Optimizing pulsed fiber laser welding process parameters of thin Ti6Al4V sheet to control angular distortion

Kuntal Maji
Mechanical Engineering Department, National Institute of Technology Patna, Bihar-800 005, India

Abstract. The present study deals with angular distortions generated in fiber laser welding of Ti6Al4V sheets performed utilizing pulsed mode of laser irradiations. Experiments were conducted considering laser power, scan speed, pulse frequency and duty cycle as input process parameters, and angular distortion measured in terms of out of plane bending was taken as the process output. A central composite design was employed for carrying out pulsed laser welding experiments. The angular distortion was modelled using the response surface methodology for correlating with the input process parameters. Angular distortion was observed to increase with the laser power and scan speed. Optimum values of laser pulse frequency and duty cycle were found for obtaining least angular distortion. The prediction accuracy of the developed model of angular distortion was found to be good. Then, the desirability function approach of optimization technique was used to determine the optimum process parameters for obtaining the minimum distortion. Optimal distortion value was verified by conducting experiments and results were found satisfactory.

1. Introduction
Pulsed laser welding is a precision fusion joining process in which thin sheet metals get joined by melting and solidifications of the two weldments by discontinuous laser beam irradiations. The out-of-plane distortions generated in pulsed laser welding depends on a number of factors namely laser power, scan speed, spot diameter, pulse frequency, duty cycle and others. Minimizing the angular distortions in laser welding of thin sheets is essential to obtain accuracy in the welded sheet metal parts. The investigations on laser welding induced distortions in sheet metal parts carried out in past by different researchers are discussed below.

Moraitis and Labeas [1] presented a two steps approach of finite element simulation of laser beam welding of high strength steel and aluminium alloy plate that estimates of keyhole size based on thermal analysis and calculated distortions and residual stresses by thermo-mechanical model. The proposed approach was found efficient for application of laser welding simulation and optimization of process parameters to minimize distortions. Gao et al. [2] studied the welding of titanium alloy (Ti6Al4V) sheet using pulsed Nd:YAG laser and tungsten inert gas arc welding. Laser welding was observed to deliver less residual distortion, finer micro-structure, narrower heat affected zone and higher hardness compared to the TIG welding. Bhargava et al. [3] conducted experiments on fiber laser welding of 304 stainless steel plate to study the effects of process parameters like laser power, welding speed, beam spot size on angular distortion, penetration depth and weld bead profile. Process window for flat bead profile and least angular distortion was identified. Fahlstrom et al. [4] studied the laser welding induced distortions in boron steel using both experiments with different clamping conditions and finite element simulations. Significant process parameters were identified to minimize
the distortions. Casalino et al. [5] carried out experimental investigations on full penetration welding of Ti6Al4V sheet using fiber laser. It was concluded that the defects in the bead geometry could be minimized through optimization of the welding process parameters. Junaid et al. [6] carried out a comparative study between pulsed Nd:YAG laser welding and pulsed-TIG welding of titanium alloy sheet and found that less distortion and better mechanical properties were obtained in case of laser welding. Microstructures and mechanical properties of laser welded titanium sheet by continuous and pulsed laser irradiations considering the effects of different process parameters were investigated by some researchers [7-8]. Derakhshan et al. [9] investigated residual stresses and distortions generated in different welding processes like laser welding, submerged arc welding and hybrid laser-arc welding of thin structural steel plates through both experiments and numerical simulations. Laser-based welding was found more suitable to control distortion compared to that by arc welding method. Zhou et al. [10] investigated fiber laser key-hole mode welding of plates to optimize welding induced angular distortions taking the different process uncertainties into account using finite element simulations and monte carlo method. The optimization of welding process parameters are essential to minimize distortions induced by laser welding. The objective this paper is study the effects of different process parameters angular distortions in pulsed laser welding of titanium alloy thin sheet.

2. Experimental procedures

This section describes the materials, equipment and design of experiments method for conducting experiments on pulsed laser welding of titanium alloy (Ti6Al4V) sheet.

2.1. Material and equipment

Pulsed laser welding experiments on Ti6Al4V sheets with 1.0 mm thickness cut into 100 mm×25 mm sized specimens. This alloy has many applications in aerospace, biomechanical, marine and chemical industries because of excellent thermo-physical and mechanical, chemical, biocompatibility, corrosion resistance and chemical properties. Joining processes of lightweight materials were investigated by various researchers in the last few decades. The major chemical composition and mechanical properties of this alloy are listed in table 1[5].

| Element | Weight (%) | Al  | Fe  | O   | Ti  | V  |
|---------|------------|-----|-----|-----|-----|----|
|          |            | 6   | 0.25| 0.2 | 90  | 4  |

| Mechanical property | Physical property |
|---------------------|-------------------|
| Ultimate tensile strength | 950 MPa |
| Yield stress         | 880 MPa |
| Hardness             | 349 VH |
| Elongation           | 14%    |
| Density              | 4430 kg/m³ |
| Specific heat        | 0.526 kJ/Kg-K |
| Thermal conductivity | 6.7 W/m-K |

Experimental tests with butt joint configuration were carried out on a 1.07 µm wavelength CNC controlled YLR-2000 fiber laser system manufactured by iPG. The characteristics of this laser machine are 2 kW maximum laser power, pulse frequency range of 50 Hz to 1000 Hz, duty cycle range of 5% to 100% and spot diameter range of 250 µm to 6.0 mm. The welding fixture and associated laser delivery system is shown in figure 1. In all experimental runs, pure (99.9%) argon with flow rate of 10lit/min was utilized to the samples as the shielding gas in order to prevent oxidation. Furthermore, the incident angle of laser beam irradiation was kept 90° to the weld line. Prior to each experimental run, sheet samples edges were polished in grinding/polishing machine. Each pair of sheets to be welded was clamped in the fixture with edges in parallel positions in butt joint configurations along the 25 mm width of sheets.
One part of the sheets pair was fixed through clamping and the other half was allowed to be free in the vertical direction. Pulsed laser welded titanium alloy sheet samples are shown in figure 2.

After pulsed laser welding, the samples were allowed to cool, then the out-of-plane distortions were measured using a laser displacement sensor (Model No.-OPTO NCDT 1420; Make: Micro-Epsilon) attached to a three axes translational stage as shown in figure 3. The out-of-plane distortions were measured and expressed in in terms of bending angles calculated by the triangulation method.
Design of experiments (DOE) is a set of techniques that can establish the relationships between input parameters and output responses from a limited number of test data [11]. Central composite design (CCD) is one of the well-known designs of experiments methodology used in response surface methodology (RSM) for process parameters analysis. In RSM, the interaction between various pulsed laser welding variables and output responses can be analysed. Furthermore, the variations of the responses with the input parameters can be studied through three dimensional response surface plots.

The most four important input process parameters in pulsed laser welding, i.e., laser power, scan speed, pulse frequency and duty cycle were considered. The beam spot size of 0.4 mm was kept constant and this value was determined through some trial test by varying spot diameters and keeping other parameters fixed. Feasible working ranges of the other four input process parameters were identified through some preliminary experiments and visual inspection of the quality of the weldment through appearance and penetration depth. The ranges of the process parameters along with their intermediate levels according to the CCD design method are listed in table 2.

Table 2: Pulsed fiber laser welding process parameters and their levels

| Parameters         | Symbols | Units | Levels          |
|--------------------|---------|-------|-----------------|
| Laser power        | p       | Watt  | Minimum (-1) 1800 | Mid (0) 1900 | Maximum (+1) 2000 |
| Scan speed         | v       | mm/min| 480 600 720      |
| Pulse frequency    | f       | Hz    | 50 100 150       |
| Duty cycle         | c       | %     | 30 40 50         |

Experimental tests were carried out following various combinations of the parameters levels as obtained from the selected CCD design of experiment (DOE) matrix. In this investigation, a CCD matrix with three replications was generated and total 25 numbers of runs were carried out for each replication involving 16 cube points, 8 axial points and 1 centre point. This experimental design has quadratic effects consisting of linear, square and interactions on the considered responses. The experimental test results matrix according to the CCD design matrix obtained by utilizing Minitab V17 software [12] is given in table 3. Some tests data were also collected apart from the combinations of input parameters according to CCD design matrix to validate the prediction accuracy of the developed model of distortion in pulsed laser welding as given in table 4.
Table 3: Design matrix and input-output experimental data

| SL. No. | Laser power (W) | Scan speed (mm/min) | Pulse frequency (Hz) | Duty cycle (%) | Angular distortion (Deg.) | Mean | S.D. |
|---------|-----------------|---------------------|----------------------|---------------|---------------------------|------|------|
| 1       | 1800            | 480                 | 50                   | 30            | 0.39                      | 0.05 |
| 2       | 2000            | 480                 | 50                   | 30            | 0.74                      | 0.07 |
| 3       | 1800            | 720                 | 50                   | 30            | 0.53                      | 0.06 |
| 4       | 2000            | 720                 | 50                   | 30            | 0.57                      | 0.03 |
| 5       | 1800            | 480                 | 150                  | 30            | 0.68                      | 0.04 |
| 6       | 2000            | 480                 | 150                  | 30            | 0.93                      | 0.06 |
| 7       | 1800            | 720                 | 50                   | 30            | 0.83                      | 0.05 |
| 8       | 2000            | 720                 | 150                  | 30            | 0.63                      | 0.04 |
| 9       | 1800            | 480                 | 50                   | 50            | 0.82                      | 0.03 |
| 10      | 2000            | 480                 | 50                   | 50            | 0.73                      | 0.02 |
| 11      | 1800            | 720                 | 50                   | 50            | 0.70                      | 0.04 |
| 12      | 2000            | 720                 | 50                   | 50            | 1.08                      | 0.02 |
| 13      | 1800            | 480                 | 150                  | 50            | 0.56                      | 0.03 |
| 14      | 2000            | 480                 | 150                  | 50            | 1.19                      | 0.06 |
| 15      | 1800            | 720                 | 150                  | 50            | 0.82                      | 0.03 |

Table 4: Pulsed laser welding test data

| SL. No. | Laser power (W) | Scan speed (mm/min) | Pulse frequency (Hz) | Duty cycle (%) | Angular distortion (Deg.) |
|---------|-----------------|---------------------|----------------------|---------------|---------------------------|
| 1       | 1850            | 540                 | 50                   | 35            | 0.83                      |
| 2       | 1950            | 660                 | 100                  | 45            | 0.81                      |
| 3       | 1850            | 660                 | 150                  | 45            | 0.97                      |
| 4       | 1950            | 540                 | 150                  | 35            | 1.05                      |
| 5       | 1850            | 540                 | 50                   | 45            | 0.85                      |
| 6       | 1950            | 660                 | 100                  | 35            | 0.75                      |

3. Modelling of distortions in pulsed laser welding
This section describes the development of mathematical model of distortions in pulsed laser welding of titanium alloy (Ti6Al4V) sheet.

3.1. Regression model development
The RSM used the 25 sets of experimental data obtained following the CCD method of experimental design to establish a second-order polynomial model describing the output welding distortions measured in terms of angular distortion ($\alpha_d$) as a function of the four input variables, i.e, laser power, scan speed, pulse frequency and duty cycle within ranges considered as given in equation (1).

$$\alpha_d = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^k \sum_{j=2}^k \beta_{ij} x_i x_j + \varepsilon,$$  \hspace{1cm} (1)

where $\beta_0$ is the response of the central point, $\beta_i$, $\beta_{ii}$ and $\beta_{ij}$ parameters are the regression coefficients of linear, squared and interaction terms in the polynomial function. These coefficients of the approximating function are estimated by the least square method.
A quadratic model was developed for the output response, angular distortion ($\alpha_d$) in pulsed laser welding as given in equation (2) based on 75 experimental data as mentioned in section 2.2 using the response surface methodology (RSM).

$$\alpha_d = -51.7 + 0.054p + 0.01293v + 0.00288f - 0.1946c - 0.000013p^2 - 0.000002v^2 + 0.002193c^2 - 0.0000006pv - 0.000003pf + 0.000017pc - 0.000007vf + 0.000012vc - 0.000124fc$$  (2)

The R$^2$-value of the fitted regression model was found 0.643 which indicated the fair correlation between experimental values and predicted values of angular distortion from the developed RSM model. Analysis of variance (ANOVA) method was also employed to investigate the significance of the different terms in the RSM model developed with consideration of 95% confidence level as given in table 5. The terms used in table 5, DF, Adj SS and Adj MS represent the degrees of freedom, adjusted sum of square and adjusted mean square, respectively [11]. In this regard, some of the terms are observed to be insignificant, however these terms were not eliminated from the model because the lack of fit was also seen to be significant.

Validity of the developed RSM model was further tested through residual plots of the response angular distortions as shown in figure 4. The residuals were observed to be located along the straight line in normal probability plot as represented in figure 4. Furthermore, approximately normal distribution was observed in the Histogram plot of the residuals.

Table 5: Results of ANOVA for angular distortion in pulsed laser welding

| Source      | DF | Adj SS   | Adj MS   | F    | P    |
|-------------|----|----------|----------|------|------|
| Model       | 14 | 2.12023  | 0.151445 | 7.73 | 0.000|
| Linear      | 4  | 0.62453  | 0.156132 | 7.97 | 0.000|
| Square      | 4  | 0.97594  | 0.243985 | 12.46| 0.000|
| Interaction | 6  | 0.51976  | 0.086627 | 4.42 | 0.001|
| Error       | 60 | 1.17511  | 0.019585 |      |      |
| Lack-of-Fit | 10 | 1.14791  | 0.114791 | 211.01| 0.000|
| Pure Error  | 50 | 0.02720  | 0.000544 |      |      |
| Total       | 74 | 3.29534  |          |      |      |

Fig. 4: Residual plots for the response angular distortion in pulsed laser welding.
The ANOVA results and the residuals plots showed the adequacy of the RSM model for the response angular distortion in pulsed laser welding. Therefore, this model could be used for further prediction of angular distortion. Prediction accuracy of the developed regression model was verified by six test data, and the average absolute deviation in prediction for the test cases was found as 13.8%.

3.2. Parametric study and optimization

The main effects of different parameters and their interaction are expressed through the three dimensional response surface pots as shown in figure 5 and 6, respectively. The input factors namely laser power, frequency and duty cycle were found to have significant effects on the angular distortions and their percentage contributions are 6, 4 and 7, respectively as shown in Fig. 5.

Angular distortion was increased with the increase of laser power due to more thermal energy input which leads to larger fusion zone and higher residual stresses after cooling. The scan speed was not found to have significant effect on angular distortion within the operating window considered for the present investigation. Distortion was found to have minimum value for optimal values of pulse frequency and duty cycle as shown in the three dimensional surface plots in figure 6.

The pulsed laser welding process has been optimized using the method of desirability function analysis which makes use of a transformation of the response variable to a unit less desirability value
lying between 0 and 1 [13]. The desirability values for the response at its goal or target, and outside the acceptable region are 1 and 0, respectively. Desirability of the response increases, when the value of the response approaches towards the target and the vice-versa. Angular distortion was optimized using desirability function method in pulsed laser welding. Minimization of the distortion was performed based on the response surface models of the out of plane distortion in pulsed laser welding as developed in section 3.1. The optimized values of angular distortion and the corresponding values of the input parameters are shown in figure 7.

Figure 7: Response optimization of angular distortion in pulsed laser welding.

The minimum value of angular distortion was obtained as 0.21° and the corresponding optimal set of input parameters were obtained as laser power of 1800 W, scan speed of 480 mm/min, laser pulse frequency of 82 Hz and duty cycle of 38%. Experiment was carried out to validate the optimal result of angular distortions by taking the optimal input parameters obtained from the optimization results by considering the nearest values of the inputs i.e., laser power, scan speed, frequency and duty cycle of 1800 W, 480 mm/min, 100 Hz and 40%, respectively, depending on the availability of the parameters in the laser system. The experimental value of angular distortion was found as 0.32° close to the theoretical value. Therefore proper selection of process parameters in pulsed laser welding could obtain the minimum angular distortion and improved accuracy in the welded parts.

4. Conclusion

Experimental investigations on pulsed laser welding of Ti6Al4V sheet using fiber laser were carried out and response surface methodology based analyses were performed to determine the optimal processing parameters to minimize angular distortion.

- A regression model of angular distortion in pulsed laser welding was built which had been able to predict the distortions with good accuracy. In fact, observing the residual plots and correlation coefficient, it proved the claim.
- Furthermore, the developed model was validated by experimental test data and it showed the reliability of the developed model.
- The minimum amount of deformation was observed for the lower values of laser power and scan speed. However, pulse frequency and duty cycle were observed to have optimal values for generating minimum angular distortion.
- Therefore, it was revealed that the deformation in pulsed laser welding could be controlled by suitable temporal and spatial form of laser irradiations.
Acknowledgments
The author gratefully acknowledges the financial support of the Department of Science and Technology (DST), Science and Engineering Research Board (SERB), India for funding this research work under Early Career Research (ECR) award with project File No.-ECR/2016/001134.

References

[1] Moraitis G A and Labeas G N 2009 Int. J. of Pressure Vessels and Piping 86 133
[2] Gao X L, Zhang L J, Liu J and Zhang J X 2013 Mat. Sc. & Enng. A 559 14
[3] Bhargava P, Paul C P, Mundra G, Prem Singh C H, Mishra S K, D. Nagpure, Kumar A and Kukreja L M Opt. & Las. in Engg. 53 152
[4] Fahlstrom K, Andersson O, Todal U and Melander A 2015 J. of Las. App. 27 S29011-1
[5] Casalino G, Mortello M and Campanelli S L 2015 J. of Manf. Proc. 20 250
[6] Junaid M, Baig M N, Shamir M, Khan F N, Rehman K and Haider J 2017 J. of Mat. Proc. Tech. 242 24
[7] Gao X L, Zhang L J and Zhang J X 2014 J. of Mat. Proc. Tech. 214 1316
[8] Hong K M and Shin Y C 2016 J. of Mat. Proc. Tech. 237 420
[9] Derakhshan E D, Yazdian N, Craft B, Smith S and Kovacevic R 2018 Opt. & Las. Tech. 104 170
[10] Zhou Q, Wang Y, Choi S K, Cao L and Gao Z 2018 App. Therm. Engg. 129 893
[11] Montgomery D C 2001 New York: Wiley
[12] Minitab Inc., Minitab 17, 2016 Statistical Software: http://www.minitab.com.