Scientific
Research

Optimization of Bead Geometry in CO₂ Laser Welding of Ti 6Al 4V Using Response Surface Methodology

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Abstract

In the presented study, the laser butt-welding of Ti 6Al 4V is investigated using 2.2 kw CO₂ laser. Ti 6Al 4V alloy has widespread application in various fields of industries including the medical, nuclear and aerospace. In this study, Response Surface Methodology (RSM) is employed to establish the design of experiments and to optimize the bead geometry. The relationships between the input laser-welding parameters (*i.e.* laser power, welding speed and focal point position) and the process responses (*i.e.* welded zone width, heat affected zone width, welded zone area, heat affected zone area and penetration depth) are investigated. The multi-response optimizations are used to optimize the welding process. The optimum welding conditions are identified in order to increase the productivity and minimize the total operating cost. The validation results demonstrate that the developed models are accurate with low percentages of error (less than 12.5%).

1. Introduction

The laser beam focuses on a small area and creates high-power density to the material surface, thus its beam can be used as a welding process [1].

Since 1940S, titanium and its alloys have been one of the most important engineering materials which have been widely used in industries because of their specific physical, chemical and mechanical properties. High strength to weight ratio, good corrosion resistance and suitable adaptability to human body lead to its application in medical, chemistry and aerospace industries. Among titanium alloys, Ti 6Al 4v with $\alpha + \beta$ phase is widely used [2].

To decrease cost and time, it is comfortable to predict laser welding parameters based on process modeling. There are various methods for predicting and optimizing of the welding parameters. Recently, design of experiment (DOE) has been used for many applications in different areas. Responses surface method (RSM) is the best known type of DOE design; the concept of RSM was introduced in the early 1950's by Box and Wilson [3].

Boumerzoug *et al.* studied the effect of arc welding on microstructures and mechanical properties of industrial low carbon steel. The results indicate that microstructures are different in various zones. Also maximum hardness value is situated in weld metal and heat affected zone areas [4].

Dissimilar Welding of Superduplex Stainless Steel/ HSLA Steel were investigated by Mendoza *et al.* The dissimilar joint has acceptable properties which are superior to the HSLA and lower than the SDSS [5].

Olabi *et al.* applied RSM to investigate the effect of laser welding parameters on residual stress distribution over the depth, at three locations from the weld centre line of AISI304 butt joints [6].

Casalino *et al.* investigated butt welding of Ti 6Al 4V alloy by using continuous CO₂ laser [7]. Olabi *et al.* used an ANN and Taguchi algorithms integrated approach to the optimization of CO₂ laser welding of medium carbon steel [8].

For butt welding of 3 mm thick Ti 6Al 4v alloy sheets, Akman *et al.* used a Nd:YAG laser with 0.3 - 50 ms pulse time and 500 Hz maximum repetition rate. Pulse energy and pulse duration were considered as variables and other parameters (repetition rate, welding speed,

focal point position and gas pressure) assumed constant. Tensile strength, microhardness and weld geometrical dimension were considered as process responses [9].

Li *et al.* used a 6 KW CO_2 laser for welding of titanium. Helium and Argon gases were used to prevent oxidation [10]. Anava *et al.* in their investigation used a CO_2 continuous laser welding for joining a dissimilar AISI 316 stainless-steel and AISI 1009 low carbon steel plates. Taguchi approach was used as statistical design of experiment technique for optimization of welding parameters (laser power, welding speed and defocusing distance) with the objective of producing welded joint with complete penetration, minimum fusion zone size and acceptable welding profile [11].

In the present study, firstly RSM is employed for development of mathematical models. Second aim is to find the optimal welding combination that would maximize the penetration depth while minimizing other bead geometry (welded zone width, heat affected zone width, welded zone area and heat affected zone area). The laser-welding parameters used in this study were parameters that can be controlled on the welding machine.

2. Response Surface Methodology

Response Surface Methodology is one of the optimization techniques in describing the performance of the welding process and finding the optimum setting of parameters. RSM is a mathematical-statistical method that used for modeling and predicting the response of interest affected by some input variables to optimize the response [12].

RSM also specifies the relationships among one or more measured responses and the essential controllable input factors [13].

When all independent variables are measurable, controllable and continuous in the process, with negligible error, the response surface model is as follow:

$$y = f\left(x_1, x_2, \cdots x_n\right) \quad (1)$$

where "n" is the number of independent variables.

To optimize the response "y", it is necessary to find an appropriate approximation for the true functional relationship between the independent variables and the response surface. Usually a second-order polynomial Equation (2) is used in RSM.

$$y = b_0 + \sum b_i x_i + \sum b_{ii} x_{ii}^2 + \sum b_{ij} x_i x_j + \varepsilon_0 \quad (2)$$

3. Experimental Design

A central composite design including five levels of factors was employed. Linear and second order polynomials were fitted to the experimental data to obtain the regression equations. The lack of fit test, variance test and other adequacy measures were used in selecting optimum models. Laser power, welding speed and focal point position considered as independent input variables. **Table 1** shows laser input variables and experiment levels.

4. Experimental Work

Titanium alloy Ti 6Al 4V with chemical composition presented in **Table 2** was used as work piece material. The size of each sample was 85 mm long × 35 mm width with thickness of 1.7 mm.

To determine the working levels of each variable, several preliminary experiments were conducted. Absence of visible welding defects and at least half depth penetration were the criteria of choosing the working ranges. To avoid any systematic error, experiments were conducted in random order using an Optimo model CO_2 laser machine, provided by OPTIMA Industries. Argon gas with constant pressure of 0.1 bar was used as shielding gas. For metallography of specimens, each transverse section of specimen was mounted. Etch solvent with the chemical composition of 2 ml HF + 10 ml HNO_3 + 88 ml deionized H_2O was employed.

Welding geometrical parameters were measured using optical microscope and image Analyzer software. The designed experiments are shown in **Table 3**. **Figure 1** presents the bead shape and size of the selected sample.

5. Result and Discussion

5.1. Development of Mathematical Models

The geometry of weld bead was measured in accordance with parameter setting in **Table 3**. Statistical analysis

Table 1. Laser input variable and experimental levels.

Level (coded)	Laser Power (P) [W]	Welding Speed (S) [cm/min]	Focal Point Position (F) [mm]
−1.68	1200	80	−1
−1	1400	145	−0.8
0	1700	240	−0.5
1	2000	335	−0.2
1.68	2200	400	0

Table 2. Chemical composition of alloy Ti 6Al 4V.

Elements	Titanium	Aluminum	Vanadium
Weight Percentage (Wt%)	balance	6%	3.98%

Table 3. Design matrix with code independent process variables.

Std Order	Run Order	Laser Power [w]	Welding Speed [cm/min]	Focal Point Position [mm]
9	1	–1.68	0	0
5	2	–1	-1	1
13	3	0	0	–1.68
2	4	1	1	–1
3	5	–1	1	–1
7	6	–1	1	1
20	7	0	0	0
17	8	0	0	0
19	9	0	0	0
6	10	1	–1	1
8	11	1	1	1
10	12	1.68	0	0
1	13	–1	–1	–1
12	14	0	1.68	0
14	15	0	0	1.68
18	16	0	0	0
11	17	0	–1.68	0
16	18	0	0	0
2	19	1	–1	–1
15	20	0	0	0

indicates that welding speed and laser power are effective and focal point position has no influence on the developed models.

Considering welded zone width, statistical analysis shows that welding speed, laser power, the second order effect of welding speed and second order effect of laser power are the significant model terms. In HAZ width model, welding speed, laser power, second order effect of welding speed, second order effect of laser power and the interaction of welding speed and laser power are the most important terms in the model.

Welding speed, laser power and second order effect of welding speed are significant in welding zone area and HAZ area models.

The final developed models in terms of significant coded factors are shown below:

$$w_{fz} = 1383.96 + 110.120P - 373.823S \\ - 23.5005P^2 + 170.6S^2 \tag{3}$$
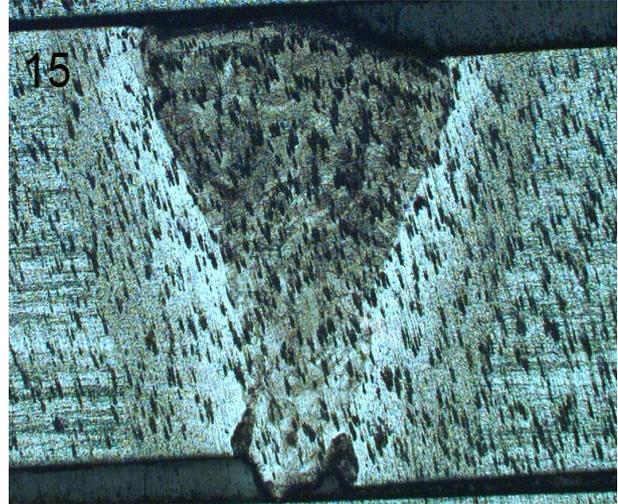
$P = 1.65$ mm; $W_{fz} = 1.357$ mm; $W_{haz} = 2.190$ mm; $A_{fz} = 1.5909$ mm^2; $A_{haz} = 1.6757$ mm^2
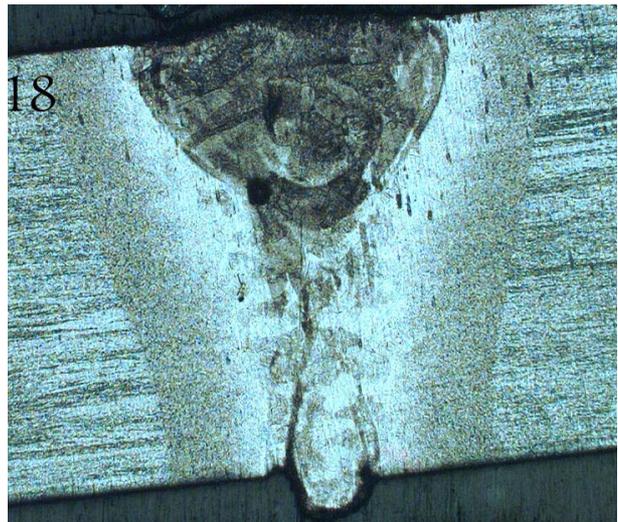
$P = 1.7$ mm; $W_{fz} = 1.319$ mm; $W_{haz} = 2.087$ mm; $A_{fz} = 1.2508$ mm^2; $A_{haz} = 1.8655$ mm^2

Figure 1. Shows the bead shape, width and penetration depth of the selected sample.

$$W_{haz} = 2159.85 + 177.406P - 626.881S - 50.6832P^2 \\ + 181.602S^2 - 31.8750S*P \tag{4}$$

$$A_{fz} = 1220976 + 2694446P - 851166S + 328657S^2 \tag{5}$$

$$A_{haz} = 1684043 + 212449P - 734612S + 170194S^2 \tag{6}$$

5.2. Optimization

Simultaneous optimization of multiple responses involves first building appropriate response surface model for each response and then trying to find a set of operating conditions that in some sense optimizes all response

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or at least keeps them in desired ranges.

In this study, process optimization was carried out by RSM method considering simultaneously five responses (welded zone width, heat affected zone width, welded zone area, heat affected zone area and penetration depth).

The criterion for perfect welding was chosen when penetration depth was 1727 μm Based on experimental results. Welded zone width, heat affected zone width, heat affected zone area and welded zone area were set equal 1380 μm, 2060 μm, 167×10^4 μm^2 and 1158×10^3 μm^2, respectively, as can be seen in **Table 4**. Process optimization carried out to reach to the above targets. Optimum parameter setting considering five simultaneous responses is shown in **Table 5**.

5.3. Validation of the Developed Models

To validate the developed models, confirmation experiments were carried out with optimum parameters setting. **Table 6** summarizes the results of optimization, the actual experimental values and the percentages of error. The validation results demonstrated that the developed models are accurate as the percentages of errors are less than 12.5%. Cross section of bead at optimum setting is shown in **Figure 2**.

6. Conclusions

From the study the following points can be concluded:

1) RSM is an accurate technique to optimize the laser welding process in order to obtain the best bead geometry.

2) A laser power of 1837.4 W, welding speed of

Table 4. Set up of software method based on five responses.

Parameter	Lower	Target	Upper
Penetration Depth (μm)	1720	1727	1730
Welded Zone Width (μm)	1063	1380	1600
Heat Affected Zone Width (μm)	1528	2060	2500
Heat Affected Zone Area (μm^2)	831,058	1,670,000	1,800,000
Welded Zone Area (μm^2)	431,517	1,158,000	1,800,000

Table 5. Optimum parameter setting considering five simultaneous responses.

Variations	Set up Value (Coded)	Set up Value (Uncoded)
Laser Power [w]	0.458971	1837.4
Welding Speed [cm/min]	0.155326	254.25
Focal Point Position [mm]	–0.647255	–0.6941

Table 6. Validation test results.

Parameter	Optimization Results	Actual Experimental Values	Percentages of Error
Penetration Depth (μm)	1727	1836	5.93%
Welded Zone Width (μm)	1375	1489	7.65%
Heat Affected Zone Width (μm)	2135	2425	11.95%
Heat Affected Zone Area (μm^2)	1,671,489	1,912,194	12.58%
Welded Zone Area (μm^2)	1,157,542	1,322,908	12.50%
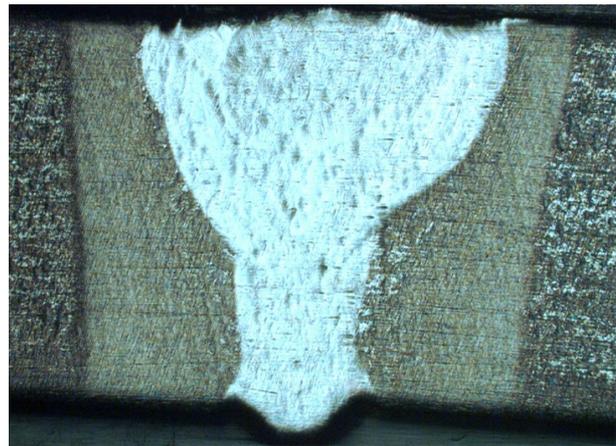
Figure 2. Cross section of bead at optimum setting.

254.25 cm/min and focal point position of 0.6941 mm are optimum parameters for obtaining the best bead geometry produced from Titanium alloy (Ti 6Al 4V).

3) The welding speed has a negative effect on all responses. However, the laser power has appositive effect on them. The focal point position has no effect on bead geometry of titanium alloy Ti 6Al 4V welding.

4) Superior, efficient and economical welds could be achieved using the welding conditions drawn from the statistical optimization.

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