The Effect of Process Parameters on Pulsed Nd: YVO_4 Laser Welding of Acrylic and Polycarbonate Sheets

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Abstract

Through transmission laser welding (TTLW) is an innovative joining process that has advantages over conventional joining process such as non-contact, non-contaminant process, and automatic, easily controllable, flexible to weld complex shapes with shorter processing time. This process has wide range of applications in every section of modern society, including science, medicine, electronic etc. The present research work, TTLW of two transparent materials without filler materials in lap joint configuration has been conducted. The important welding parameters, namely, laser power, scanning speed and frequency have been selected. The ultimate load has been measured as response. The effect of process parameters on response has been investigated by using an empirical model developed by response surface methodology. The quadratic model has been developed to correlate the input parameters with response. Analysis-of-variance (ANOVA) has been conducted to find out the significant parameter/s in the process. The mathematical model is used to determine the optimum welding conditions to achieve the desired weld quality. Confirmatory tests have been conducted to validate the applied optimization techniques.

Keywords: TTLW; Ultimate load; Response surface methodology; ANOVA; Optimization.

1. INTRODUCTION

In the present day advanced manufacturing scenario, the components produced must strictly adhere to the dimensional, laser welding found a place in industrial-scale situations only in the last decade. Several research publications, articles and information are available in the field of through transmission laser welding of plastics. People made experiments and analyses emphasizing on parametric effects on weld quality, process optimization, performance evaluation and other related aspects. A study performed by Hansch *et al.* [1] that pigments have a limited and intensive range of absorption in the visible range. They noted that two joining parts may appear alike for the human eye. But that have different absorption characteristics in the near infrared region. Herfurth *et al.* [2] have studied laser welding of translucent plastics and have concluded that Holmium:YAG laser can be used for welding operation based on volume absorption of laser energy in a butt joint configuration. Ilie *et al.* [3] have studied the weldability of a polymeric material through simulation using Monte Carlo method and finite element method to develop the model for estimating the temperature field into both parts to be welded followed by the validation of results. Coelho *et al.* [4] have found that different gap sizes between the joining parts have bridgeable depending on the carbon black concentration and the applied welding strategy welding of white and transparent thin films of polypropylene and polyethylene of low and high density at high speeds of 20 m/s using a carbon dioxide laser. Grewell *et al.* [5] have studied the relationship between optical characterization of coloured and non-coloured polyamides and laser welding process parameters and observed that addition of pigments can enhance the scatter of laser radiation, which can increase the effective weld time or minimal energy requirement to make a weld. Truckenmiller *et al*. [6] have discussed a process for building up polymer fluidic micro sensors and actuators with foreign matter free, inert flow path which is based on ultrasonic welding of polymers parts. An investigation on laser transmission welding of polypropylene using diode laser has been done by Abed *et al*. [7]. They have concluded that crystalline morphology observed in different zones in the welded part is related to specific thermal cycle. Kagan *et al*. [8] have attempted to optimize the spread of the laser beam at the weld bead by adjusting the dimensions of the laser beam incident at the surface of the transmitting part. Jansson *et al*. [9] have investigated the welding strength of laser transmission welded polymers such as transparent polycarbonate (PC), coloured ABS-polycarbonate alloy. Douglass *et al*. [10] have investigated laser welding of polyolefin elastomers (POE) to determine the weld ability of two different POEs to thermoplastic elastomers using a fibre laser and found that power and speed have the most significant effects on strength.

Within scope of literature review, it has been observed that little or almost no information is available on transparent to transparent sheet welding using Nd:YVO_4 laser. Hence an urgent need of research work is required in the field of transparent to transparent laser welding.

2. EXPERIMENTAL SET UP AND PROCEDURE

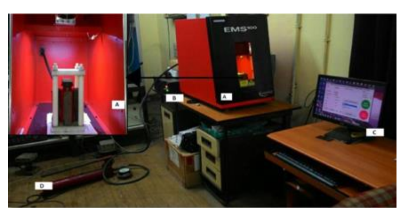

Fig. 1. Pictorial view of experimental set up: A. Work station; B. Laser beam delivery unit; C. Computer interface and D. Hydraulic pump with pressure gauge

In the present study Electrox EMS 100 laser marking set up has been used for the welding of plastics. The 12 W Nd: YVO_4 (Neodymium-doped yttrium orthovanadate) laser with 1064 nm wavelength has been used for the laser transmission welding purpose. The dimensions of acrylic and polycarbonate plastic

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sheets of size 100 mm × 35 mm × 0.5 mm have been chosen. Overlapping length is 70 mm. No additional absorbent has been used. The laser used with spot diameter of 50 µm. The experimental set up used for the welding process is shown in Fig. 1. The selected process parameters and their limits are given in Table 1.

Table 1
Process control parameters and their limits

Parameters with units	Notation	Levels				
		-2	-1	0	+1	+2
Power, W	P	9.19	9.60	10.20	10.80	11.21
Scanning speed, mm/s	S	0.65	1.00	1.50	2.00	2.34
Frequency, kHz		265.91	300.00	350.00	400.00	434.09

3. RESULTS AND DISCUSSION

The lap joints are made by using laser welding process and results of ultimate loads (UL) have been presented in Table 2.

Table 2

Measured value of ultimate load of each welded samples

Experiment no.	P (W)	S (mm/s)	f (kHz)	UL (N)
1	10.80	2.00	300.00	235.27
2	10.80	1.00	400.00	314.77
3	10.20	2.34	350.00	214.70
4	9.60	2.00	300.00	**191.78**
5	10.80	2.00	400.00	230.88
6	10.20	1.50	350.00	281.78
7	9.19	1.50	350.00	261.46
8	10.20	1.50	350.00	282.37
9	10.20	1.50	350.00	280.12
10	10.20	1.50	265.91	270.11
11	9.60	1.00	400.00	329.19
12	9.60	2.00	400.00	234.40
13	10.20	1.50	350.00	280.43
14	9.60	1.00	300.00	329.95
15	10.80	1.00	300.00	357.52
16	10.20	1.50	350.00	281.65
17	10.20	1.50	350.00	292.94
18	10.20	0.65	350.00	**425.18**
19	11.21	1.50	350.00	278.38
20	10.20	1.50	434.09	288.39

The maximum and minimum ultimate loads have been obtained for sample no. 18 and sample no. 4 respectively. The mathematical model for response has been developed (Eq. 1); also response surface plots have been generated. To investigate the influence of process parameters on ultimate load, RSM based analysis has been made and mathematical model for response parameter has been developed using MINITAB 17 software. Response surface plots have been developed to find the combined effect of two parameters on ultimate load (UL) by keeping third parameter fixed at their respective level value.

$$UL= -2793 + 64.1P + 4.32f - 498S - 0.29P^2 -0.00158f^2 + 41.7S^2- 0.445Pf + 1.34PS + 0.409fS \quad (1)$$

The pictorial views of samples with maximum ultimate load and minimum ultimate load are presented in Fig. 2a and 2b respectively. The laser weld seam may be identified form Fig. 2.

(a) **(b)**

Fig. 2. The pictorial view of sample having (a) maximum ultimate load and (b) minimum ultimate load

Load vs. extension curves for maximum and minimum load obtained in tensile test are shown in Fig. 3 and Fig. 4 respectively. The main effect plots for ultimate load are shown in Fig. 5.

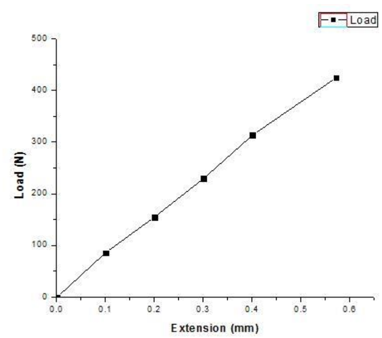

Fig. 3. Load vs. extension plot for maximum ultimate load

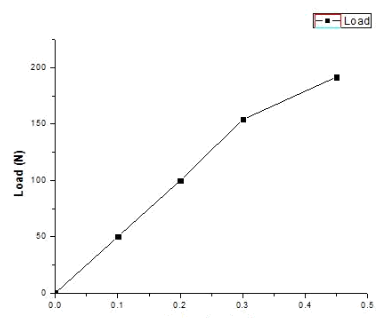

Fig. 4. Load vs. extension plot for minimum ultimate load

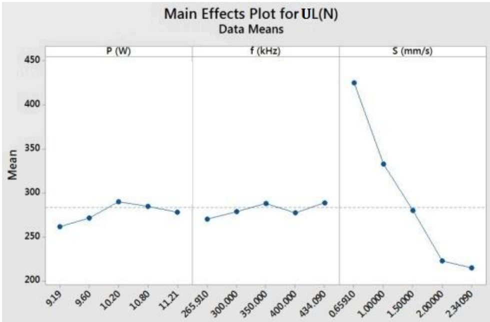

Fig. 5. The main effect plots of ultimate load

From Fig. 5, it can be concluded that, with the increase in power up to certain limit gives more heat energy which in turn results in stronger weld. After that it starts decreasing due to material decomposition. Although, an increase in scanning speed up to a certain limit helps reduce weld width, producing less HAZ, speed above the limit results insufficient melting of material to bond well thus weaker weld.

Table 3
Analysis-of-variance for ultimate load

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remarks
Model	9	51338.4	5704.3	62.17	0.000	Significant
Linear	3	46590.9	15530.3	169.26	0.000	Significant
P	1	487.3	487.3	5.31	0.044	Significant
f	1	47.5	47.5	0.52	0.488	Not significant
S	1	46056.1	46056.1	501.96	0.000	Significant
Square	3	2832.4	944.1	10.29	0.002	Significant
P^2	1	759.5	759.5	8.28	0.016	Significant
f^2	1	226.1	226.1	2.46	0.148	Not significant
S^2	1	1566.3	`1566.3	17.07	0.002	Significant
2-Way Interaction	3	1915.2	638.4	6.96	0.008	Significant
Pf	1	990.1	990.1	10.79	0.008	Significant
PS	1	89.9	89.9	0.98	0.346	Not Significant
fS	1	835.2	835.2	9.10	0.013	Significant
Error	10	917.5	91.8			
Lack-of-fit	5	800.4	160.1	6.83	0.27	Not significant
Pure Error	5	117.1	23.4			
Total	19	522256.0				

R^2= 98.24%, adjusted R^2 =96.66% and predicted R^2=88.08%

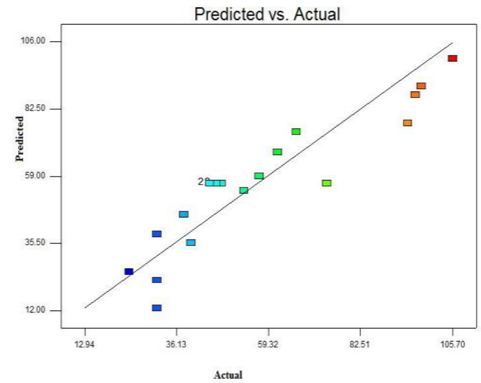

Fig. 6 Actual vs. predicted plot for ultimate load

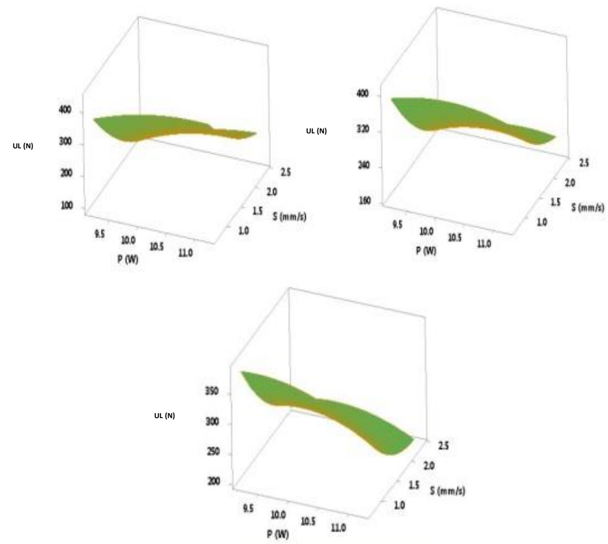

Fig. 7. Response surface plots for combining effect of power and scanning speed on ultimate load (UL) at (a) f= 265.91 kHz; (b) f= 350 kHz and (c) f= 434.09 kHz

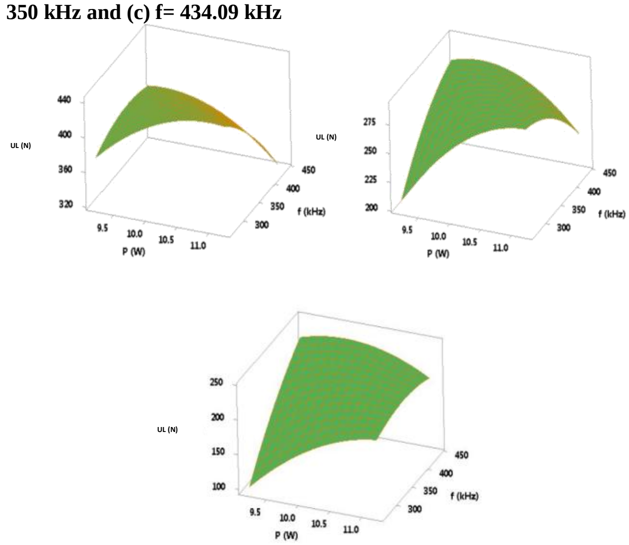

Fig. 8. Response surface plots for combining effect of power and frequency on ultimate load (UL) at (a) S = 0.65mm/s; (b) S= 1.5 mm/s and (c) S= 2.34 mm/s

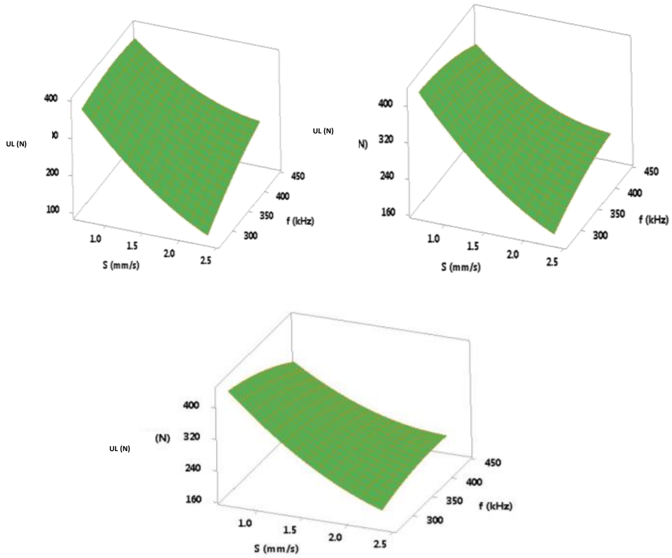

Fig. 9. Response surface plots for combining effect of speed and frequency on ultimate load (UL) at (a) P= 9.19 W; (b) P= 10.2 W and (c) P= 11.21 W

No regular trend has been obtained for frequency. Fig. 6 shows the relationship between the actual and predicted values of UL. This figure also indicates that the developed model is adequate and the predicted results are in good agreement with experimental data. Table 3 shows the analysis-of-variance of the ultimate load and shows the significant model ($P < 0.05$) at 95% confidence level. The ANOVA indicated that the P, S, interaction effect of Pf, fs, quadratic effect of P^2 and S^2 are the significant process parameters. The 3-D response surface plots for the effect of process parameters on UL have been constructed according to the fitted quadratic model (Fig. 7 - 9). From Fig. 7 it has been found that with increase laser power UL gradually increasing. With increase in laser power, energy input to the work piece increase and higher energy input cause larger the weld width. Consequently, high strength has been achieved. But, with increase in scanning speed UL gradually decreases because line energy decreases with increasing value of scanning speed. Hence, weaker strength is obtained. Remaining plots can also be explained similarly. Fig. 10 shows the optimization plot for the maximization of ultimate load.

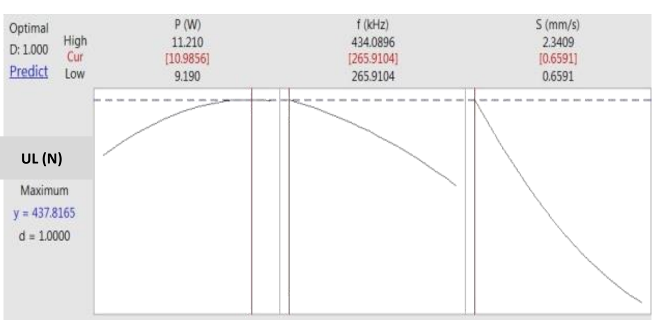

Fig. 10. Single objective optimization for ultimate load

4. CONCLUSIONS

From the forgoing analysis and discussion, following conclusions can be drawn:

- Maximum ultimate load has been obtained for the parametric combination of power= 10.98 W, scanning speed= 0.6591 mm/s and frequency= 265.91 kHz.
- From ANOVA table of ultimate load (UL), the power (P) and scanning speed (S) are the most significant input parameters.
- Adequacy of the model has been validated by plotting the actual vs. predicted values.
- The combined effect of input parameters on responses is understood by developing 3-D response surface plots.

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