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Research Paper

STATISTICAL MODELLING OF CO_2 LASER BEAM WELDING OF 20MnCr5 ALLOY STEEL

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In this study CO_2 Laser Beam Welding (LBW) is used for joining an automotive gear with the synchrocone ring both made of alloy steel (20MnCr5) optimized. Laser power and welding speed combinations are carefully selected with the objective of producing the welded joint with deep penetration, high aspect ratio with minimum defects. The entire quality characteristic will be evaluated as a function of the selected laser welding parameters. Taguchi method is used as the tool statistical Design Of Experiment (DOE). This study demonstrates the successful use of ANOVA and Regression analysis for getting desired results. Regression analysis found to be good in prediction. This method is proposed as a way to enhance process efficiency and design laser welds which display deep penetration and high depth-to-width or aspect ratios with acceptable range of defects.

Keywords: CO_2 LBW, Taguchi method, ANOVA, Regression analysis

INTRODUCTION

Laser Beam Welding (LBW) is a joining process that produces coalescence of materials with the heat obtained from the application of concentrated coherent light beam impinging upon the surface to be welded. For welding, the beam energy is maintained below the vaporization temperature of the work piece material, the laser beam must be focused to a small spot size to produce a high-power density. This controlled power density melts the metal and, in case of deep penetration welds, vaporizes some of it. When solidification occurs, a fusion zone or weld joint results (American Society of Metals, 1983). Taguchi methods are a system of quality engineering that focus on utilizing engineering knowledge to create the best product or process at the lowest possible cost. This method achieves the integration of DOE with the parametric optimization of the process yielding the desired results. The

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orthogonal array (OR) provides a set of well balanced experiments (Bagchi, 1993). Taguchi's method uses signal to noise ratios (S/N), which are logarithmic functions of desired output to serve as objective function for optimization. The parameter level combination that maximizes the appropriate S/N ratio is the optimal setting. There are many different possible S/N ratios, three of them (nominal-is-best, smaller-is-better, and larger-is-better) are considered standard and are generally applicable in the situations. The purpose of the ANOVA is to investigate the design parameters that significantly affect the quality characteristic. The larger F value indicates the effect of that factor is large compared to other (Phadke, 1989). Regression analysis determines the structure of relationship between input and output parameters and predicts the values of output variables (Malhotra, 2007).

Mathematical modeling of the laser spot welding process has emerged as a useful tool for the prediction of the temperature-time history and weld pool dimensions but the reliability of the predicted values of temperature history and weld dimensions significantly depends on the accuracy of the input parameters (Trivedi *et al.*, 2006; and Bag *et al.*, 2008). It was observed that decreasing the welding speed could reduce the porosity within the visually sound welds (Fong, 2006). Beam expansion ratio, the average laser power, the engraving speed, and the interaction between beam expansion ratio and focal length significantly affect the engraving line width (Chen *et al.*, 1996). The laser power was found to have the most dominant effect on the penetration depth among the welding parameters (Kim *et al.*, 2007). CO_2 and diode laser welding processes were investigated for Ti_6Al_4V alloy sheet joining. Artificial neural networks processed the data coming from the experimental trials to form a suitable database for the analysis of the variance and the Taguchi analysis of the means (Casalino *et al.*, 2008). The weld quality was influenced by laser power, welding speed, and the shielding gas. Weldability and productivity were considered to obtain the optimal values. Tensile strength was carried out to evaluate the weldability (Park and Rhee, 2008). Taguchi method was adopted to perform the initial optimization of the pulsed Nd: YAG laser micro weld process parameters and showed improvement of the defective rate from the initial conditions to the optimal parameters is 3.34% (Lin and Chou, 2008). Shanmugan *et al.* applied FEM in predicting the weld bead geometry in laser spot welding of AISI 304 stainless steel by taking beam power, incident angle of beam and beam exposure time as input parameters (Shanmugam *et al.*, 2012). An empirical relationship was developed to predict tensile strength of the laser beam welded AZ31B magnesium alloy by incorporating process parameters such as laser power, welding speed and focal position (Padmanaban and Balasubramanian, 2010). RSM was used to analyse the effect of laser power, welding speed and focus position on heat input, bead geometry, tensile strength and welding operation cost and it was found that the welding speed was the most significant parameter (Reisgen *et al.*, 2012). Laser transmission contour welding process was modelled and analysed using FEA and DOE techniques using laser power, welding speed, beam diameter and carbon black content as input parameters, weld bead geometry and maximum temperature at interface taken as responses (Acherjee *et al.*, 2012). Sathiya *et al.* investigated the effect of laser power, travel speed, focal position and shielding gas on bead geometry and tensile strength using ANN and GA (Sathiya *et al.*, 2012). Taguchi method was successfully used for optimization of the laser power, welding speed and wire feed rate in laser welding with filler wire process (Dongxia *et al.*, 2012). Chuan *et al.* conducted the numerical and experimental analysis of residual stresses in full penetration laser beam welding of titanium alloy using FEM and found that residual stress distribution on the surfaces are different from those in the interior of the welding seam (Chuan *et al.*, 2009). In analytical modelling of deep penetration LBW of stainless steel dependencies of penetration depth, width, and aspect-ratio of zone were successfully derived as a function of laser power and welding speed (Franco *et al.*, 2014). It was found that the joints fabricated using a laser power of 2500 W, welding speed of 5.5 m/min and focal position of –1.5 mm yield superior tensile properties compared with the other joints in laser beam welding of magnesium alloy (Padmanaban and Balasubramanian, 2011). In the present work laser power and welding speed selected as process parameters, Taguchi method was found to be most effective and easy to use statistical experimental process, ANOVA used to verify the optimal condition which investigates the parameters hat significantly affect the quality characteristics and Regression analysis to predict the results.

EXPERIMENTAL PROCEDURE

The current study was carried out to join an automotive gear with the synchrocone ring both made of alloy steel (20MnCr5), with CO_2 laser.

Figure 1: Laser Welding Setup

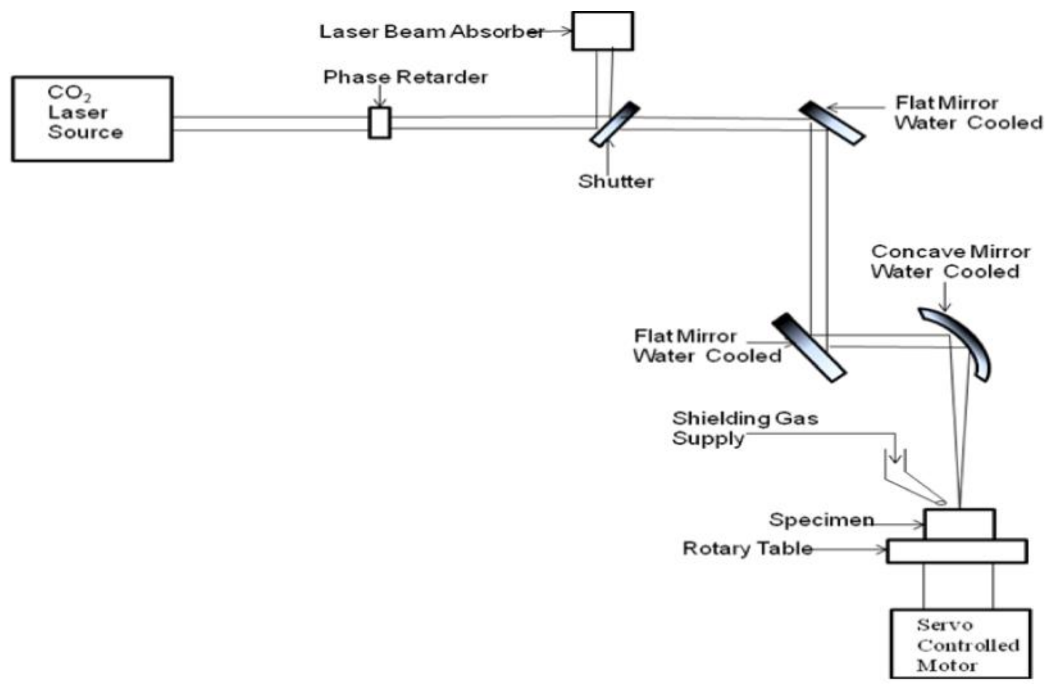


Figure 1 shows the setup of laser welding experimentation. Table 1 shows the composition in Wt % and Table 2 shows the mechanical properties of 20MnCr5 alloy steel. The pre laser welding activities includes the press fitting of gear and synchro ring followed by washing with 0.8% soap solution and drying with hot air blower at 100 °C. The laser gas composition involved varying percentages of He, O_2, Xe, CO_2, CO and N2. The chamber contains laser gas, having pressure of 200 hPa. Shielding gas kept at pressure of 1.5 bar, its composition having Helium (30%) and Argon (70%) and the average flow is 15 liters/min. Chill water flow rate was 2 liters/min and it kept at a temperature of 25 °C. Laser beam wavelength is 10.6µm, diameter range was 20-25 mm and it was kept at 20 mm for the experiments, frequency is 5000 Hz, and the Laser power ranges from 250 to 2500 watts. The Focal distance was 250 mm and focal point kept at 1 mm below from the surface of the component to be welded with 0.1 mm diameter to produce high power density.

Table 1: Composition of 20MnCr5

C	Mn	Si	Cr	S	Pmax
0.17-0.22%	1.1-1.40%	0.15-0.40%	1.00-1.30%	0.035%	0.035%

Table 2: Mechanical Properties of 20MnCr5

Y.P	T.S	E	R.A.
685 N/mm^2	980/1280 N/mm^2	8%	35%

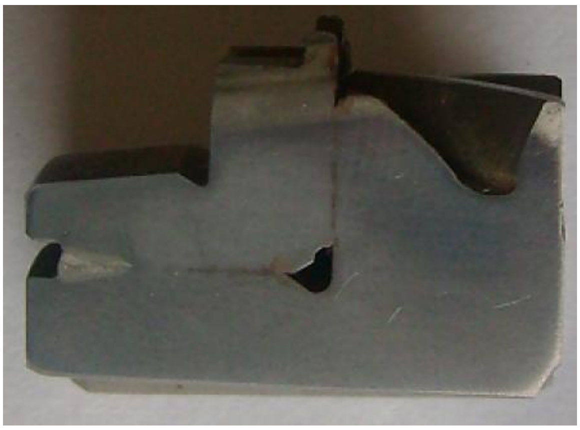
The appropriate quality characteristics to be measured were the depth of penetration, fusion width, and defects, i.e., blow holes and unfused volume %. The acceptable maximum value for blow holes cumulative should not exceed 10% per unit volume, 3% for blow holes unitary (largest) and 2% for unfused volume. Weld quality and productivity were considered to obtain the optimal values. Weld quality was evaluated in terms of depth, depth-to-width ratio and defects. The independently controllable process parameters affecting the bead geometry and quality were selected for optimization: laser beam power, and welding speed and for each factor three levels (or setting) is selected (Table 3). These settings were adjusted in CNC machine via programs for each experiment. The underscore at the level values shows the initial condition (conditions before the matrix experiment). The machine on which the experiment was conducted is CINETIC, France make and the laser source is CO_2 gas. The L9 orthogonal array was selected to conduct the experiment for 2 factors, i.e., Laser power, and welding speed, each at three levels. For L9 orthogonal array total number of experiments is 9. Total 72 experiments was conducted, means 8 experiments for each setting The destructive testing was used for measuring the weld depth and width (bead geometry) for all the welded parts.

Table 3: Selected Control Factors and Their Levels

Factors	Levels		
	1	2	3
A. Laser Power (KW)	1.8	2.0	2.5
B. Welding Speed (m/min)	1	1.5	2

A small piece of welded gear and synchrocone ring was placed in the Profile Projector, NIKKON, JAPAN for measuring bead geometry. A profile projector projects a magnified profile image of an area or feature of a workpiece onto a screen and dimensions can be measured directly on the screen. The most basic use of profile projector is to identify a point or edge on the shadow and from this point to calculate a length. In Figure 2, the triangular image shows the welding profile. Blow holes and Unfused Volume % was measured with the help of ULTRASONIC MACHINE manufacturer BOTEST, ITALY. Defects were identified as a function of the diminution of the ultrasound echo received by the receptor as the sensor is moved. The ultrasound manual control station was a semi-automatic machine able to carry out gear welding in a fully automatic way. The ultrasound control method allows non destructive testing on mechanical pieces, covering their volume and making it possible, in this way, the detection of inner defects. The assembly that were placed manually on the control station, were immersed in a solution of water and additive (the mixture has to be made up of the 3% antioxidant additive, diluted in demineralised water by means of which ultrasound propagate for welding control) and were subjected to ultrasound control which was able to establish if the welding of synchronizer (synchrocone ring) on pinion (gear), meets specification required.

Figure 2: Welding Profile (the Triangular Welding Profile Shows Inside the Circle)



RESULTS AND DISCUSSION

A summary of factor effects calculated by Taguchi method and F-value calculated by ANOVA is tabulated in Table 4. The following observations about the optimum setting from Taguchi method and ANOVA analysis are:

1. Laser Power has the largest effect, and welding speed has less significant effect on weld depth. By increasing the laser power from initial setting of 2.0 to 2.5 kW can be improved by 1.64 dB. The optimum value for laser power is 2.5 kW, and welding speed is 1 m/min. The laser power and welding speed are responsible for 59.563 and 39.555% in variation of weld depth respectively.
2. The laser power shows little effect on blow holes cumulative and blow holes unitary but again it can be seen that the welding speed has the moderate effect on these defects. Optimum value for these defects is 2.5 kW laser power and 1 m/min welding speed. The laser power and welding speed are responsible for, 25.313 and 49.946% in changing the blow holes cumulative respectively, and 20.663 and 52.150% in blow holes unitary respectively.
3. The laser power shows little effect on unfused volume, the welding speed dramatically improves and effect of welding speed is quite large compared to laser power. Laser power has little negative effect while changing from 2 to 2.5 kW. Optimum value for welding speed while considering unfused volume is 1 m/min. The laser power and welding speed are responsible for

Table 4: Summary of Factor Effects

Factor	Levels	Weld Depth		Weld Width		Blow Holes Cumulative		Blow Holes Unitary		Unfused Volume	
		¦	F	¦	F	¦	F	¦	F	¦	F
Laser Power (kW)	1.8	10.329	135.018	–5.678	108.019	–11.466	1.966	–8.278	1.520	0.025	1.260
	2.0	11.204		–6.131		–5.842		–4.491		14.043	
	2.5	12.845		–7.946		0.342		1.307		12.870	
Welding Speed (m/min)	1.0	12.561	89.663	–8.418	208.147	3.271	3.802	4.913	3.836	27.649	5.470
	1.5	11.330		–6.038		–7.345		–6.918		0.711	
	2.0	10.487		–5.300		–12.892		–9.457		–1.421	
Overall Mean		11.459		–6.585		–5.654		–3.821		8.979	

14.434 and 62.659% in variation of unfused volume respectively.

4. The effect of welding speed is more compared to the laser power while considering weld width, and these both have the larger effect than error means larger contribution in changing the width of the weld. Weld width improves when the laser power is at lower level, i.e., 1.8 kW and welding speed at 2 meters/min. the contribution of, laser power is 34.972%, and welding speed is 64.409%, in changing the weld width.

At 1 m/min and 2500 watts laser power the weld depth is higher. The laser power has the larger effect on weld depth variation. The relationship between laser power and welding speed is almost inversely proportional. The defects such as blow holes and unfused volume are also reduced at higher laser power and lower welding speed combination, as welding speed increases from this range the defects increases. The welding speed shows larger contribution in variation of defects than laser power. The effect of welding speed is large compared to laser power in case of weld width. The width decreases as the laser power decreases, and the welding speed increases. With the setting of 2.5 KW laser power, and 1 m/min welding speed, large improvement in weld depth (26.31%) and defects such as: blow holes cumulative (93.4%), blow holes unitary (94.5%), and unfused volume (98.3%), obtained with negative effect on aspect or depth-to-width ratio (–15.8%). If high precision requires in defects such as in aircrafts part welding, then this setting can be recommended. Welding speed is directly related to productivity. Decrease in welding speed showers down the productivity and also results in larger HAZ (heat affected zone). The recommended settings of laser power and welding speed are 2.5 KW and 1.5 m/min respectively, the results obtained for this setting shows improvement in weld depth (22%), depth-to-width ratio (13.7%), with permissible limits of defects. The equations derived with multiple regression analysis may be used for prediction of the outcomes with unknown values of input parameters (laser power and welding speed) for weld depth, weld width and unfused volume. The regression equations derived for blow holes cumulative and blow holes unitary are not significant to predict them.

Table 5: Summary of Multiple Regression Analysis

S. No.	Quality Characteristics	R^2 %	Adjusted R^2 %	~	Multiple Regression Equation
1.	Weld Depth	96.2	96.1	0.05	H = 1.87+1.56*A-0.910*B
2.	Weld Width	92.0	91.7	0.05	W = 1.60+0.845*A-0.798*B
3.	Blow Holes Cumulative	43.3	35.8	0.05	B_1 = 6.68-5.680*A+5.74*B
4.	Blow Holes Unitary	58.3	52.8	0.05	B_2 = 2.40-1.90*A+2.49*B
5.	Unfused Volume	67	62.6	0.05	U = 0.028-0.304*A+0.936*B

The results obtained with the equation for weld depth, width and unfused volume found to be good with 0.07, 0.12 and 0.20 error respectively for new sets of input parameters.

Summary of Multiple Regression analysis for all the quality characteristics is shown in Table 5. Weld Depth, Weld Width, and Unfused Volume with R^2 96.2%, 92.0% and 67% respectively are statistically significant for prediction for new observation at ~ = 0.05.

CONCLUSION

This study is carried out to optimize laser beam welding process, used to join automotive gear with synchrocone ring. This welded assembly is used in transmission of vehicles to transmit torque. During running conditions the welded assembly is subjected to various dynamic forces and for the part to sustain these forces high quality of welded joints required.

The result in this work supports the following conclusions:

1. The relationship between laser power and welding speed is almost inversely proportional.
2. Taguchi method and ANOVA was effectively used in analysis the cause and effect of selected process parameters on response.
3. The recommended optimum settings, i.e., 2.5 kW laser power and 1.5 m/min welding speed shows large improvement in depth of penetration, and aspect ratio, while maintaining defects within permissible limits.
4. Regression analysis can be employed easily for developing an equation for predicting weld bead geometry and unfused volume in the laser welding process which can be used effectively in analysis. The predictions compared with actual experimentation, and found to be good in laboratory conditions.

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