An Experimental Investigation on Laser Beam Welding of Acrylics

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ABSTRACT

Laser beam welding (LBW) is nowadays increasingly used in the fabrication industry due to some of its distinct advantages. LBW offers high energy density around its focus thereby making it well suited for welding of certain category of materials that are considered difficult-to-weld. Since the laser follows the principles of optics, it is easy to regulate the laser beam by selecting appropriate lenses. In the present work, laser beam welding (LBW) is carried out to make lap joint of two acrylic flats- one opaque and the other transparent. Laser beam passes through the transparent piece of plastic flat and is focused on to the opaque flat around the interface region. Laser beam gets absorbed in the opaque flat in the interface region and generates heat energy causing local melting, and subsequent welding of both the flats. Clamping pressure is varied four times, and two levels of current flow and scanning speeds are set to find out a condition corresponding to sound, strong weld joint within the experimental domain. Good quality joint between transparent and opaque acrylic components with high weld strength of 8.33 MPa is obtained under 280 mm/min scanning speed and 2 MPa clamping pressure with 34 A weld current set, and hence, this condition may be recommended to apply to obtain enough weld strength.

Keywords: Laser, welding, LBW, Laser beam welding, acrylic, plastic welding.

1.0 INTRODUCTION

Laser beam welding (LBW) is nowadays increasingly used in welding of typical metallic and non-metallic components due to its distinct advantages because of its high energy density characteristic [1-3]. This high energy density welding method has been applied for successful welding of different metals and alloys, such as manganese alloys [4], titanium alloys [5], aerospace aluminium alloys [6], powder metallurgy components [7], etc. Different types of polymers have been experimented [8-11] to find out the optimum parametric conditions corresponding to a flawless, strong weld. Process modeling through computational techniques has also been tried [9,11,12]. Laser beam welding research has also been extended to dual beam welding for large heat input [13], under water welding in dry process [14], etc. Monitoring of laser welding through imaging has also been explored [15] in some other work.

In laser beam welding of acrylic, high energy laser is focused on two overlapping thermoplastic flats, one of which is transparent and the other is opaque. The laser beam penetrates the transparent plastic and heats up the absorbing opaque part. Heat is conducted from the opaque absorbing flat to the transparent flat, allowing both materials to melt to create a bond. The bonding between the two components occurs by the interpenetration of the molecular chains in this area, that is promoted by fluidity of acrylic during welding [3, 8, 16-18]. This method is named as through transmission laser welding. Acrylics are used widely in typical applications due to their light weight, more impact-resistant than glass, rigidity, good weather resistance, etc. Hence, sound joining of acrylics through welding is much needed.

Effect of different process parameters on good quality laser transmission welding of polymers was explored many researchers. Acherjee et al. performed [18] experiments on joining acrylic (polymethyl methacrylate) specimens by varying laser power, welding speed, size of the laser beam and clamp pressure, with regard to its lap-shear strength and weld-seam width. Misra et al. carried out [11] finite element analysis to simulate laser transmission welding of polycarbonates to facilitate selection of suitable process parameters to obtain a sound weld. Casalino and Ghorbel did [9] numerical modeling of CO2 laser welding of thermoplastic polymers to facilitate selection of appropriate process parameters. Sung et al. evaluated [10, 19] the effect of laser beam for plastic adhesion. In their work, three adhesion parameters, such as input power level, working time of laser beam and pulse per second, were systematically adjusted for suitable adhesion. Relationships between adhesive surface by laser beam and above three parameters were found out. Barma et al. studied [8] experimentally to investigate the weld joint characteristics of acrylic components under different scanning speed, current and clamping pressure combinations. They evaluated some parametric combinations to achieve desired weld quality.

On the other hand, Sabah and Mohammed [20] experimented on CO_2 laser welding of two different types of high density polyethylenes. They found penetration depth to increase with increasing laser output at a constant welding speed. Also a relation between spot width and depth calculated using MATLAB software program was explored. Mingareev et al. [21] investigated on relations between laser process conditions and dimensions and quality of the seam by means of optical and phase-contrast microscopy using thulium fibre laser radiation of 2 mm wave length. Laser welded polyethylene samples revealed a tensile strength of greater than 80% of the bulk material strength. In another work, Apostol et al. [22] used Finite Element Analysis on a single pass butt welding model to illustrate distortion and residual stress field developed in the thermo-elastic-plastic weld made by laser beam. They found residual stresses and distortion to increase with that of power, and to decrease with increase in speed. There was a reduction of residual stress and distortion as spot diameter increased.

In a recent research work, Bates et al. [23] made a thorough investigation on the reflectivity, transmissibility and absorptivity of laser beams in transmission laser welding. They introduced a tapered channel, within which if laser transmission welding is done, reflection of laser beams is restricted to a substantial amount. If glass fibre reinforcement is done within transparent part, reflection of laser beams can be reduced greatly due to multiple reflections made by different orientations of glass fibre pieces, reported.

In the present investigation, three process parameters such as scanning speed, clamping pressure and current are varied to find out the condition giving sound lap welding of acrylic specimens- one transparent and the other opaque, with enough tensile shear strength using laser beam welding.

2.0 EXPERIMENTAL CONDITIONS AND PROCEDURE

The laser unit system used in this work is based on diode laser system with a CNC Controller. The experimental set up is schematically shown in **Fig.1**. The laser can have repetitive operating current less than 60 A with pulse frequency of 0.25-10 kHz. The 30 W lasing system is of spectral width of 1.69 nm, beam divergence of less than 0.20 numerical aperture (N.A.) and beam diameter of 800 μm with a wavelength of 809.40 nm.

Flats of transparent and opaque polymethyl methacrylate, popularly known as acrylic, have been taken as work materials. Photographs of these two types of specimens are shown in **Fig.2.** Size of the two workpieces is 70 mm × 30 mm × 2 mm. Opaque acrylic specimens are procured from market with carbon black mixed in the transparent acrylic. First, the specimens are cleaned to remove the moisture and dust particles which cause improper weld joint. The transparent piece is put at the top most position for transmitting the laser beam through it. The absorbable opaque material is placed at the bottom position to absorb the laser to produce heat as shown in **Fig.1.** 20 mm overlap between these two materials is provided. Standoff distance is kept at 30 mm. The process of contour welding is utilized for this arrangement. The laser head is moved through the transverse section of the overlapping samples as illustrated in **Fig.3.**

As laser plastic welding is reported [10] to require appropriate clamping pressure system to facilitate good quality welding. In the present work, clamping pressure is varied to find its suitable value. Uniform pressure on to the welding zone is provided to reduce the defect due to improper holding of the specimens. Suitable mechanical clamping pressure is applied hydraulically to specimens for proper contraction between surfaces of both types of plastic materials. Clamping pressure

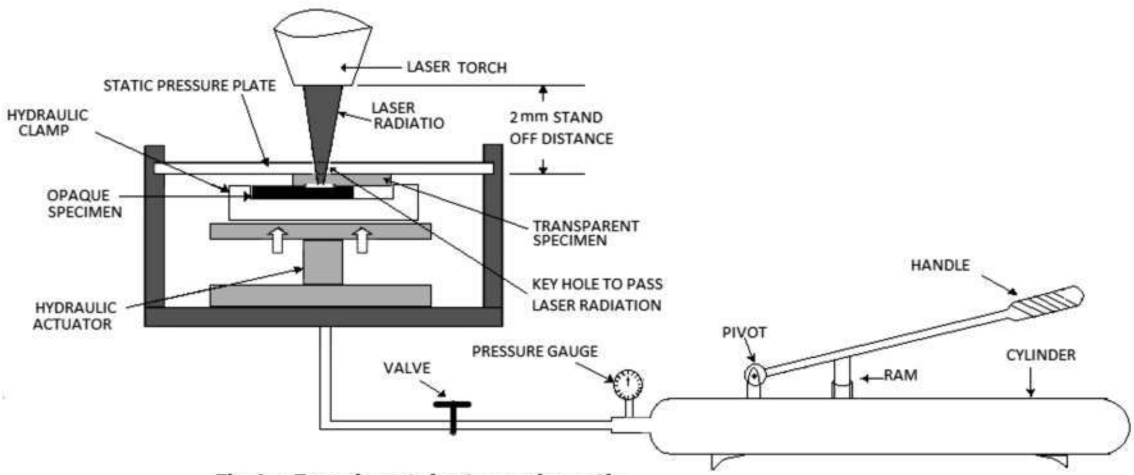
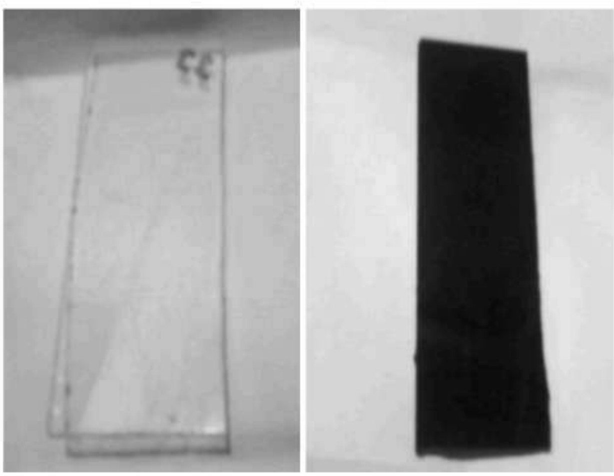


Fig.1 : Experimental set up schematic



(a) (b)

Fig.2: Photograph of (a) transparent and (b) opaque acrylic flats

promotes inter-mixing of the materials during welding. The pressure is applied by the hydraulic pump through the hydraulic jack within the range of experimental domain. A welding fixture is used to maintain the overlap constant for every run. Details of three variables, such as scanning speed, clamping pressure and current are set according to the design matrix as detailed in **Table 1**. Scanning speed and current flow are varied twice. Scanning speed of 240 mm/min and 280 mm/min, and current flow of 31 A and 34 A are considered, when clamping pressure is varied at four levels of 2 MPa, 3 MPa, 4 MPa and 5 MPa in this work.

Width of the weld zone plus HAZ (heat affected zone) has been measured under a Mitutoyo, Japan make tools makers microscope. This width is the total width of welded portion and heat affected zone at both the sides of weld zone. This width consists of the zone of melting and mixing along with the heat affected zone that is responsible for determining the strength of bond. Using a Metzer, India make metallurgical microscope, microstructure of the welded specimen is observed through viewing it from the top of the transparent acrylic specimen. Next, tensile shear strength of the lap welded joint has been evaluated through tensile shear tests with the load applied perpendicular to the weld direction as shown in **Fig.4**. These tests have been done at National Test House, Kolkata.

3.0 RESULTS AND DISCUSSION

In the present investigation on lap welding of plastic acrylic flats, three parameters like scanning speed, current flow and clamping pressure are varied to find out their influence on welding. A typical laser beam welded lap joint (obtained in experiment run 13) is shown in **Fig.3**. Width of the weld zone plus HAZ (heat affected zone) as measured under a Mitutoyo, Japan make tools makers microscope, is given in **Table 1**.

The melting and mixing area is bounded by deep white longitudinal marks which is the affected region by weld heat along both the two boundaries as shown in **Fig.5**.

Typical microstructure of weld specimen No. 8 (**Fig.6(a)**) shows the extent of mixing of both transparent and opaque acrylic materials. Small amount of mixing of transparent acrylic with that of opaque acrylic can be observed from **Fig.6(a)**. For this, tensile shear strength obtained at this experimental run is moderate, and this value is 3.23 MPa. Black and white spots are corresponding to opaque and transparent acrylic specimens. Gray spots are due to intermixing of opaque and transparent grains. When the microstructure of a weld bead contains

Table 1 : Observation table

Sl. No.	Scanning Speed (mm/min)	Current (A)	Clamping pressure (MPa)	Width of Weld + HAZ (mm)	Load (N)	Tensile shear strength (MPa)
1	240	31	2	1	700	5.83
2	240	31	3	1	800	5.93
3	240	31	4	1	470	3.48
4	240	31	5	1	568	5.41
5	240	34	2	1	680	4.12
6	240	34	3	1	570	3.45
7	240	34	4	1	534	3.24
8	240	34	5	1	484	3.23
9	280	31	2	2.34	750	5.56
10	280	31	3	2.7	500	3.33
11	280	31	4	4.43	550	3.06
12	280	31	5	2.19	560	4.67
13	280	34	2	2.06	1000	8.33
14	280	34	3	2.48	600	5.0
15	280	34	4	3.23	820	5.47
16	280	34	5	2.30	540	3.0

uniformly dispersed white, gray and black spots, tensile strength of the weld is expected to be high. From **Fig.6(b)**, it is observed that there is comparatively high mixing of white, gray and black spots than the microstructure shown in **Fig.6(a)**. As a result, high tensile shear strength of 8.33 MPa is achieved for specimen No. 13. Therefore, uniform mixing of opaque and transparent parts is desired to obtain high joint strength.

Influence of laser beam welding parameters, like clamping pressure at two different scanning speed and current flow is explored in this work. Variation of width of weld plus HAZ with four levels of clamping pressure at current flow of 31 A and 34 A and scanning speeds of 240 mm/min and 280 mm/min are indicated in **Table 1**. It is seen that width of weld plus HAZ is of only 1 mm at a scanning speed of 240 mm/min under all the 8 experimental runs. At a lower clamping pressure, larger load could be withstood by the weldment, and correspondingly, larger tensile shear strength could be obtained. At 31 A current and at clamping pressure of 2 and 3 MPa, tensile shear strength of 5.83 MPa and 5.93 MPa could be achieved respectively, while at 34 A current and 2 MPa clamping pressure, as high as 4.12 MPa tensile shear strength could be obtained.

However, at a higher scanning speed of 280 mm/min, width of weld zone plus HAZ is found to be remarkably higher. At 31 A current flow and lower clamping pressure of 2 MPa, higher tensile shear strength of 5.56 MPa could be had that at the other clamping pressures of 3, 4 and 5 MPa. When current flow was somewhat higher at 34 A, higher tensile shear strength of 8.33 MPa has been achieved than that at higher clamping pressure set.

From the above results and discussion, it can be stated that at high current flow of 34 A and low scanning speed of 240 mm/min, maximum heat input is there at the weld, and at this condition, less tensile shear strength is obtained. On the other hand, at 31 A current and 280 mm/min scanning speed, minimum heat input is there and correspondingly less tensile shear strength is attained. At the moderate heat input with 34 A current flow and 280 mm/min scanning speed, high tensile shear strength is achieved, and this may be considered to the

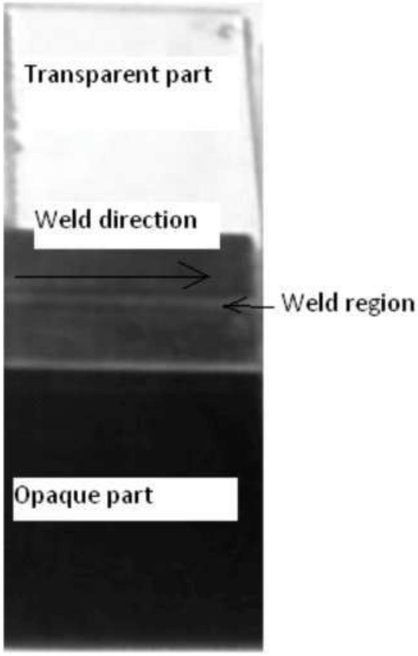


Fig.3 : Typical plastic laser welded specimen (No. 13)

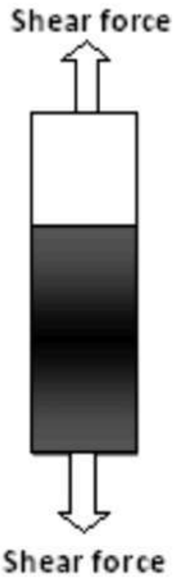


Fig.4 : Tensile shear test specimen indicating application of shear force

optimal experimental condition at low clamping pressure of 2 MPa.

4.0 CONCLUSION

In this experimental work, investigation is made on laser beam welding of transparent and opaque acrylic specimens at varying clamping pressure, scanning speed and current.

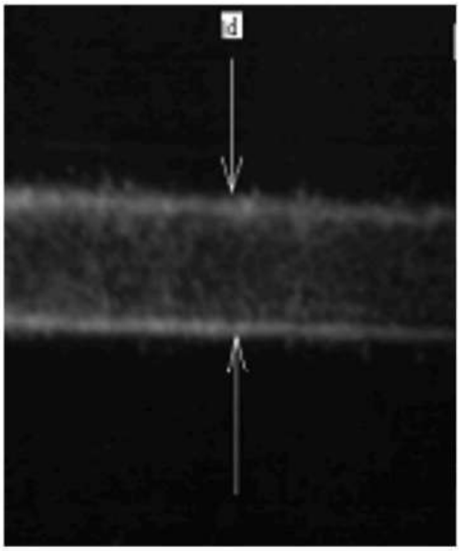
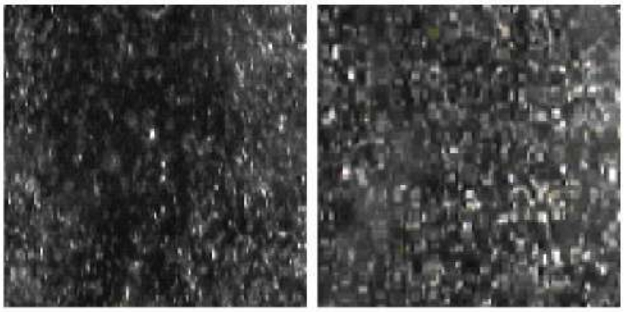


Fig.5 : Photographic view of a typical weld seam



(a) (b)

Fig.6: Microstructure (X25) of weld seam of (a) specimen No. 8 obtained at 240 mm/min weld speed, 34 Amp current flow and 5 MPa clamping pressure, and (b) specimen No. 13 obtained at 280 mm/min weld speed, 34 Amp current flow and 2 MPa clamping pressure

Following conclusions may be made from the results obtained from the experimental work.

- Width of weld zone plus HAZ is influenced by the variation of scanning speed, current flow and clamping pressure.
- Maximum tensile shear strength of 8.33 MPa is obtained at 280 mm/min scanning speed at 34 A current and 2 MPa clamping pressure. At this case, moderately high width of weld zone plus heat affected zone is obtained, and quite high fracture load of 1 kN is achieved. Hence, this condition may be recommended to adopt.

REFERENCES

[1] Richardson, D. J., Nilsson, J. and Clarkson, W. A. (2010); High power fiber lasers: current status and future perspectives, J. Optical Society of America: B Optical Physics, 27(11), pp.B63-B92.

[2] Pal, T. K. (2010); Laser welding, Proceedings of the Workshop on Application of Laser in Materials Processing, Jadavpur, Kolkata, pp.65-66.

[3] Shanker, K. (2010); Laser welding of metals, micro to hybrid, Proceedings of the Seminar on Application of Laser in Materials Processing, Jadavpur, Kolkata, pp.98-100.

[4] Cao, X., Jahazi, M., Immarigeon, J. P. and Wallace, W. (2009); A review of laser welding techniques for magnesium alloys, J. Materials Processing Technology, 171, pp.188-204.

[5] Akman, E., Demir, A., Canel, T. and Sınmazc, T. (2009); laser welding of Ti6Al4V titanium alloys, J. Materials Processing Technology, 209, pp.3705-3713.

[6] Verhaeghe, G. (2007); Low-porosity laser welding of 12.7 mm thickness aerospace aluminium, Proceedings of the INALCO 2007, Tokyo, Japan.

[7] Hamill, J. A. (1994); Laser welding p/m for automotive applications, Proceedings of the SAE International Congress and Exposition, Detroit, Michigan, USA, pp.1-11, SAE Technical Paper No. 940355.

[8] Barma, J. D., Pal, P. K. and Bandyopadhyay, A. (2010); Study on the effects of different process parameters in through transmission laser welding, Proceedings of the Seminar on Application of Laser in Materials Processing, Jadavpur, Kolkata, pp.193-195.

[9] Casalino, G. and Ghorbel, E. (2008); Numerical model of CO2 laser welding of thermoplastic polymers, J. Materials Processing Technology, 207, pp.63-71.

[10] Sung, J. P., HaeJae, Y. P. and Ji, Y. S. (2007); Laser welding parameter variations and its application for plastic adhesion, Electrical Engineering & Technology, 2(1), pp.112-117.

[11] Misra, D., Acherjee, B., Kuar, A. S. and Mitra, S. (2005); Transmission laser contour welding of polycarbonates with a moving laser beam: process simulation via FEM, Proceedings of the 24th International Congress on Applications of Lasers & Electro-Optics, pp.11-14.

[12] Ilie, M., Cicala, E., Grevey, D., Mattei, S. and Stoica, V. (2004); Diode Laser Welding of ABS: Experiments and Process Modelling, University of Timisoara, Project No. 71-088.

[13] Xie, J. (2002); Dual beam laser welding, Welding Journal, 81(10), pp.223s-230s.

[14] Zhang, X., Ashida, E., Shono, S. and Matsuda, F. (2006); Effect of shielding conditions of local dry cavity on weld quality in underwater Nd:YAG laser welding, J. Materials Processing Technology, 174, pp.34-41.

[15] Olsson, R. (2009); Signal processing and high speed imaging as monitoring tools for pulsed laser, Licentiate Thesis submitted to the Division of Manufacturing Systems Engineering, Lulea University of Technology, Lulea, Sweden.

[16] Petri, L., Saara, R., Tuomas, P., Hannu, M. and Veli, K. (1998); Simultaneous sub second laser welding of polymers with diffractive optics, Technical Research Center of Finland, Paper No. 702.

[17] Majumdar, J. D. and Manna, I. (2003); Laser processing of materials, Proceedings of the Workshop on Application of Laser in Material Processing, 28(3&4), pp.495–562.

[18] Acherjee, B., Misra, D., Bose, D. and Venkadeshwaran, K. (2009); Prediction of weld strength and seam width for laser transmission welding of thermoplastic using response surface methodology, Optics & Laser Technology, 41(8), pp.956-967.

[19] Sung, J. P., Sung J. P., Hae, Y. P., Jae, W. P., Ji, Y. S., Jin, Y. C and Hee, J. K. (2007); Laser welding parameter variations and its application for plastic adhesion, Journal of Electrical Engineering & Technology, 2(1), pp.112-117.

[20] Sabah, F. A. and Mohammed, S. N. (2012); Welding of thermo plastic material using CO2 laser, Diyala Journal of Engineering Sciences, 5(1), pp.40-51.

[21] Mingareev, I., Weirauch, F., Olowinsky, A., Shah, L., Kadwani, P. and Richardson, M. (2012); Welding of polymers using a 2mm thulium fiber laser, Journal of Optics & Laser Technology, 44, pp.2095–2099.

[22] Apostol, G. M., Solomon, G. and Iordachescu, D. (2012); Input parameters influence on the residual stress and distortions at laser welding using finite element analysis, U.P.B. Science Bulletin, Series D, 74(2), pp. 153-164.

[23] Chen, M., Zak, G. and Bates, P. J. (2014); Measurement of the optical properties of thermoplastics used in laser transmission welding, Proceedings of the 67th Annual Assembly of the International Institute of Welding: Commission XVI- Polymer Joining and Adhesive Technology, Seoul, Korea.