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Chapter

Parametric Studies on Transmission Laser Welding of Acrylics

Ramesh Rudrapati

Abstract

Due to limitations of injection molding of polymer/plastic materials, complex plastic parts are often assembled from two or more injection-molded components. Joining of polymers can be achieved by chemical-based technologies and thermal methods such as welding. Welding technique is one of the important manufacturing routes that can be used to refine product design and reduce production cost. Plastic welding processes typically involve heating the joining faces to induce localized melting and subsequently applying pressure to cause molecular diffusion at the molten interface, which produces a solid weld upon cooling. The need for an effective welding process that is fast, accurate, and with no relative part movement has fueled the development of laser-transmission welding (LTW) technology. LTW is an innovative joining process for acrylate materials. The quality of weld highly depends on correct selection of process parameters in LTW. The systematic study and analysis are required to conduct LTE process economically and efficiently. In the present chapter, current prospects of applications of acrylates and joining of them using LTW has been analyzed. The main emphasis has been given to analyze the variations of quality performance characteristics with varying input welding factors and concluding remarks has been drawn from present work. From this study, it is observed that acrylics are future innovative industrial materials, which need to be joined to create complex features on them. Welding of acrylics using LTW to achieve better and more economical weld performance is still under continuous research by scientists/industrialists.

Keywords: acrylics, plastic welding, laser transmission welding, laser welding parameters

1. Introduction

Manufacturing is a methodology that is used to transform the raw materials into useful products by performing series of operations on it [1]. Steels and its alloys are highly consuming materials by industrialists to produce a variety of structures or products through different manufacturing techniques [2]. Apart from the many advantages of the steels and its alloys, it has some major limitations such as weight, cost, complexities of production, difficulties in creating complex features, lower corrosion resistance in wet environments, etc., which limits its usage for some industrial applications. Because of the mentioned reasons, industrialists/engineers

looking for another alternative material to replace the steels, found plastics as the best substitute compared to glass and composite materials. Nowadays, plastics/polymers are used to produce a wide variety of industrial products from the very simple ones to the extremely complex featured ones ranging from domestic purpose parts to advanced products such as food storage, medical, optical materials, coatings, electrical devices, electronics, automobiles, space vehicles, etc. [3, 4], due to its good strength to weight ratio, ease of fabrication of complex shapes, low cost, ease of recycling, etc. [5]. Two different types of plastics, such as thermoplastics and thermosets, are extensively used to create industrial products. Thermoplastic materials are softened by applying heat and can be molded into the required shape and size [6, 7]. Important thermoplastics are acrylic, polypropylene, polystyrene, polythene and PVC. Whereas thermosets are formed by heating process and then set its final shape like concrete. The shape of the thermosets cannot modify by reheating them. The materials namely melamine, Bakelite, polyester and epoxy resins are important examples of thermosets. Thermoplastics are the materials which found to be fast growing ones in various industrial purposes due to its excellent properties like strength-to-weight ratio, good high fracture toughness and fatigue resistance, ease of recycling, ease of fabrication of complex parts, low material and processing cost, enhanced thermal insulation and flexibility features [8–11].

The production of complex feature plastics components in any near net manufacturing processes is difficult and not recommended methods regarding to economic aspects. Different types of fabrication methods like plastic adhesive joining, mechanical fastening and welding techniques have been used by various industries [12] to weld two or more plastics parts to create a complete complex plastic product. The welding techniques are more suitable to join plastics compared to other joining techniques, due its advantages like fast and easy processing, tightness of the joint, high strength, etc. [13–15]. There are several welding techniques like tungsten inert gas (TIG) welding, metal inert gas (MIG) and laser welding to join plastics, which are often used by industrialists. Among other methods, laser transmission welding (LTW) is based on lasers and constitutes one of the most innovative fabrication techniques, which are used to join plastic materials into a variety of geometries [16–18] due to process flexibility and better weld quality [19]. Nowadays, the technology of laser transmission welding has been developed to weld a variety of polymers [20] including polycarbonates, acrylic, polyvinylchloride and polyamides using different types of lasers such as CO_2, Nd:YAG, and diode lasers. The usage of LTW in the welding of plastics is increasing due to its advantages and performance capabilities like non-contact, flexible process, easy to control, automate, speed, localized heat, fine spot during welding, etc., compared to other joining technologies.

In LTW, a laser beam is focused on two overlapping thermoplastic materials to be joined. The first part is designed to be transparent to the laser wavelength and second part is absorbent in IR spectrum. The laser beam penetrates the top transparent part and then heat is absorbed and transformed into the underlying absorbing part. Because of the relative motion between the laser beam and the parts to be joined, the laser beam is continuously operating to irradiate the line of specific width of welding zone. This heat is transferred to the transparent part by thermal conduction between the joining parts. Subsequently, surface layers of both materials are melted and welded due to the generated heat. The principle of the laser welding is shown in **Figure 1**. The quality levels of weldment in LTW is depending on the welding material behavior during laser irradiation, controlling of optical properties [21] and correct choice of laser process parameters [22]. To understand the optical phenomena of welding plastic materials various experimental approaches are used to determine the effects of fillers, pigments, reinforcement, combined effect of thickness and color, etc. One of the limitations in laser welding is the energy lost

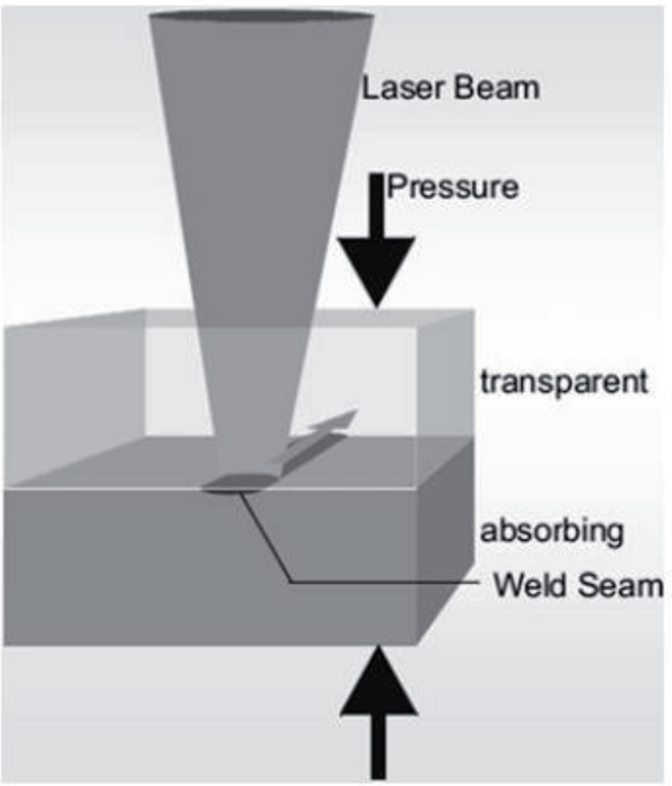


Figure 1.
Schematic diagram showing basic principle of laser transmission welding process, in which laser beam transferred through transparent part to absorbing part and generation of weld seam [34].

due to reflection and absorption due to scattering from the laser transparent part. Polymer degradation and surface burning which affect the strength and the visual appeal of the weldment. In order to achieve a successful weld through laser transmission welding, a good understanding of the issues associated with the welding process are necessary. Due to the complexity of modeling the heating phase of laser transmission welding, experimental methods has been utilized to study welding parameters. In the present chapter, focus has been given to investigate the significances of laser process parameters on weld quality characteristics in laser transmission welding of acrylic materials.

Acrylics are important materials of thermoplastics and its demand is increasing for many industrial applications. Acrylic materials are available in a wide range of thicknesses and colors. They can be opaque, translucent or transparent. They are available in sheet, rod, and tube for use in injection molding, extrusion and vacuum forming. Acrylics withstand all of the weather conditions and it can also be stable in sunlight as well. Transparent acrylics can be used in optical equipment such as cameras due to its finest optical glass property. Acrylics are used widely in typical applications due to their light weight, more impact-resistant than glass, rigidity, good weather resistance, etc. [23]. Various types of acrylics, which are widely used for industrial purposes, include: poly(methyl methacrylate) [24], poly(2-hydroxyethyl acrylate) [25, 26], poly (2-hydroxyethyl methacrylate), etc. [27]. The application of acrylics includes aircraft windows, aerospace [28], electrophoretic applications in the biotechnology industry for separation purposes, identification and preparation of pure samples of nucleic acids, proteins, carbohydrates [29], thermoforming applications such as shower or tub enclosures, outdoor signs [30], medical applications [31, 32], automobiles, house hold applications, etc. For many of the mentioned applications, two or more similar or dissimilar acrylics can be joined to create the complex shape products. Laser transmission welding (LTW)

is very often used to join these acrylic materials [23, 33]. LTW of acrylics is an important area of research because of the complexity of the welding process and its associated problems during joining of acrylics [22, 32].

2. Laser transmission welding (LTW)

By means of LTW, welding of plastics is performed by transmitting a laser beam through a laser-transparent material, named as direct laser welding, and weld at interface with the laser-absorbing part, called laser transmission welding [35, 36]. By both welding methods, laser beam is utilized to weld plastic materials. **Figure 2** represents the working principle of laser transmission welding process.

The selection of the laser beam type is depending on the thermo-optical properties of the beam and workpiece. Generally, plastics are transparent to laser radiation at its nature state. This property helps to weld the plastics very easily. During welding, when laser beam focused on transparent plastic sheet, some fractions of the incident light is reflected and the remaining light is transmitted through the job. The absorbing capability of the plastic part by radiation energy can be calculated by the Beer–Lambert law. Molecular diffusion can occur and with the application of clamping pressure, a contact portion of the two parts are joined and thus, a solid joint is formed. Different steps of LTW is shown in **Figure 3**.

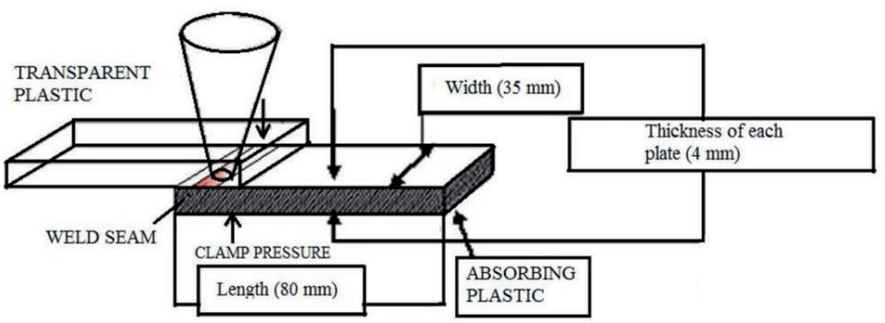


Figure 2.
Schematic diagram showing laser transmission welding setup in which one can find both transparent plate and absorbing plate and focused laser beam and weld seam generation [37].

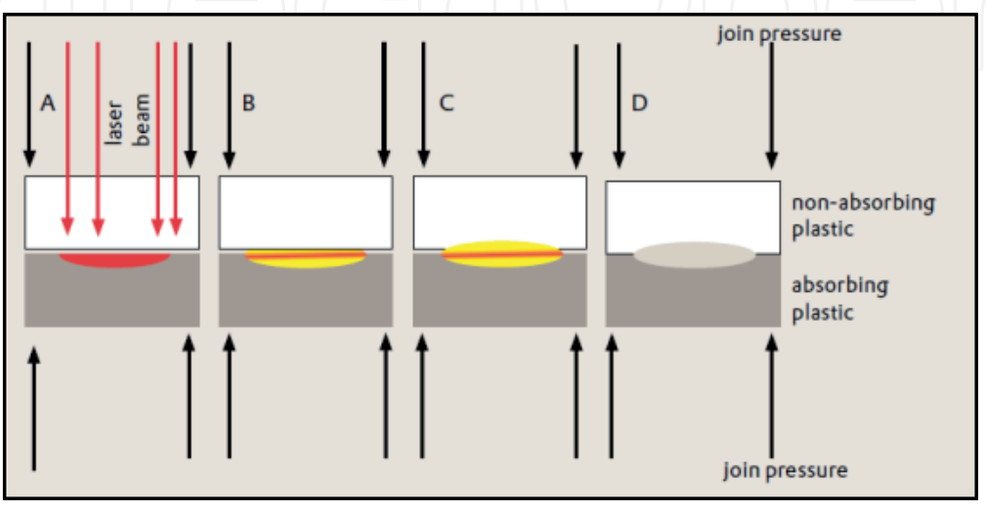


Figure 3.
Schematic diagram showing three stages of laser welding process to join plastic materials with the application of laser beam, melting and welding of plastic plates [38].

3. Literature survey

Very few research studies on LTW of plastics have been done. Thus, several aspects need to be extensively explored to enhance the welding performance. In the present study, transmission laser welding of thermoplastics, especially acrylics, has been analyzed with respect to varying input parameters. Some of the reported articles from the literature related to welding of acrylics using LTW are discussed in the following paragraphs.

Mandal et al. [23] maximized the weld strength of laser beam welding of transparent and opaque acrylic specimens. Researchers considered clamping pressure, scanning speed and current as process parameters. Thus, they found from their investigation that the strength of the welded joint was highly influenced by the variation of scanning speed, current flow and clamping pressure. On the other hand, Acherjee et al. [33] studied and analyzed the laser transmission welding of acrylics to determine the optimal welding parameters to attain a desired weld seam with maximum joint strength. Direct and interaction effects of process welding parameters on output responses were illustrated through overlay contour plots. The optimal parametric setting was obtained by overlay contour plots to enhance the welding performance. Acherjee et al. [34] also carried out research work on laser transmission welding process of thermoplastics (acrylics) to predict the multiple quality characteristics. They applied combined applications of gray-Taguchi methodologies to plan the experiments and optimize the multi-responses, weld strength and weld width by controlling welding parameters, like laser power, welding speed and defocal position. Analysis of variance was applied on experimental data to identify the most significant process variable for the overall output feature of the LTW operation. They stated from ANOVA results that laser power had the most dominant effect on both responses: defocal position and welding speed.

Kumar et al. [37] studied and analyzed the influences of laser process parameters to optimize weldment quality performances by through transmission laser welding (TTLW) of acrylic materials. They conducted the experiments based on orthogonal array of Taguchi method to determine the factor effects on output responses of acrylic joints by TTLW. The statistical tools like signal-to-noise ratio and analysis variance were utilized to depict the significances of laser process variables on joint strength and weld width of laser welded joint. From the analysis, researchers stated that quality characteristics of laser-welded acrylics were significantly influenced by process parameters and the Taguchi method was robust tool for analyzing and optimizing the TTLW of acrylics. Acherjee et al. [39] studied and optimized the weld quality characteristics by performing experiments on joining acrylics (poly(methyl methacrylate)) specimens by laser transmission welding by varying process parameters namely laser power, welding speed, size of the laser beam and clamp pressure. They developed the mathematical models between the input parameters and out responses to generate mathematical relationships between them. Analysis of variance (ANOVA) had been used to determine the effects of laser variables on weldment responses: lap shear strength and weld seam width. Investigators stated from the performed research that the control and the optimization of the process parameters were very important in laser transmission welding to enhance its efficiency. Acherjee et al. [40] utilized the integrated Taguchi method and desirability function approach to analyze and optimize the welded joint responses of acrylic plastic material in LTW. The authors conducted experiments as per orthogonal array of Taguchi method. ANOVA was used to find the influential process variables on weld responses. From this study, the researchers mentioned that Taguchi method and ANOVA were useful tools to study and optimize the process conditions to improve the responses of acrylic welded joints in LTW.

Acherjee et al. [41] carried out an experimental investigation to analyze the significances of process variables and control them to enhance the process efficiency of LTW of acrylic materials. Experimental runs were performed by orthogonal array of Taguchi method. The dependency of weld strength on correct selection welding parametric conditions were studied by using the analysis variance technique. The authors of this work stated from the study that laser power showed the highest influence on weld strength, followed by focal distance and welding speed. The optimal parametric setting was obtained by Taguchi method, which was conformed through the confirmatory test. Barma et al. [42] conducted experimental analysis to investigate the weld joint characteristics of acrylic components under varying input process conditions namely scanning speed, current and clamping pressure. These investigators studied the variations of weld quality responses with varying process parameters. They evaluated some parametric combinations to obtain desired weld quality. Nitesh et al. [43] carried out a research to analyze, model and optimize the laser process variables namely laser power, scanning speed and frequency to improve the quality characteristics of acrylic and polycarbonate welded joint in through transmission laser welding. Analysis of variance was utilized to determine the influential process parameters, which had detrimental effects on process performances. They stated from this study that selection of optimal parametric setting plays a critical role to obtain the desired weld joint qualities.

Kumar et al. [44] studied the effects of process parameters on the circular contour laser transmission welding of acrylic plastics. Experiments were conducted based on orthogonal array of Taguchi method by considering laser current, stand-off distance and rotational speed as input parameters. The significances of process parameters on output responses, weld width and breaking load were studied by ANOVA. They mentioned in their research that welding responses were significantly influenced by process parametric conditions. Acherjee et al. [45] made an experimental investigation on diode laser transmission welding of dissimilar thermoplastics between poly(methyl methacrylate) and acrylonitrile butadiene styrene to study the effects of the laser welding parameters like laser power, welding speed, stand-off distance and clamp pressure on responses: weld strength and weld width. The ANOVA technique was applied on experimental data to identify the significant process variables, which were expected to influence the welding responses. Graphical contour plots were also drawn to study the direct and interaction effects of input variables on welding performances. Nakhaei et al. [46] utilized the applications of artificial neural network (ANN) to study and model the effects of laser power, welding speed, clamp pressure and stand-off distance on output response, weld lap-shear strength in laser transmission welding (LTW) of acrylics. They developed ANN based model to analyze and predict the complex relationships between laser parameters and weld quality response. They observed from their research analysis that weld lap-shear strength was increasing with increasing laser power and clamp pressure and decreasing with increasing welding speed and stand–off distance.

Kumar and Bandyopadhyay [47] analyzed the contour laser transmission welding (LTW) of thermoplastics by process modeling, finite element method (FEM) and response surface methodology (RSM) integrated approach. They studied the effect of process parameters on temperature field and weld bead dimension. Interaction effects of process parameters on the responses were studied using the graphical response surface plots. They observed from their investigation that responses such as weld width, depth of penetration in absorbent part and maximum temperature at weld interface decreased with increasing scanning speed, laser power and spot diameter, which were significant factors on the maximum temperature at weld interface. Seo et al. [48] used LTW to join acrylics and other thermoplastic materials. These experiments were conducted with varying specific

energy and weld time. They stated that LTW was not only a useful method for welding acrylics but also cost effective in comparison with the other plastics joining methodologies. Shashi et al. [49] made a study on pulsed Nd:YAG laser welding of poly(methyl methacrylate) to determine the influences of process parameters namely lamp current, pulse frequency, pulse width and cutting speed, on microchannel characteristics, microchannel width, microchannel depth, burr width and burr height. They conducted experiments based on response surface methodology (RSM). Mathematical relationships between the input parameters and output responses were made by RSM. They explored the variations of output responses with varying input parameters using ANOVA and graphical plots and stated that process parameters were most significant for enhancing the welding performance.

From the extensive literature survey made in the present chapter, it can be stated that acrylics are the one of the most important industrial material family of polymers. The usage of these materials is growing for various industrial needs as mentioned earlier [50–53]. Laser transmission welding (LTW) is effective and efficient for welding of acrylics or other polymer materials [54–59]. Parametric studies related to various aspects of joining of acrylics by LTW can make sound knowledge base, from which industrial persons may select optimal parametric settings to produce economically and predictably desired weld joint quality performances. The present chapter is one-step forward for it. Many more related studies will make the LTW of acrylics simple and easy.

4. Conclusions

The conclusions drawn from the present study of joining of acrylic materials using the laser transmission welding (LTW) process are presented as follows:

i. Importance and necessity of welding of plastics have been discussed.

ii. Thermoplastic materials are extensively used in advanced industrial purposes such as automotive, aerospace, medical, etc.

iii. The importance of joining of thermoplastics, especially acrylics, have been discussed.

iv. Laser transmission welding is one of the most important plastic joining techniques, among others, which is used to create complex shape jobs.

v. Understanding the relationships between input and output responses plays a critical role in welding of acrylics by LTW.

vi. Correct selection of laser process parameters is crucial to obtained desired weld qualities on acrylic welded joints.

vii. Polymer degradation and surface burning are notable defects during thermoplastic welding.

viii. The effects of laser parameters on performance characteristics of weldments needs to be properly understood to conduct LTW in an optimum manner.

ix. Statistical tools like analysis of variance, signal-to-noise ratio are useful to study and analyze the factor effects on outcome of the LTW.

x. More experimental research works related to thermoplastic welding by laser transmission welding (LTW) needs to be conducted to enhance the performance of welding.

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Conflict of interest

The author declaring no conflict of interest.

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