single pulse is shown in Table 2.

<table>
<thead>
<tr>
<th>Expt. Number</th>
<th>Material thickness mm</th>
<th>Image Resolution</th>
<th>Frames recorded for single pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. of frames</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>1016 x 1016</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>448 x 416</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>1016 x 1016</td>
<td>26</td>
</tr>
</tbody>
</table>
5. Results and discussion

The depth of penetration and bead width values obtained from GUI, experimental and analytical methods are presented in the Table 3. The maximum variation of 5.77 % is observed in depth of penetration between experimental and analytical method. The maximum bead width variation of 14.16 % is observed between image processing technique and experimental method.

**Table 3: Comparison of weld bead geometry**

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>Image Processing BW µm</th>
<th>Experimental BW µm</th>
<th>Analytical DOP µm</th>
<th>Error %</th>
<th>Error DOP µm</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>736.78</td>
<td>842.4</td>
<td>621.2</td>
<td>1.47</td>
<td>12.53</td>
<td></td>
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<tr>
<td>2</td>
<td>858.36</td>
<td>931.2</td>
<td>434.2</td>
<td>5.77</td>
<td>7.82</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1053.36</td>
<td>880.6</td>
<td>218.1</td>
<td>3.16</td>
<td>14.16</td>
<td></td>
</tr>
</tbody>
</table>

This variation is due to change in dimensions of the bead width from pulse to pulse, location of the cross section and duty cycle of the welding machine. The thermal cycles generated from images by using image processing technique is presented in Table 4. A high energy density laser beam takes 2 ms for melting and 7.9 ms for cooling of 0.5 mm thick sheets whereas 0.7 mm thick sheet takes 2.2 ms for melting and 12.95 ms for cooling.

**Table 4: Estimation of thermal cycle**

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Heating Time 27 °C - 2700 °C µs</th>
<th>Cooling Time 2700 °C - 1450 °C µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>790</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>790</td>
</tr>
<tr>
<td>2</td>
<td>2.2</td>
<td>12948</td>
</tr>
</tbody>
</table>

The cooling curves obtained by image processing technique for weld pool surface area and bead width are shown in Figure 7(a) - Figure 7(b). The exponential form of cooling curves obtained from image processing techniques resembles with the exponential form of analytical equation. In Figure 8, the hardness variation in weld region is higher than the heat affected zone and the base metal. It shows that the hardness value is maximum at the centre line and decreases drastically from 386 HV to the base metal hardness as it moves away on either side of the weld.

The measured average hardness value of galvanized iron and stainless steel is 128 HV and 176 HV respectively. It can be also observed from Figure 8, the value of hardness varies over a distance of ±0.3 mm from weld centre line. This variation is due to faster cooling rate and relative proportions of chemical composition in the base metal. The result depicts that, as the thickness of material increases the hardness in the weld zone decreases. The maximum hardness value obtained in 0.5 mm and 0.7 mm thick material are 386 HV and 294 HV respectively.
The rapid cooling rate during welding causes relatively coarse grains in the fusion zone and HAZ.

![Figure 9: Peak patterns obtained from XRD](image)

The peak patterns obtained from Philips make, XRD patterns are used for estimation of grain size is shown in Figure 9. The average grain size in the weld zone is estimated by using Debye-Scherer’s formula. It has been found that the grain size in weld zone increases from 27.60 µm at centre of the weld to 10.23 µm towards HAZ and similar results are obtained by changing the pulse duration from 1 ms to 2 ms.

### 6. Conclusions

The images recorded from high speed camera are successfully used for predicting weld pool geometry. A high cooling rate of weld pool is observed from the results obtained by high speed camera. The results obtained from experimental and analytical methods shows a maximum variation of 5.77 % in depth of penetration and 14.16 % in bead width. The laser power and pulse duration have significant effect on hardness value. The cooling rate and weld bead geometry obtained from experimental and analytical methods are in close agreement. The grain size in weld zone increased from 27.60 µm at centre of the weld to 10.23 µm towards HAZ. This work can be further extended for online prediction of weld pool dynamics and geometry.

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