Journal of Manufacturing Engineering, March 2019, Vol. 14, Issue. 1, pp 001-005

OPTIMIZATION OF PROCESS PARAMETERS IN ND: YAG LASER WELDING OF HASTELLOY SHEETS THROUGH TAGUCHI METHOD

https://doi.org/10.37255/jme.v4i1pp001-005

***Saravanan S**

Assistant Professor, Department of Mechanical Engineering, Annamalai University, Annamalainagar-608002

ABSTRACT

Optimization of weld width and tensile strength in pulsed Nd: YAG laser welded Hastelloy C-276 sheets, subjected to varied welding speed (350-450 mm/min), pulse energy (10-14 J) and pulse duration (6-8 ms), is attempted. Experimental conditions are designed based on Taguchi L_9 orthogonal array. The parameters for attaining a minimum weld width and maximum tensile strength were determined by computing the Signal-to-Noise ratio. Further, a mathematical model is developed for determining the weld width and tensile strength of the weld, based on the regression analysis using statistical software MINITAB-16 and the level of fit are determined by analysis of variance.

Keywords: *Nd: YAG laser welding, Hastelloy, weld width; optimization and tensile strength.*

1. Introduction

Hastelloy C-276, a nickel based super alloy, is employed in the chemical and nuclear industries due to its superior oxidation resistance and good mechanical properties at elevated temperatures. Welding of complex aeronautical components, made of Hastelloy C-276, demand high reproducibility with a sound metallurgical property [1]. Of the available methods, pulsed laser welding upholds the above demands and replace the other competing welding methodologies, because of the formation of a narrow weld zone, high depth to width ratio, low distortion, rapid cooling and a more refined grain structure occurring during the process. In addition, Pulsed Nd: YAG laser holds a distinct advantage of achieving higher penetration and lower power consumption [2].

As pulsed laser welding is very swift and precise, the microstructure and mechanical properties are dictated by the proper selection of process parameters viz. laser power, pulse energy, pulse frequency, laser power, shielding gas and focal position [3]. Though lower weld width and a higher tensile strength is desirable, they will be affected if the parameters are not selected properly [4]. To aid in the selection of process parameters, which dictates the mechanical properties, different methods viz., design of experiments, numerical simulation, and mathematical modeling were attempted by earlier researchers [5-7]. However, the studies on developing a mathematical model to predict the width of the weld and tensile strength of Hastelloy C-276 weld joints using Taguchi analogy is limited, and is attempted herein. In this study, the influence of process parameters viz. welding speed, pulse duration and pulse energy for attaining minimum weld width and maximum tensile strength is attempted. In addition, a regression equation is developed using analysis of variance (ANOVA) and signal to noise (S/N) ratio to determine the lack of fit of each process parameters in achieving minimum weld width and higher tensile strength.

**Corresponding Author - E- mail: ssvcdm@gmail.com*

2. Determination of Parametric Limits

The identification of the process parameters (factors) which affect the weld width and tensile strength (responses) is a significant step in the design of experiments. Taguchi experimental design, an orthogonal array with three factors and three levels (L_9) was selected, and experiments were conducted as per the standard orthogonal array. Sivagurumanikandan et al., while welding super duplex stainless steel, recommended a welding speed of 350-450 mm/min for attaining complete penetration[8]. In another study, Khan et al. [7] concluded that pulse energy greater than 15 J, enhances the heat input to result in the formation of detrimental compounds at the interface, thereby inhibiting the properties of the weld. Meanwhile, Kumar et al. reported that the pulse duration less than 10 ms results in an optimum weld width with good mechanical properties [9]. Based on the recommendations of above said researchers, and trial experiments, the process parameters welding speed, pulse energy and pulse frequency were chosen, and tabulated in Table.1. The ranges of parameters were fixed with the objective of attaining minimum weld width and a maximum tensile strength.

Table 1: Range of process parameters

Variables	Symbol	Unit	Level-1	Level-2	Level-3
Welding speed	S	mm/min	350	300	400
Pulse energy	E	J	10	12	14
Pulse duration	D	ms	6	7	8

3. Experimental Procedure

Weldability of Hastelloy C-276 (Wt % C-0.004, Si-0.029, Mn-0.387, S--0.006, P-0.003, Cr-14.963, Fe-5.534, Mo-15.676, Co-0.224, Nb-0.010, Cu-0.138, V-0.023, Al-0.085, W-3.154, Ni-Bal), by 600 W Nd: YAG laser welding machine, in pulsed mode, was attempted. The samples (size: 50 X 30 mm^2, thickness being 1 mm) were cleaned by acetone to remove dirt, if any present. The Nd: YAG laser beam (JK 600 HP-average power 600 W, maximum peak power 10 kW, maximum pulse energy 100 J, maximum frequency 1000 Hz, pulse range 0.2–20 ms) with 0.6 mm irradiation spot diameter was focused on the surface of the base alloy to attain a conductive butt weld in a pure (99.9 %) argon atmosphere (10 l/min).To identify the influential process parameters, an experimental design was devised in MINITAB-16, statistical software, employing Taguchi L_9 orthogonal analogy. Three parameters were opted for this study viz., welding speed, pulse energy and pulse duration. The detailed experimental conditions attempted were displayed as Table 2.

Subsequent to welding, the samples from each welding conditions, were sliced in the perpendicular direction for metallographic and tensile testing. Before examining under the VERSAMET image analyzer, samples were subjected to grinding with various grades of emery sheets (200 # to 2500 #). The ground surface was etched (30 seconds) in the solution containing 15 ml HCl, 10 ml HNO_3 and 10 ml glacial acetic acid. The top width of the weld was measured, as per standard procedure, and the results are given in Table 2. Tensile testing (ASTM E8-2016) was executed in a 100 KN servo controlled universal testing machine (UNITEK-94100) and the strength was determined.

Table 2: Experimental conditions

Exp. No.	Welding Speed, S (mm/min)	Pulse Energy, E (J)	Pulse Duration, D (ms)	Heat input (J/mm)	Laser Power(W)	Weld Width (mm)	Tensile Strength (MPa)
1	350	10	6	34	200	2.19	920
2	350	12	7	41	240	2.48	895
3	350	14	8	48	280	2.57	825
4	400	10	7	30	200	2.07	945
5	400	12	8	36	240	2.33	912
6	400	14	6	42	280	2.50	892
7	450	10	8	27	200	2.04	975
8	450	12	6	32	240	2.18	942
9	450	14	7	37	280	2.34	906

4. Results and Discussion

4.1 Weld Width Optimization

The influence of each parameter in attaining a smaller weld width, in terms of signal to noise ratio (SNR) is determined based on 'smaller the better' criteria in MINITAB-16. The SNR for smaller the better is given by the following equation [10] and the results are presented by means of main effect plot (Fig.1) and an ANOVA table (Table 3) respectively

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{n} Y_i^2\right) \qquad (1)$$

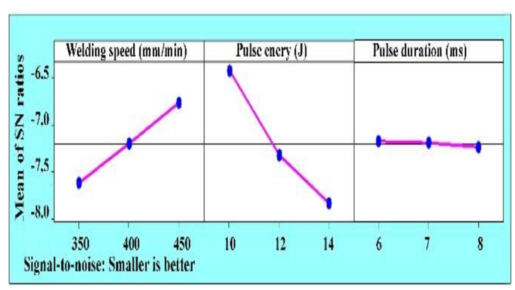

Fig.1. Main effect plot for attaining minimum weld width

From the main effect plot, it is obvious that minimum weld width is obtained at highest welding speed (3rd level: 450 mm/min), lowest pulse energy (1st level of 10 J) and lowest pulse duration (1st level of 6 ms). When the welding speed increases, width of the weld increases. On the contrary, an increase in the pulse energy decreases the width of the joint.

Table 3: ANOVA table for weld width

Source	Degrees of Freedom	Sum of Squares	Mean sum of squares	F	P
Regression	3	0.289017	0.096339	43.50	0.001
Residual error	5	0.011072	0.002214		
Total	8	0.300089			

In regression analysis, the regression coefficient (R^2) is 0.96, indicating the fit of experimental data is satisfactory [11]. The P-value (0.001), in the ANOVA table, indicates that the linear and squared terms are significant at 95 % confidence level (Table 3). Further, it is observed from Fig.1 that pulse energy is the most dominant factor in dictating the width of the weld, followed by welding speed - the second influential parameter. The third parameter, pulse duration holds the least influence on the width of the weld within the range of parameters chosen in this study. In continuation of this, a contour plot (Fig.2) and an expression are generated to predict the width of the weld between two prime influencing factors viz., welding speed and pulse energy.

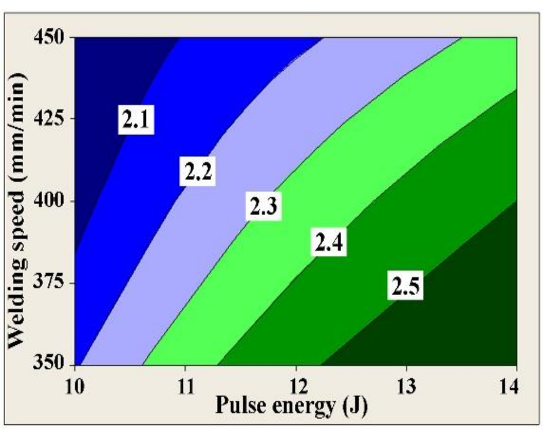

Fig. 2. Effect of welding speed and pulse energy on weld width

The mathematical expression, based on regression analysis, in terms of chosen process parameters for determining the weld width, performed in MINITAB-16, is given by

Weld width = 2.03 - 0.0023 welding speed + 0.0933 pulse energy + 0.01 pulse duration (2)

4.2 Optimization of Tensile Strength

The influence of each parameter to attain a higher tensile strength, in terms of signal to noise ratio, is determined based on the 'larger the better' in MINITAB-16. The SNR for larger the better is given by [10]

$$\frac{S}{N} = -10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \qquad (3)$$

The outcome in terms of the main effect plot and ANOVA table is displayed in Fig.3 and Table 4respectively. From the main effect plot (Fig. 3), it is noticed that the higher tensile strength is obtained at the highest welding speed (3rd level: 450 mm/min), lowest pulse energy (1st level of 10 J) and lowest pulse duration (1st level of 6 ms).

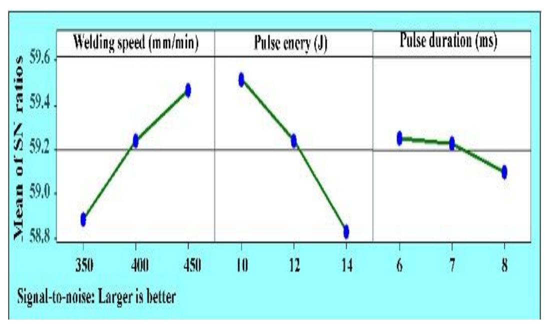

Fig.3. Main effect plot for attaining maximum tensile strength

Table 4: ANOVA table for tensile strength

Source	Degrees of Freedom	Sum of squares	Mean sum of squares	F	P
Regression	3	13723.7	4574.6	38.73	0.001
Residual error	5	590.6	118.1		
Total	8	14314.2			

When the pulse energy and pulse duration reduce, the tensile strength of the joint reduces whereas it follows a parabolic route with the welding speed. In addition, the parameter pulse energy is the principle factor influencing the tensile strength, followed by welding speed and pulse frequency. Hence, it is concluded that all the chosen parameters influence the tensile strength of the joints, at different assent fraction. In regression analysis, the regression coefficient (R^2) is 0.959, indicating the fit of experimental data is satisfactory [12]. The analysis of variance (ANOVA) table for the regression analysis is shown in Table 4. The P value (0.001) indicates that the linear and squared terms are significant at 95 % confidence level.

The tensile strength of the laser weld, considering the effect of two influencing parameters viz., welding speed and pulse energy, is determined for any value, within the parameter range, from the contour plot shown in Fig.4. In terms of mathematical expressions, tensile strength in terms of the chosen process parameters, calculated in MINITAB-16, is given by

Tensile strength = 934+ 0.610 x welding speed – 18.1 x pulse energy - 7 x pulse duration (4)

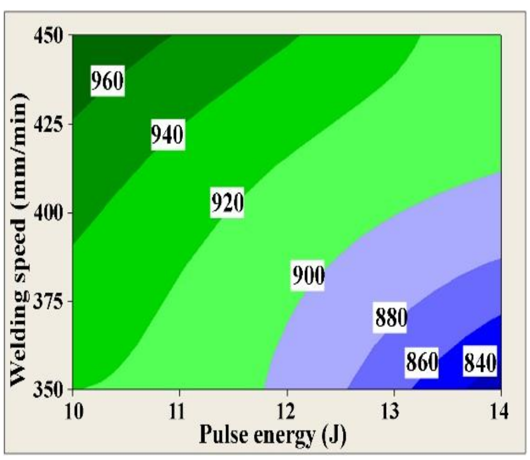

Fig.4. Effect of welding speed and pulse energy on tensile strength

4.3 Testing of Optimal Data

The pulsed laser welding experiments, at optimal conditions, were performed twice (S-450 mm/min, P-10 J, D-6 ms) and the average weld width and the tensile strength were determined in order to avoid bias if present (Table 5).

Table 5: Comparison of weld width and tensile strength at optimum condition

Optimum parameters			Weld width (mm)		Tensile strength (MPa)	
Welding speed, S (mm/min)	Pulse energy, E (J)	Pulse duration, D (ms)	Exp.	Regression	Exp.	Regression
450	10	6	1.95	1.988	982	985.5

The experimental and predicted weld width and tensile strength obtained for the optimal process parameters holds a deviation lesser than 2 % indicating the developed equation can effectively be used in the selected range of pulsed Nd: YAG laser welding.

5. Conclusions

The optimized process parameters for the pulsed Nd: YAG laser welding of Hastelloy C-276 was determined by employing Taguchi design of experiments. The influence of opted process parameters on weld width and tensile strength was studied using the signal-to-noise ratio and ANOVA techniques. The following salient conclusions are drawn from this study:

(1) The opted process parameters viz., welding speed, pulse energy and pulse duration influences the width of the weld and the tensile strength of the weld, at different levels.

(2)Taguchi experimental design reveal that over the range of parameters chosen in this study, the optimum range of process parameters are welding speed: 450 mm/min, Pulse duration: 6 ms: Pulse energy: 10 J for attaining the minimum weld width and maximum tensile strength.

(3) The developed regression model predicts the weld width and tensile strength of the weld precisely.

References

1. *Thakur A and Gangopadhyay S (2016), "State-of-the-art in surface integrity in machining of nickel-based super alloys", Int. Jnl. of Machine Tools and Manufacture, Vol.100, 25-54.*

2. *Saravanan S, Raghukandan K and Sivagurumanikandan N (2017), "Studies on metallurgical and mechanical properties of laser welded dissimilar grade steels", Jnl. of the Brazilian Society of Mechanical Sciences and Engineering, Vol.39 (9), 3491-3498.*

3. *Saravanan S, Raghukandan K and Sivagurumanikandan N (2017), "Pulsed Nd: YAG laser welding and subsequent post*

weld heat treatment on super duplex stainless steel", Jnl. of Manufacturing Processes, Vol. 25, 284-289.

4. *Saravanan S, Raghukandan K and Sivagurumanikandan N (2017), "Parametric optimization to enhance the tensile strength of Nd: YAG laser welded austenitic stainless steel", Lasers in Engineering, Vol. 37, 385-399.*
5. *Han Q, Kim D.W, Kim D.C, Lee H and Kim N (2012), "Laser pulsed welding in thin sheets of Zircaloy-4", Jnl. of Materials Processing Technology, Vol.212, 1116-1122.*
6. *Ventrella V.A, Berretta J.R, and de Rossi W (2012), "Pulsed Nd: YAG laser welding of Ni-alloy Hastelloy C-276 foils", Laser Assisted Net Shape Engineering, Vol. 7, 569-576.*
7. *Khan MMA, Romoli L and Dini G, (2013), "Laser beam welding of dissimilar ferritic/martensitic stainless steels in a butt joint configuration", Optics and Laser Technology, Vol. 49, 125–136*
8. *Sivagurumanikandan N, Raghukandan K, Saravanan S (2016), "Nd: YAG laser butt welding of super duplex stainless steel", Lasers in Engineering Vol. 35, 217-225.*
9. *Kumar G.S, Sivagurumanikandan N, Saravanan S and Raghukandan K (2016), "Effect of welding speed on microstructural and mechanical properties of pulsed Nd: YAG laser welded dissimilar metals", Jnl. of Manufacturing Engineering, Vol. 11(3), 161-165.*
10. *Roy R.K, (1990), "A primer on the Taguchi method, competitive manufacturing series", New York, Van Nostrand Reinhold.*
11. *Bagchi A, Saravanan S, Shanthoskumar G, Murugan G, and Raghukandan K (2017) "Numerical simulation and optimization in pulsed Nd: YAG laser welding of Hastelloy C-276 through Taguchi method and artificial neural network" Optik-Int. Journal for Light and Electron Optics Vol. 146, 80-89.*
12. *Elango E, Saravanan S and Raghukandan K, "Optimization of process parameters in dissimilar explosive cladding through Taguchi method", Jnl. of Manufacturing Engineering, Vol. 10(4), 194-199.*

