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Process parameter optimization for wobbling laser spot welding of Ti_6Al_4V alloy

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Abstract

Laser beam welding (LBW) coupled with "wobble effect" (fast oscillation of the laser beam) is very promising for high precision micro-joining industry. For this process, similarly to the conventional LBW, the laser welding process parameters play a very significant role in determining the quality of a weld joint. Consequently, four process parameters (laser power, wobble frequency, number of rotations within a single laser pulse and focused position) and 5 responses (penetration, width, heat affected zone (HAZ), area of the fusion zone, area of HAZ and hardness) were investigated for spot welding of Ti_6Al_4V alloy (grade 5) using a design of experiments (DoE) approach.

This paper presents experimental results showing the effects of variating the considered most important process parameters on the spot weld quality of Ti_6Al_4V alloy. Semi-empirical mathematical models were developed to correlate laser welding parameters to each of the measured weld responses. Adequacies of the models were then examined by various methods such as ANOVA. These models not only allows a better understanding of the wobble laser welding process and predict the process performance but also determines optimal process parameters. Therefore, optimal combination of process parameters was determined considering certain quality criteria set.

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Keywords: Wobble laser welding; wobbling, beam oscillation; Ti_6Al_4V; titanium alloy; design of experiment; process optimization

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1. Introduction

Excellent mechanical properties of commercially pure titanium and titanium alloys, such as Ti_6Al_4V (grade 5), open a wide range of applications and interest toward this category of nonferrous metal (Mazumder and Steen 1982, Yang et al. 2010, Fan et al. 2015, Tomashchuk et al. 2015). Although titanium is still more expensive than ferrous metals, it has been used in the marine, aerospace, military, electronics, and chemical processing industries as well as some premium sports equipment and consumer electronics (Mazumder and Steen 1982, Akman et al. 2009, Akbari et al. 2014, Casalino et al. 2015). The reason is in its superior strength-to-weight ratio, fatigue and crack resistance, corrosion resistance, high melting point, and ability to withstand extreme temperatures without creeping (Mazumder and Steen 1982, Akman et al. 2009, Akbari et al. 2014, Casalino et al. 2015).

On the other hand, high precision, noncontact processing, low heat input, and small heat affected zone (HAZ) introduce Laser Beam Welding (LBW) as one of the major manufacturing process in joining industry. Hence, understanding the laser-material interaction of specific materials is of high importance to control and/or optimize a given manufacturing process. This is particularly true for titanium as it is very sensitive to the environment and contaminations. Accordingly, the influence of process parameters on the weld quality of titanium has been investigated in several studies. Casalino et al. (2005) investigated the effects of the welding parameters on the shape and hardness of the welded Ti_6Al_4V sheets using CO_2 and diode laser. A statistical study has been performed by Blackburn et al. (2010) to determine the optimum position and flow rate of the inert gas jet, with respect to reducing the weld metal porosity and optimizing the weld profile for Nd:YAG laser welding on Ti_6Al_4V plate. Lee et al. (2006) have used the Taguchi method and regression analysis to optimize Nd:YAG laser welding parameters to seal a titanium capsule.

However, recent advancement in the fiber laser industry allows developing more robust, compact and efficient systems with higher beam quality. These systems can readily perform laser welding at a relatively higher energy density to reach keyhole mode and produce deep penetration and/or a larger melting volume with lower heat input (as compared to the conventional LBW or inert gas arc welding). Keyhole laser welding is known to be a big challenge in terms of quality especially in the joining industry (Berger and Hügel 2013, Casalino et al. 2015).

In this study, a robust fiber laser source has been coupled with a highly flexible prototype processing laser processing head to profit of both the keyhole welding mode and wobbling strategy (fast oscillation of laser beam). A multi-level full factorial design of experiment (DoE) was used as an efficient method to statistically investigate the effects of wobble laser welding parameters on the spot weld quality such as its geometry and microhardness. Consequently, semi-empirical mathematical models were developed and employed to determine the optimal combination of the welding parameters according to a given set of quality criteria. In this contribution, the objectives were to maximize molten volume (or fusion area) and wobbling speed (wobbling frequency), while minimizing the laser power. These are very typical requirements of many industries (e.g. automotive industry) to minimize the cost and increase the production rate.

2. Experimental procedure

2.1. Experimental set-up

A single-mode fiber laser source StarFiber 150 P [1] with a 1070 nm wavelength was used in this study. The laser beam was transmitted through a single-mode optical fiber with a 12 µm core diameter and focused on the specimen surface by a lens with a 150 mm focal length. This provides a spot size of about 30 µm diameter at the focal point. A laser processing head has been developed integrating a collimation unit, a 2D-scanner and a beam splitter and focusing optics. The scanner unit is composed of two lightweight mirrors which are rotated by Galvano motors. This permits to steer the laser beam (up to 2.8 kHz) through the predesignated trajectory over the workpiece. In addition, to prevent the potential weld contamination such as oxidation, the experiments were carried out in a controlled

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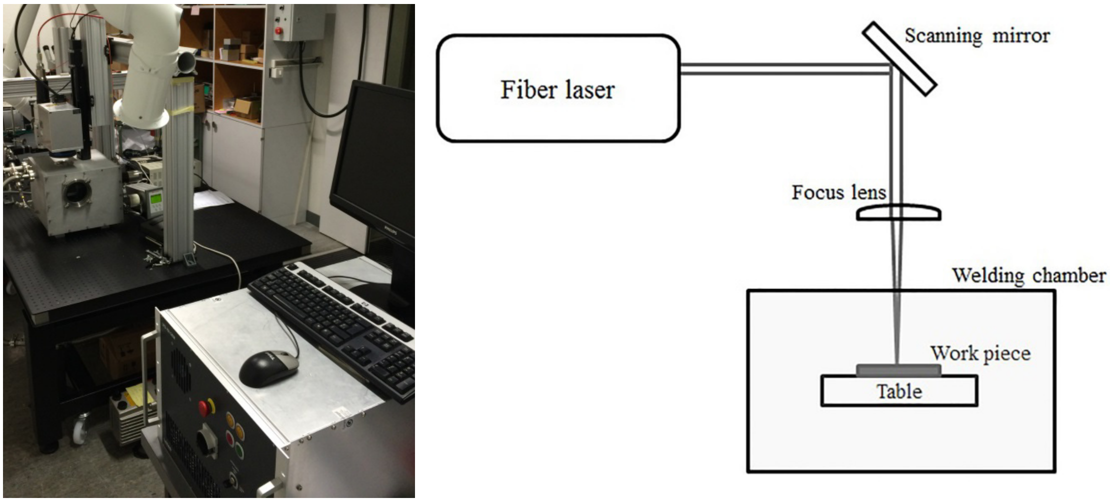
[1] Fiber Laser - StarFiber 150 P / 300 P - Long Pulse Fiber Laser Systems

environment (i.e. a welding chamber filled with inert gas). Fig. 1 displays a photograph as well as schematic view of the experimental set-up used in the present study.



(a) (b)

Fig. 1. Experimental set-up; (a) photograph, (b) schematic view:

2.2. Process parameters and output responses

In this study, a Gaussian beam has been used to facilitate the keyhole formation. Moreover, wobbling the laser beam with an appropriate frequency (beam velocity) allows managing the heat conduction and convection in the weld zone to control the weld microstructure and quality. This is important depending on the device application. For conventional stationary laser beam welding (LBW), many factors may influence the quality of the laser welding process. For wobbling LBW, new parameters have to be taken into account due to the oscillation of the beam. In this work, four process parameters were considered as the most important. Consequently, the Laser Power (LP), Wobbling Frequencies in the two perpendicular axes (WF_1 and WF_2), Number of Rotations during a single laser pulse (NR) and Focused Position with regard to the beam focal point (FP) were considered as main factors to investigate their influences on the weld quality responses such as bead geometry features and hardness. The working range of each factor was defined based on the results of the 20 preliminary tests with respect to the energy limits considering the corresponding process map of Ti_6Al_4V. The factors, their pertinent levels and considered responses are listed in Table 1.

Table 1. Summary of investigated process parameters and the measured responses.

Process factors	Symbols	Levels of each factors		
		1	2	3
Laser power [W]	LP	150	-	250
Wobbling frequency of axis 1 and 2 [Hz]	$WF_1=WF_2$	250	500	1000
Number of rotation [-]	NR	1	-	3
Focused position [mm]	FP	0	-	0.75

Response factors	Measured features
Weld bead geometry	Penetration depth (PD), width (W), heat affected zone (HAZ), area of fusion zone (A_{FZ}), heat affected zone (A_{HAZ})
Mechanical property	Vickers microhardness ($HV_{0.2}$)

The tangential velocity (wobbling speed) of the beam oscillation is a key factor which is correlated to the wobbling frequencies in the two axes. To avoid any deviation due to the gradient of wobbling velocity, this term has to be uniform to correctly determine its relevant effect for every individual trial. Thus an identical wobbling frequency extent for the both axes ($WF_1=WF_2$).

2.3. Design of experiments

A multi-level full factorial design was selected as a statistical design of experiment (DoE) technique to develop the semi-empirical mathematical models correlating the process parameters to each measured responses. This statistical method provides a wider view and could bring some light to the understanding of the output results in any experimental test design (Hinkelmann and Kempthorne 2007). In this scheme, each factor is described by coded (standardized) value ranging from -1 to 1. Moreover, the semi-empirical mathematical models were inferred based on the measured responses including the linear and multiple interaction effects of the process parameters. The response function is generally written as:

$$\begin{aligned} Y = {} & a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_{12}X_1X_2 + a_{13}X_1X_3 + a_{14}X_1X_4 \\ & + a_{23}X_2X_3 + a_{24}X_2X_4 + a_{34}X_3X_4 + a_{123}X_1X_2X_3 + a_{124}X_1X_2X_4 \\ & + a_{134}X_1X_3X_4 + a_{234}X_2X_3X_4 + a_{1234}X_1X_2X_3X_4 \end{aligned} \tag{1}$$

where X_1 to X_4 are respectively the standardized laser power (LP), wobbling frequency (WF), number of rotations (NR), and focused position (FP) (all ranging from -1 to 1); a_i are the constants depending on the process parameters and their interactions. Y stands for the selected experimental responses; either the weld geometry features (penetration depth, width, HAZ, area of FZ, area of HAZ) or the mechanical property (microhardness). In addition, the corresponding model matrix was examined before running the welding trials to avoid any potential collinearity, correlation, inflation, and aliases in the correlated coefficients (goodness of the design). According to the factors and their pertinent levels listed in Table 1, 24 experiments were ordered randomly and carried out to consider the influence of the factors over the prescribed design space.

The significance of the terms was evaluated using an analysis of variance (ANOVA) with a 95% confidence interval. In this case, the terms with the p-values less than 0.05, and *F*-values greater than 3 are considered as significant terms (Montgomery 2006). Accordingly, the *F*-value, *p*-value, *R*-squared, adjusted *R*-squared, predicted *R*-squared and the adequate precision were evaluated in a sequential inspection scheme to measure either the significant model terms or the model's adequacy. In other words, all the terms were considered first as presented in Eq. (1). However, insignificant terms (based on the adequacy measure) were excluded from the model, starting with the term at highest level of interactions, and then the ANOVA was recomputed. This procedure was followed to eliminate all the not significant terms from the model (reduced model) considering the adjusted *p*-values and other adequacy measures mentioned above. Finally, these reduced semi-empirical mathematical models were used to determine the optimal combination of process parameters to meet a given set of quality criteria.

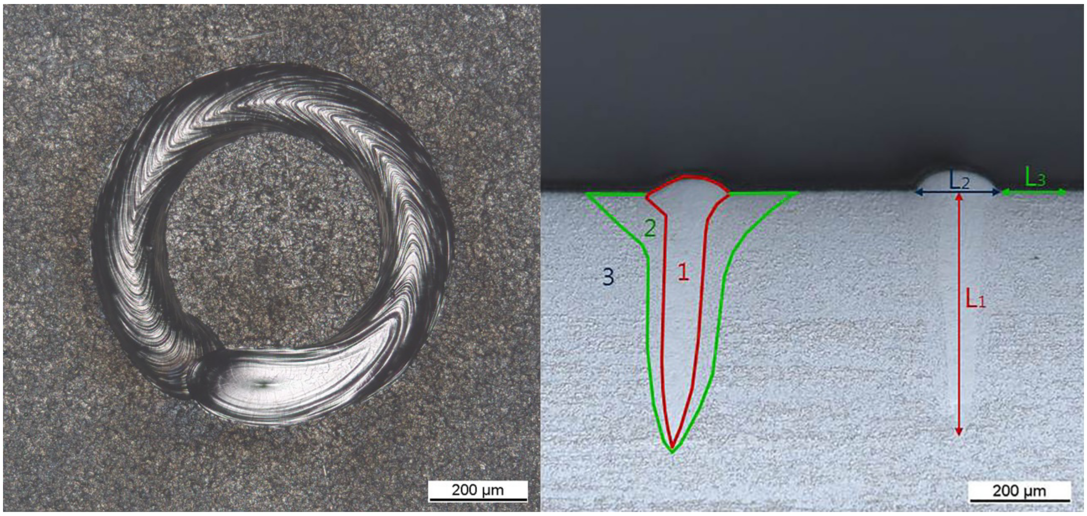
The commercial statistical software Design-Expert® V10 was used to create the design matrix and analyze the experimental data. However, all computations and analyses were verified with self-made MATLAB code.

3. Results

3.1. Sample analysis

Generally, the quality of the bead on plate welds is assessed from observations of the top surface and cross-sectional views, as well as microhardness measurements. Fig. 2 shows a typical example of the present spot weld appearances as well as the quantifiable of the weld bead geometry features such as the weld penetration (L_1), width (L_2), HAZ (L_3), area of FZ (1) and HAZ (2); noting area of the HAZ does not include the FZ. The aesthetic weld quality such as spattering, coloration, and ripple are not considered in this contribution.

To minimize the uncertainty of the measurements, each weld was cut and measured at several positions (shown in Fig. 2 a). Finally, those values were averaged to determine the corresponding responses. In addition, microhardness Vickers HV0.2 tests were performed at the half-penetration (to avoid any extremity and side effects at either the surface or the tip) to evaluate the weld mechanical property.



(a) (b)

Fig. 2. Representative picture of a spot weld, (a) top surface view, (b) cross-sectional view; penetration (L1), width (L2), HAZ (L3), area of the FZ (1), area of the HAZ (2), and base material (3).

3.2. Mathematical model and analysis of variance (ANOVA)

In this section, due to space constraint, the procedure and analysis of variance is only presented for the weld penetration depth response. For the other responses, only the optimized/ reduced models are presented in Table 5. As already mentioned, a multilevel factorial design with 24 tests has been performed to investigate the effects of laser power, wobbling frequency, number of rotation, and focused position on the bead on plate spot weld quality within the selected design space (see Table 1). The step-wise procedure (see Section 2.2) was also applied to eliminate the not significant model terms considering the *p*-values, adjusted and predicted *R*-squared values. The detailed ANOVA representing the significant terms for the weld penetration depth is summarized in Table 2.

Table 2. Analysis of variance including the significant terms for the weld penetration depth.

Source	**SS**[a]	**df**[b]	**MS**[c]	***F*-value**	***p*-value**	
Model	4.35E+005	5	87163.19	44.14	< 0.0001	significant
LP	96709.85	1	96709.85	48.97	< 0.0001	
WF	2.72E+005	1	2.72E+005	137.80	< 0.0001	
NR	25252.59	1	25252.59	12.79	0.0022	
FP	22015.98	1	22015.98	11.15	0.0037	
LP-WF	9690.24	1	9690.24	4.91	0.0399	
Residual	35545.02	18	1974.72			
Total	4.71E+005	23				
$R^2 = 0.9246$	Adj. $R^2 = 0.9036$		Pred. $R^2 = 0.8748$		Adeq. Precision = 22.94	

[a] Sum of square

[b] Degree of freedom

[c] Mean square

Table 3. Summary of model coefficients (half-effect) and the relevant uncertainty for the weld penetration.

Factor	**Coefficients (or HE)**	**RHE [%]**	**df**	**SE**	**95% CI Low**	**95% CI High**	**VIF**[a]
a_0	248.77	-	1	9.15	229.55	267.99	
a_1	64.03	25.7	1	9.15	44.81	83.26	1.02
a_2	-128.11	-15.5	1	10.91	-151.03	-105.18	1.00
a_3	32.44	13.0	1	9.07	13.38	51.49	1.00
a_4	30.29	12.2	1	9.07	11.23	49.34	1.00
a_{12}	-24.17	9.7	1	10.91	-47.10	-1.25	1.02

[a] Variance inflation factor

As shown in Table 2, the proposed model for the weld penetration depth is reduced to the main factors and only the LP-WF (as a two-factor interaction, 2FI) term. The reduced model has an *F*-value and adequate precision of approximately 44 (much greater than 3) and 23, respectively, which implies that the model is significant. This is confirmed by the adjusted and predicted *R*-squared values that are high (> 0.87). Such high adequacy values indicated that even though it is a semi-empirical mathematical model, taking into account the physical phenomena would complicate significantly the model for only a slightly improvement of the model. The model coefficients (i.e. the half-effects, HE) as well as the relative half-effect (RHE) for the penetration depth prediction with their corresponding standard errors (SE) and the coefficient interval (CI) for 95% confident level are summarized in Table 3.

The final semi-empirical mathematical model to predict the weld penetration depth of the bead on plate spot weld of Ti_6Al_4V in terms of the effective process parameters is expressed as:

$$\mathrm{PD} = 248.77 + 64.03\,\mathrm{LP} - 128.11\,\mathrm{WF} + 32.44\,\mathrm{NR} + 30.29\,\mathrm{FP} - 24.17\,\mathrm{LP}\times\mathrm{WF} \tag{2}$$

Afterwards, several validation tests have been carried out to verify the model. These welding trials comprise both replicated and new experiments within the investigated domain space and they are given in Table 4. This allows not only validating the model but also evaluating its reproducibility.

Table 4. Summary of the standardized matrix of experiments for the model validation.

Run	**X_1 (LP)**	**X_2 (WF)**	**X_3 (NR)**	**X_4 (FP)**
		Replicated tests		
1	1	1	-1	-1
2	-1	-0.33	-1	-1
3	-1	-0.33	1	1
4	1	-0.33	-1	-1
		New tests		
5	0	-0.33	-1	-1
6	0	-1	-1	-1
7	0	1	-1	-1
8	0	1	-1	-1
9	0	-0.33	0	-1
10	0	-0.33	1	-1

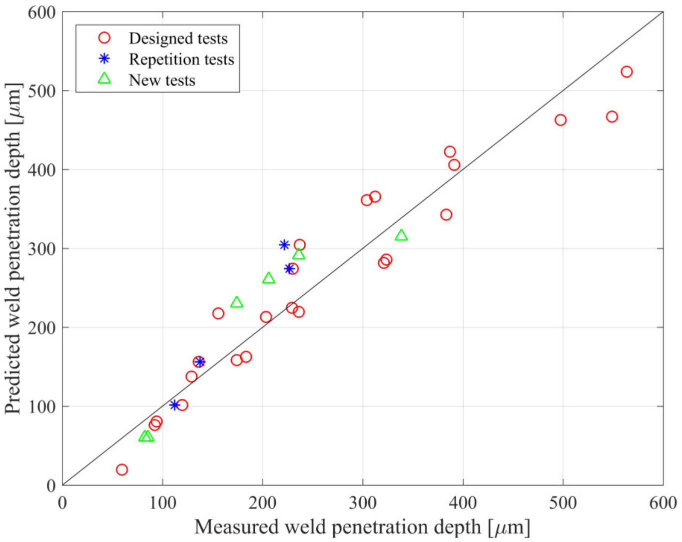


Fig. 3. Comparison between the measured weld penetration depth and prediction; designed experiments (circle), repetition experiments (asterisk), new experiments (triangle).

Fig. 3 presents the experimentally measured weld penetration depth versus predicted ones from Eq. (2). A high correlation coefficient of 0.95 is observed. Also, as seen in this figure, the repetition tests (asterisk) and new experiments (triangle) which were not used for developing the model are located close to the predicted line. This is a good validation of the developed model, and confirms the model is significant. Consequently, the validated model can be used to optimize the process parameters.

Identical analyses have been performed for the other responses. However for the sake of brevity, only the reduced model coefficients (half-effects) are presented in Table 5. Accordingly, linear models with reduced two-factor interaction (2FI) were found to be sufficient to correlate well the weld quality with the process parameters based on the adequacy measures.

Based on Table 5, it is seen that, except for the microhardness ($HV_{0.2}$), all semi-empirical models have high adequacy values (> 0.77). This is quite remarkable considering the following four facts. First, it is known that the responses have generally non-negligible variations for a given set of process parameters. Then, the responses are very sensitive to the process parameter. Third, laser processing is known to be a highly non-linear process. Finally, these models are purely based on linear regression and do not take into account the physical phenomena.

3.3. Process parameter optimization

As mentioned in section 3.2, all the models have been validated with both the repetition and the new experiments (see Table 4) within the investigated domain. Therefore, the validated models can be used to optimize the process parameters for a given quality criteria. Reducing the laser power and increasing the welding speed (i.e. wobbling frequency) are the most commonly key targets in joining industries (e.g. automotive industry) to fulfill relatively low-cost, high production rate, and excellent weld joints. In addition, maximizing the volume of fusion zone is evidently lucrative to bridge a larger gap size. Therefore, as an example, we defined a set of quality criteria for process parameter optimization and they are: a weld penetration of 350±35 μm, weld width of 180±10 μm, minimization of the laser power, maximization of the wobbling frequency and fusion zone. Table 6 summarizes the quality criteria, lower and upper limits of the process parameters and the measured responses as well as their relevant importance.

Table 5. Model coefficients for each response surface model reduced to linear and 2FI.

	Model Coefficients (HE)					
Factor	**Penetration**	**Width**	**HAZ**	A_{FZ}	A_{HAZ}	$HV_{0.2}$
a_0	248.8	160.4	59.2	23244	21324	345
a_1	64	19.5	6.1	7129	6506	-[a]
a_2	-128.1	-47.5	-16.9	-14976	-15234	-
a_3	32.4	32.4	13.5	6561	8201	10.4
a_4	30.3	-8.5	-7.2	-	-	-
a_{12}	-24.2	-	-	-4010	-4607	-
a_{13}	-	11.8	2.7	3175	2990	-4.4
a_{14}	-	-	-4.1	-	-	-
a_{23}	-	-12	-4.5	-4189	-5831	-
a_{24}	-	-	3.9	-	-	-
a_{34}	-	-	-3.2	-	-	3.5
R^2	0.925	0.902	0.948	0.899	0.880	0.614
Adj. R^2	0.904	0.867	0.914	0.863	0.837	0.556
Pred. R^2	0.875	0.806	0.844	0.818	0.774	0.444
Adeq. precision	22.9	17.5	20.5	15.9	14.3	8.8

[a] not significant term

Table 6. Defined quality criteria and the best optimal solution.

Factors/Responses	**unit**	**Range**		**Importance**	**Criteria**	**Best solution**
		lower	upper			
Laser power	[w]	150	250	3	Minimize	206
Wobbling frequency	[Hz]	250	1000	3	Maximize	443
Number of rotation	[-]	1	3	-	In the range	2
Focused position	[mm]	-0.75	0	-	In the range	0
Penetration depth	[µm]	315	385	3	350±35	350
Weld width	[µm]	170	190	3	180±10	177
Heat affected zone	[µm]	23	125	-	In the range	59
Area of fusion	[µm^2]	3552	73715	3	Maximize	31561
Area of HAZ	[µm^2]	2683	85635	-	In the range	29728
Microhardness	[kgf/mm^2]	313	384	-	In the range	345

This optimization problem was solved by using the Design-Expert® V10 software based on the quality criteria as listed in Table 6. Fig. 4 visualizes the optimal region as well as the best solution on an overlay plot.

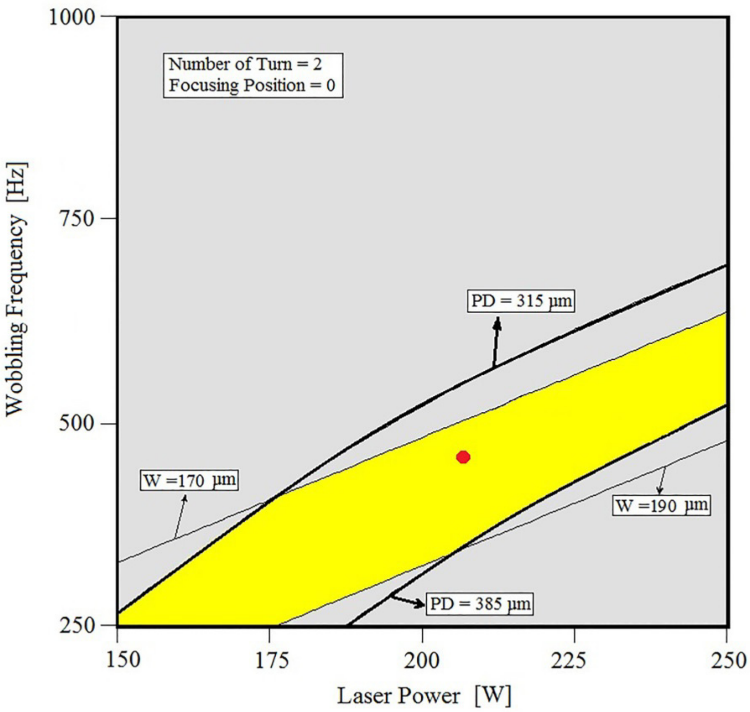


Fig. 4. Overlay plot showing a graphical representation of the optimal region (yellow) and the best solution (red circle).

4. Discussion

In this section, the effects of process parameters on the weld quality and its geometry are discussed to evaluate the weldability of the Ti_6Al_4V alloy.

The half-effect coefficients (listed in Table 5) indicate the significance of each factor (process parameters) with respect to a given response (measured responses) in the design space (Montgomery 2006).

4.1. Effect of laser power

According to the results presented in Table 5, the laser power has a positive effect on all responses; although it is not a significant factor for the microhardness. Hence, all the weld geometry features increase as laser power rises. This is not surprising and this is basically due to the additional heat input brought into the material. Furthermore, a keyhole may form depending on the heat input extent. When the heat input is sufficiently high, the melting material is evaporated forming a vapor capillary which in turn can direct the laser light into the material. Under such circumstances, the energy is absorbed more efficiently as a result of the multiple reflections of the laser emission within the vapor capillary at the depth of the vapor-liquid interface. Accordingly, it primarily results in a deeper weld and a greater fusion volume. As a secondary effect, it broads the weld width, HAZ, and heat affected volume. Interestingly, it is found out that the laser power has a significantly less impact as compared to the wobbling frequency within the prescribed ranges of the process parameters. Similar conclusions were also reported in (Benyounis et al. 2005, Khan et al. 2011, Rathod and Haribhakta 2014) testing either low carbon Steels or Stainless steels.

4.2. Effect of wobbling frequency

With regard to the results of Table 5, it is clear that the wobbling frequency has a negative effect to the all responses, except the microhardness. In other words, by increasing the welding speed, the weld bead is decreased. This can be explained by the fact that an increase in the wobbling frequency leads to a proportional increase in the corresponding beam velocity (i.e. reduction of the effective exposure time for a given area). Obviously this results in a reduction of the heat input leading to a lower thermal penetration. Thus, all measured responses (penetration, width, HAZ, A_{FZ} and A_{HAZ}) decrease with an increase in the wobbling frequency. Based on the present results, the wobbling frequency (or the corresponding wobbling velocity) was found to be the process parameter having the most influence on the weld geometry features.

4.3. Effect of number of rotations

To start with, this parameter is found to be significant and has positive effects for all measured responses. Moreover, it is the only main effect that has a significant influence on the microhardness. Essentially, additional rotations provide not only more heat input to the welded material but also increase thermal penetration. This is mainly due to the consequent preheating resulted from the previous heat cycle (i.e. the former rotation). This results in a higher temperature of the fusion zone, thus a higher cooling rate, which is known to increases the material hardness. In addition, the number of the rotations within a single laser pulse is found out to have a major effect on the weld width, HAZ, A_{FZ}, A_{HAZ} and material microhardness. However, its effect on the weld penetration and fusion volume, although considered as a significant factor, is nevertheless secondary as compared to both the laser power and wobbling frequency (see in Table 5).

4.4. Effect of focused position

Based on the ANOVA in the design space, the focused position is considered to be a significant parameter with respect to the weld penetration depth, width and HAZ. However, its contribution is relatively low as compared to other process parameters. In other words, laser welding of titanium with our set up does not require a high costly rigorous position system as the influence of a small shift in the focused position is determined to be minor. In this study, the focused position was changed within the Rayleigh range, so that the spot size and its corresponding power density were subjected to little changes. However, it is evident that the larger the deviation of the beam focal point, the greater its effect. This conclusion is also supported by the findings reported in (Benyounis et al. 2005, Khan et al. 2011).

4.5. Effect of interactions

In general, the factor interactions can account for the weight and curvature of the responses. Based on the present results, only the 2FI terms remained in the final models as the higher level of interactions were not significant terms with respect to the measured responses. In most of cases, only one or two of the 2FI terms are sufficient to correlate well the responses with the factors (see in Table 5). For instance, only the LP-WF interaction term is adequate to account for the weight and curvature of the response surface model to estimate the weld penetration depth. This indicates the corresponding response has a low curvature over the investigated domain.

5. Conclusions

In the present study, several important process parameters for spot welding of Ti_6Al_4V plate with a wobbling laser beam were analyzed using a design of experiment (DoE) approach. Four factors were considered which are: the laser power, the wobbling frequency (i.e. wobbling speed), the number of rotations within a single pulse, and the focused position. Based on the DoE results and ANOVA analyses, semi-empirical mathematical models were developed and optimized. The main conclusions are as follows:

- Several semi-empirical mathematical models have been developed based on the experimental results of the present study. These mathematical models allow determining the effects of the main parameters and their corresponding interactions on the spot welding quality of Ti_6Al_4V plate. The quality was defined in terms of weld geometry features (penetration, width, HAZ, area of fusion zone (A_{FZ}) and area of HAZ (A_{HAZ}) as well as the weld microhardness. It was demonstrated that linear models with two-factor interaction were adequate to correlate the weld quality to the investigated process parameters.
- It was also understood that the main factors have the dominant effects in most cases and the interactions have surprisingly a limited impact on the spot weld quality within the investigated domain.
- The proposed models can be used not only to predict spot weld quality of the wobbled laser beam but also to optimize the corresponding process parameters with respect to requisite weld quality of any specific applications.
- As expected, the laser power is a significant factor with positive effects affecting on the all measured responses except the weld microhardness.
- The wobbling frequency is found to be the factor having the most influence on the weld geometry features within the design space. However, its effect on the weld microhardness is not significant.
- The number of the rotations within a single laser pulse is found to have a major positive effect on the weld width, HAZ, A_{FZ}, A_{HAZ} and microhardness. However, its effect on the weld penetration is of secondary importance as compared to both the laser power and wobbling frequency.
- The focused position is found to be a significant factor on the weld penetration, width and HAZ. Nevertheless, it has a limited influence as compared to the other parameters within the prescribed design space.

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