EXPERIMENTAL INVESTIGATION ON DIODE LASER WELDING OF POLYCARBONATE TO ABS

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Abstract: *In this paper, an experimental investigation into diode laser welding of dissimilar plastics between polycarbonate and ABS (acrylonitrile butadiene styrene) has been carried out. The effect of the laser welding parameters such as laser power, welding speed, defocal position and clamp pressure on weld strength is studied. Weld strength is determined by shear lap tensile testing of the welded samples as the maximum load to failure in Newton. Response surface methodology (RSM) is applied to plan and analyze the experiments. Analysis of variance is further used to check the significance of the process parameters.*

Keywords: LASER WELDING, DIODE LASER, PLASTIC WELDING, WELD STRENGTH, ANOVA, POLYCARBONATE, ABS

1. Introduction

Polycarbonate is a clear, colorless polymer, having high strength, toughness, heat resistance, and excellent dimensional stability, which is used extensively for engineering and optical applications. ABS (acrylonitrile butadiene styrene) a copolymer, is comprised of polymerized styrene and acrylonitrile with polybutadiene, which exhibits a balanced combination of mechanical toughness, good dimensional stability, chemical resistance and electrical insulating properties. These combinations of properties make them suitable for various applications in diverse fields.

Joining of polycarbonate with ABS is already found in a number of applications such as automotive components like flood lights, looking mirror, dashboard components etc; displays and cabinets; and also in cell phone assemblies. Joining of dissimilar plastics requires the application of an appropriate joining technology. In case of welding, both the materials must have chemical compatibility and the difference between the melting temperatures of those materials should not be too high.

Laser welding technique often provides solutions where conventional plastic joining techniques have failed or required to be improved upon. The flexibility of this process is second to none and the quality of the weld is better than that achieved with most other plastic joining techniques. This technique involves localized heating at the interface of two overlapping thermo-plastic parts to be joined to produce strong, hermetically sealed welds with minimal thermal and mechanical stress, no particulates and very little flash [1].

In this process a laser beam is passed through the first material which is transparent, directly heating only the second material, precisely at the mating surface. With this technique, melt is only created where it is needed, in the joining area of both partners, reducing the energy input to a minimum [2]. Presence of reinforcements, mineral fillers, impact modifiers, and some heat stabilizers in polymer matrix affect the optical and mechanical properties of the materials and thereby the mechanical performance of the weld [3-6]. Prabhakaran et al. [7] studied the effects of contour laser welding parameters on meltdown and weld strength for T-joint-welded 30% glass reinforced Nylon 6. It is found that optimum weld strength can be achieved by an appropriate combination of laser power and welding speed values. For the range of weld parameter studied, meltdown increases, but weld strength decreases with increase of the weld pressure. Baylis et al. [3] investigated the effects of laser welding parameters on the weld quality, defined by weld width and strength for lap welded thermoplastic elastomers to polypropylene. It is observed that both the weld width and weld strength increase with line energy, i.e. the laser input energy per unit length. Douglass and Wu [8] considered laser power, welding speed and clamping pressure as input parameters and determined their effect on the lap shear strength of lap-welded soft and hard polyolefin elastomer (POE) to thermoplastic polyolefin (TPO). The regression analysis resulting equations for lap shear strength of soft and hard POEs to TPO-welded specimens confirm that the power and speed have the most significant effects on the welding. Acherjee et al. [9] studied the effects of laser welding parameters on the weld quality of acrylics. It is observed that the optimum weld strength can be achieved at a favorable value of energy density with an appropriate combination of laser power and welding speed.

In the present research, an experimental investigation into laser welding of dissimilar plastics between polycarbonate and ABS has been carried out. Response surface methodology (RSM) is employed to develop mathematical relationships between the welding process parameters and the output variable. The developed mathematical model is tested by analysis-of-variance (ANOVA) method to check its adequacy. This mathematical model is useful not only for predicting the weld strength, but also for selecting the optimum process parameters. The effects of process parameters on weld strength are discussed based on the developed mathematical model.

2 Response surface methodology

Response Surface Methodology is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes [10]. The most extensive applications of RSM are in the particular situations where several input variables potentially influence some performance measure or quality characteristic of the process. If all variables are assumed to be measurable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, ..., x_k) \quad (1)$$

where y is the response of the system, and x_i the variables of action called factors.

In the practical application of RSM it is necessary to develop an approximating model for the true response surface. The approximating model is based on observed data from the process or system and is an empirical model. Multiple regression analysis is a collection of statistical techniques useful for building the types of empirical models required in RSM. Usually a second order polynomial equation is used in RSM

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^{\,2} + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} x_i x_j \quad (2)$$

where, parameters $\beta_{i,\, j=0,\, 1,\, ..,\, k}$ are called the regression coefficients.

3. Experimental work

In the present research, experimental investigations are performed with a continuous diode laser system. The system installation consists of a 30 W Coherent FAP diode laser with a 3-axes CNC work table, coordinated with the motion system and computer interface. The diode laser is operated at 809.4 nm wavelength and the focal length used is 13 mm. The FAP system optical radiation is delivered via SMA 905 connector, which mates to an 800 µm diameter transport fiber. A welding fixture is used for repeating work, to maintain the lapping area constant i.e., 20 mm x 35 mm, for every run and to prevent misalignment between the parts to be welded in lap joint geometry. Natural polycarbonate and opaque ABS plaques of dimensions 80 mm x 35 mm x 4 mm of each are used as the work materials. They are placed on the metal plate of the holding fixture with the polycarbonate sample on top, with an overlap between the natural and black plaques of approximately 20 mm. Hydraulic clamp pressure is applied in between the workpieces to ensure the intimate contact between them. The pressure applied to the workpieces is determined from the reading of the pressure gauge, fitted to the hydraulic pump, converted to the pressure experienced by the plaques based on the actual area of contact between the overlapped sections of each sample. The contour welding variant of laser transmission welding is adopted for this study. The photographic view of the experimental set up for present work is shown in Fig. 1.

Fig. 1 *Photographic view of experimental setup.*

The following independently controllable parameters are identified to carry out the experiments: power, welding speed, defocal position and clamp pressure. Trial runs are conducted by varying one of the process parameters at a time while keeping the rest of them at constant value. The working range is decided by inspecting the weld seam for a smooth appearance and the absence of any visible defects. The selected process parameters and their levels, units and characters are given in Table 1.

Table 1: *Process control parameters and their limits*

Parameters	Units	Notations	Limits				
			-2	-1	0	+1	+2
Power	Watt	P	8	11	14	17	20
Welding speed	mm/ min	S	240	420	600	780	960
Defocal position	mm	F	25	30	35	40	45
Clamp pressure	MPa	C	0.9	1.8	2.7	3.6	4.5

The experimental matrix is designed based on a four factors five levels central composite rotatable design with full replications consisting of 30 sets of coded conditions and comprising a full replication of 2^4 (=16) factorial design plus six center points and eight star points. The experiments are carried out according to the arrangement of the design matrix. Figure 2 shows a laser welded polycarbonate/ABS sample.

The strength of the weld is measured with tensile strength test using a microprocessor-controlled 100 kN Instron universal tester with an accuracy of ± 0.4% of the rated capacity. The crosshead speed during the shear test is kept constant at 0.5 mm/min. The weld strength is calculated as the maximum load to failure in Newton.

Statistical software Design-Expert® is used to code the variables and to establish the design matrix. RSM is applied to the experimental data using the same software to obtain the regression equations and to generate the statistical and response plot.

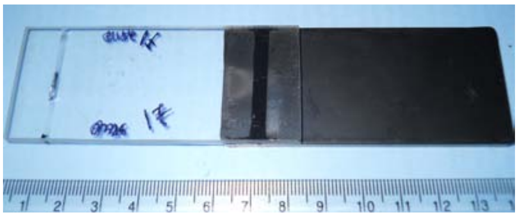

Fig. 2 *Laser welded polycarbonate/ABS sample in lap joint geometry.*

4. Development of mathematical model

The fit summary for weld strength suggests the quadratic model where the additional terms are significant and the model is not aliased. The ANOVA table of the quadratic model with other adequacy measures R^2, adjusted R^2 and predicted R^2 are given in Table 2. The associated p-value of less than 0.05 for the model (i.e, α = 0.05, or 95% confidence level) indicates that the model terms are statistically significant. The lack-of-fit value of the model indicates non-significance, as this is desirable. The insignificant model terms are eliminated by backward elimination process to improve model adequacy.

Table 2: *Results of ANOVA*

Source	F-value	Probability > F	
Model	63.78	< 0.0001	significant
P	7.38	0.0159	
S	7.76	0.0139	
F	395.36	<0.0001	
C	1.04	0.3230	
$P\ S$	7.44	0.0156	
$P\ F$	1.32	0.2683	
$P\ C$	16.47	0.0010	
$S\ F$	24.16	0.0002	
$S\ C$	79.67	<0.0001	
$F\ C$	0.25	0.6232	
P^2	207.34	<0.0001	
S^2	67.27	<0.001	
F^2	144.76	<0.001	
C^2	0.10	0.7517	
Lack of fit	1.79	0.2520	Not significant
	R^2 = 0.9835 adjusted R^2 = 0.9681 predicted R^2 = 0.9198 Adequate precision = 29.14		

The adequacy measures R^2, adjusted R^2 and predicted R^2 are in reasonable agreement and are close to 1, which indicate adequacy of the model. The adequate precision compares the signal to noise ratio and a ratio greater than 4 is desirable. The value of adequate precision ratio of 29.14 indicates adequate model discrimination. The lack-of-fit F-value of 1.89 implies that the lack-of-fit is not significant relative to the pure error.

The final mathematical models for weld strength (W_{str}), which can be used for prediction within same design space, are given as follows:

W_{str} = -15483.592 +517.564 P +10.036 S +514.330 F +205.722 C - 0.080 $P\ S$ +23.898 $P\ C$ - 0.087 $S\ F$ - 0.876 $S\ C$ -19.488 P^2 - 3.091E-003 S^2 -5.866 F^2

5. Effect of parameters on weld strength

Figs. 3-6 are one factor plots, which illustrates the effect of individual factors at the center point in the design space. Fig. 3 shows that the weld strength increases with laser power upto 14 W and then starts decreasing. The weld strength is restricted by very high heat input, which causes overheating and partial decomposition of the material, and a very low energy heat input results in lack of fusion. Increasing the laser power increases the heat input to the weld zone, thus, more base material being melted, resulting higher weld strength and wider width. However, heat input should be checked below the decomposition temperature of the base material.

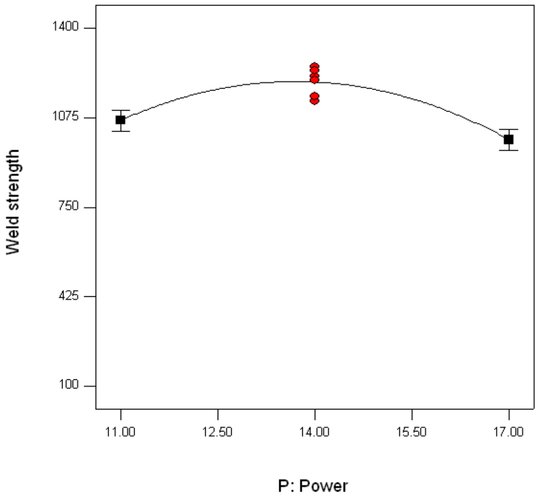

__Fig. 3__ Effect of power on weld strength.

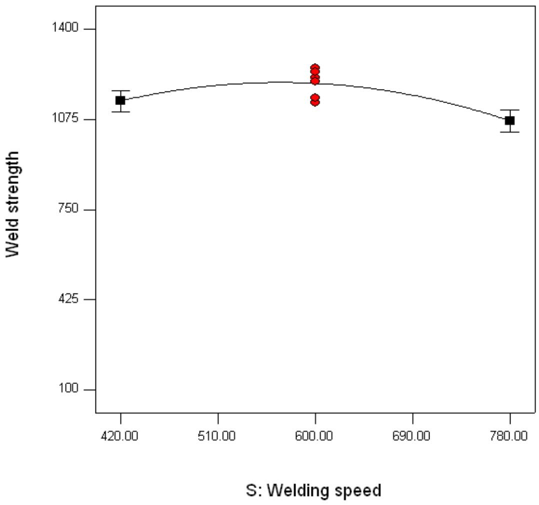

__Fig. 4__ Effect of welding speed on weld strength.

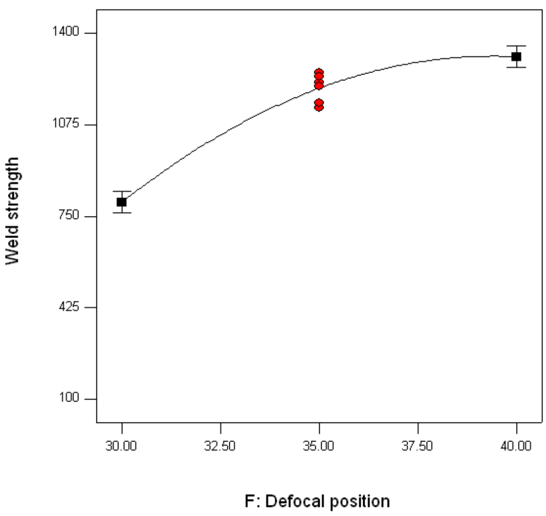

__Fig. 5__ Effect of defocal position on weld strength.

The trend of Figure 4 indicates up that the weld strength increases with welding speed upto 600 mm/min and thereafter it starts to decrease. The energy deposition and heat diffusion into the material depend on irradiation time and laser power density. At low welding speed, higher the irradiation time, resulting in overheating and degradation of the material, consequentially lowers joint strength. Further increasing welding speed improves the joint strength. While increasing the welding speed above 600 mm/min results in lower irradiation time, thus causing low-heat input and lack of penetration, which decreases the joint strength.

It is evident from the Fig. 5 that the weld strength increases with the increase of defocal position. In this study, the beam spot area is controlled by varying the defocal position of the beam. The beam spot diameter at the weld interface increases with the defocal position from material surface, thus decreasing laser power density as defocused portion of the beam is used. Increasing the beam spot area results in spreading the laser energy onto a wide area. This causes a wide weld seam resulting in higher weld strength.

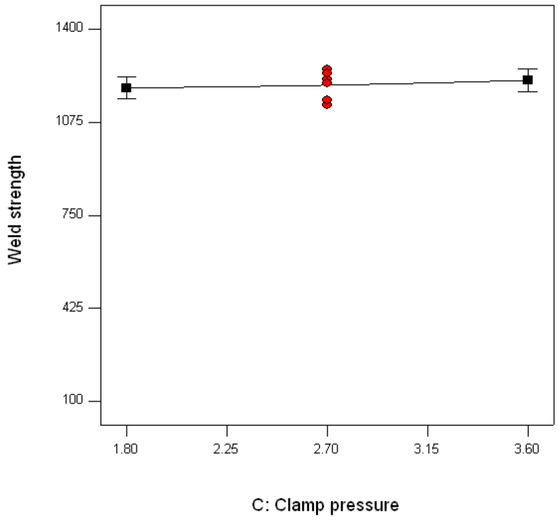

__Fig. 6__ Effect of clamp pressure on weld strength.

It is observed from the Fig. 6 that clamp pressure has statistically insignificant but a little positive effect on weld strength. The clamp pressure ensures intimate contact between overlapped materials, which is the basic requirement for this process as the laser transmission welding process largely relies on contact conduction.

6. Conclusions

The following conclusions can be drawn from this study based on the range of values of parameters considered.

1. Increasing laser power increases the weld strength until it reaches its center value, the strength then starts to drop as power is increased above the center limit.

2. Weld strength increases with welding speed upto 600 mm/min and thereafter it starts to decrease.

3. The weld strength is limited by very high heat input, which causes overheating and partial decomposition of the material, and a very low heat input results in lack of fusion.

4. Weld strength increases with the increase of defocal position.

5. Clamp pressure contributes positively with statistically insignificant effect on the weld strength.

6. It can be observed from the ANOVA tables that the defocal position has the maximum effect on weld strength and it is followed by laser power and welding speed.

7. The developed model can predict the response adequately within the limits of welding parameters being used.

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