A State-of-the-Art Review of Laser Welding of Polymers — Part I: Welding Parameters

This paper reviews the influence of different processing parameters, including laser power, scanning speed, standoff distance, and clamping pressure

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ABSTRACT

Polymers are widely used in automotive parts and fields like mechatronics and biomedical engineering because of their excellent properties, such as high durability and light weight. Welding of polymers has grown to be an important field of research due to its relevance among products of everyday life. Through transmission laser welding (TTLW) has been frequently selected by the contemporary researchers in the field of welding as it is relatively modern and more efficient than other welding processes. This paper reviews the influence of different processing parameters, including laser power, scanning speed, standoff distance, and clamping pressure. The present article is expected to provide the reader with a comprehensive understanding of TTLW and research on the aforementioned four welding parameters in TTLW. The significance of finite element modeling, a few simulation studies, different optimization approaches, morphological characteristics, and other behaviors of laser welded polymers will be included in the next part of the review.

KEYWORDS

• Polymers • Laser Welding • Optimization • Morphology
• Finite Element Modeling

Introduction

The polymer is known to be an important engineering material due to several reasons. The combination of a wide range of properties like toughness, good strength-to-weight ratio, noncorrosive, good chemical resistance, moisture resistance, low thermal and electrical conductivity, ease of fabrication into complicated shapes, and so on are unattainable from any other materials. In addition, more desirable properties can be achieved by incorporating various compound-

ing ingredients, such as reinforcing agents, colorants, plasticizers, stabilizers, flame retardants, and more (Ref. 1).

Joints between polymer/plastic parts can be of three types — namely mechanical, adhesive, and welded joints. While mechanical joints are composed of screws, snap-fit, or press-fit, which result in the least time of production, they cannot be leak proof. When it comes to the remaining two types, where a complete leak-proof joint can be achieved, the advantage with adhesive joints over welded ones is the versatility of the types of materials and the shapes of joining parts. The disadvantages with the former include high material cost, which is not beneficial for high-volume production, and slow curing time, which leads to longer production time. On the other hand, plastic welding has been a rapidly improving field in which the disadvantages are being addressed effectively and efficiently through extensive research. Among the many methods adapted for welding of polymers, like ultrasonic, friction stir, hot plate, and hot gas welding, laser welding is one of the most promising techniques due to its ability to produce highly accurate and strong joints maintaining tighter tolerances (Refs. 17–23). Although electron beam welding can also perform with similar benefits, it is more expensive because of the complexities in setup, such as requirement of a vacuum, and is less safe due to the production x-rays. The few disadvantages of laser welding, in general, include a high initial cost of setup, which makes it uneconomical for low-volume production, requirement of careful joint design to avoid costly mistakes, and so on. The basic types of laser welding in practice are given below.

Types of Laser Welding of Plastics (Ref. 5)

Contour Welding. Contour welding is a process where welding is done in one pass. This method is highly flexible to facilitate high quality control. A disadvantage is that the welding speed is less than that of other methods.

Fig. 1 — Schematic diagrams of various modes of laser welding: A — Conduction mode; B — transition mode; C — keyhole mode.

Simultaneous Laser Welding. In this type of welding, heating and welding of the entire joint are done at the same time. Multiple lasers are designed into arrays using multiple fiber optic cables, and the beam itself is formed in the shape of the joint. This method has an advantage of faster welds. But the complexity involved in designing the arrangement with multiple laser tools results in higher costs.

Quasi-Simultaneous Laser Welding (QSLW). In this type of welding, the laser beam is fed into a mirror system, which will facilitate it to trace the joint multiple times rapidly. Since the joints are heated repeatedly at faster pace, the heating is almost simultaneous.

Hybrid Laser Welding. In this method, a halogen lamp is added to the contour welding in which the parts will be provided with extra heat. This will facilitate preheating and also stress relieving of the joining parts to allow a better gap filling.

Modes of Laser Welding (Ref. 5)

Conduction Mode. In this mode, the heat required for fusion is conducted from the surface with a beam of low energy density. The weld nugget formed is smooth and wide with a low depth of penetration.

Transition Mode. The beam in this method has a medium power density and produces more penetration than conduction mode. This mode is almost exclusively used by a pulsed Nd:YAG laser for many seam and spot welding applications.

Keyhole or Penetration Mode. In this mode, a high peak power density beam is used, which produces a narrow and deep hole in the part by melting the material. The hole gets filled with molten metal during the weld. With the aspect ratio higher than 1.5, this method is used for thick job parts.

The schematic heat transmission profiles for the three above mentioned welding modes can be seen in Fig. 1. The relative amount of heat propagation is proportional to the size of the arrow in the corresponding direction.

Transmission Welding by Incremental Scanning Technique (TWIST). This mode of welding is used to optimize the heat distribution throughout the weld zone to prevent the material damages occurring at the focal spot. The energy is provided using overlapping oscillations of the laser beam moving along the weld contour (Ref. 39). Two sample oscillation profiles can be seen in Fig. 2.

The current study focuses on through transmission

Fig. 2 — Sample oscillation profiles of the laser beam in TWIST mode.

laser welding (TTLW), also referred to as laser transmission welding (LTW), a high-energy-density joining process. Initially, it was used to join molded thermoplastic articles or films. Nowadays, it has become an established process for welding polymer products, including composites (Refs. 2–4). They are widely used in industries like automotive, microelectronics, aerospace, medical, packaging, optoelectronics, microsystems, and so forth (Ref. 5). Welding of different materials having varying thicknesses and configurations is also possible using this technique (Ref. 6). Through an industrial perspective, the key advantages of TTLW are reproducibility of the process without wear and tear of the tool combined with increased productivity and better quality. It is a noncontact, flexible, and easily controllable process with almost no contamination (Ref. 7). With the use of lasers, narrow and localized heat zones can be created. However, there are various investigations still going on in this field (Ref. 8).

The TTLW process is widely used with varying types of lasers for joining plastic parts (Ref. 9). A CO₂ laser produces an infrared (IR) light beam with wavelength bands at 10.6 μm (Ref. 10). These lasers are restricted to welding of thin films (micrometers to 1 mm) (Ref. 11), whereas the Nd:YAG laser and diode lasers are suitable for welding of thick parts due to the high transmission of polymers in the near IR field (Ref. 12). Diode lasers are the most widely used lasers in industries due to their compactness, modular setup, high energy efficiency, and relatively low cost per watt of photon energy (Refs. 13–16). The difficulty in joining plastic parts can be overcome using this innovative type of laser (Refs. 17–21). Apart from some research publications, little information is available in the field of TTLW of polymers. Although many experiments, process optimizations (Refs. 19, 22–43), modelings (Refs. 44–83) and analyses emphasizing morphology (Refs. 71–85), performance evaluations, etc., have been carried out, there are certain lapses observed during the literature survey.

Process Overview and Important Parameters of Transmission Welding

Extensive studies have been done in the process overview of laser welding of polymers (Refs. 12, 17–23, 24–114). The process overview is summarized in this section along with the important process parameters.

Process Overview of Through Transmission Laser Welding

The most basic configuration for TTLW of polymers is an overlap joint assembled by a transparent polymer work material placed on the top of an absorbing polymer — Fig. 3 (Refs. 17, 19, 22, 23). The laser beam is transmitted through the upper transparent part and is converted into heat by the absorbing lower part (Ref. 25). Both the parts are to be clamped together during the process. Due to this clamping force, the two surfaces come in intimate contact with each other, and heat is conducted from the absorbing lower part to the transmissive part. This allows both parts to melt and create a joint only where the laser beam is directed. Nearly all thermoplastics can be welded using this technique. Special additives/pigments also allow TTLW of two opaque materials as well as two transparent workpieces (Refs. 85, 88, 90–93). To determine whether two polymers are weldable (i.e., weld compatible), weldability charts are available for six selected materials by Juhl et al. (Ref. 18). TTLW has various advantages as compared to conventional techniques, such as ultrasonic welding, hot plate welding, and adhesion. While these techniques have their own significance, each has limitations either related to the process or the materials besides dedicated tooling requirements. In terms of running costs, electrical efficiency of diode lasers is greater than 30% as compared to typical levels for CO₂ (10%) and Nd:YAG (4%) (Ref. 21).

The present study is primarily divided into three sections that are essential to formulate a complete working understanding of TTLW. The first section deals with the most significant process parameters of the TTLW, namely laser power, scanning speed, standoff distance, and clamping pressure. Each parameter is analyzed with respect to its effects on the weld quality. Weld quality is basically described through various output parameters, namely joint strength, weld geometry, heat-affected zone (HAZ), etc. The relationships between these aspects are rather complex and not proportional to each other. In addition, the quality of a weld is not dependent on one single parameter. Instead, it is the combined effect of all the output parameters to deliver the performance of the joint to the extent it is designed for.

Important Parameters of Through Transmission Laser Welding

It is clearly observed in various studies of TTLW of polymers (Refs. 12–114) that the main influencing factors are laser power, scanning speed, spot radius, standoff distance, clamping pressure, frequency, energy density, and more. In this subsection, the major parameters of TTLW have been discussed in brief.

Laser Power

The laser power is the main source of heat in TTLW (Ref. 114). In general, higher power allows greater travel speeds for welding and faster welds required higher power. The weld width increases with laser power (Refs. 23–27, 52). During through transmission laser (diode) welding of transparent acrylics to opaque ones (thickness = 4 mm), it is observed that joint strength increases with laser power (19–24

Fig. 3 — A scheme of the laser transmission welding process.

W) (Ref. 22). A similar result for TTLW of white thermoplastics to polycarbonate (PC), in terms of breaking load, and polyamide, in terms of maximum load, has been achieved by Mamuschkin et al. (Ref. 108) and Chen et al. (Ref. 113), respectively. It is also found from through transmission laser (Nd: YVO₄) welding of transparent acrylic (thickness = 0.5 mm) and transparent PC (thickness = 0.5 mm) that weld width increases and breaking load decreases with the laser power (7.6–11.6 W) (Ref. 23). The results of laser welding of acrylonitrile butadiene styrene (ABS) and PC-based polymers using a continuous wave diode laser with a laser power between 6 and 8 W, as well as a scanning speed of 1500, 3000, and 4500 mm/min, concluded that the weld width decreases as the total heat input decreases by increasing the scanning speed or lowering the input power. While no regular trend has been obtained between heat input and average shear strength (Ref. 24), it is observed during diode laser welding of natural and black (containing 0.2 wt-% carbon black as color pigment) acrylic plaques of dimensions 80 * 35 * 4 mm each that weld width and lap-shear strength increase with laser power (Ref. 25). Tao et al. (Ref. 123) obtained a maximum shear strength of 2052N with an optimum power of 700 W. They concluded that the optimum power resulted in a large interfacial joining area with no decomposition. It can be inferred from their observations that an increase in power results in an increased joining area up to certain extent, and further increase in power results in decomposition, which in turn reduces the joint strength.

It is also found from the perturbation plot that the joint strength and weld width increase with the laser power in laser transmission joining of PC (thickness = 1 mm) while laser power has a nonsignificant effect on joint cost (Ref. 27). The penetration depth against laser power has been calculated for polypropylene (PP) and high-density and low-density polyethylene. It has been concluded that penetration depth increases with laser power for all types of polymers (Ref. 50). The results of TTLW of polyethene terephthalate (PET) and PP showed that weld width and depth in absorbing PP increase with laser power (Ref. 52). The works of Chen et al. (Ref. 58) and Coelho et al. (Ref. 59) show that the weld strength of TTLW of polymers varies with the energy density. They have concluded that there is no regular trend between energy density and weld strength. Dwivedi and Sharma (Ref. 34) noticed that the joint strength of a

PET and 316 stainless steel weld increases with the increase of laser power. This is because in the laser transmission joining process, heat input increases with the laser power resulting in an increased weld seam width. The higher the weld width, the higher the melting joint area will be (Ref. 105), and, consequently, the joint strength. Literature by Ilie et al. (Ref. 61) reveals that the failure force of diode-laser-welded ABS first increases then decreases with laser power and, hence, is the trend for the joint strength concerning the line energy in the diode TTLW process (Refs. 106, 107, 112). This is because the heat induced to work materials increases until the line energy reaches a threshold value, which results in improving the joint strength. Above the threshold limit of line energy, the heat input to the material gets excessive, leading to the material burning and partial decomposition and, hence, lowering the joint strength. Ghasemi et al. (Ref. 105) developed a model that simply explains the effects of various process parameters on meltdown characteristics in QSLW. They found that an increase in power reduces induction time and overshoot and, therefore, produces higher meltdown when the number of passes is kept constant. Devrient et al. (Ref. 111) found that with an increase in the laser power, the cross section of the HAZ gets bigger and becomes more elliptical or lenticular in shape (losing the symmetry to the joining plane).

Choi et al. (Ref. 124) investigated the effect of laser power on the adhesion between a graphene layer and the PC surface. Later, they also studied the effect of bending on the capacitance of the laser irradiated supercapacitors.

Scanning Speed

Scanning speed is one of the important parameters that increases the productivity of the welding process. In addition, weld width, joint strength, joint cost, and depth of penetration are affected by the welding speed (Refs. 22, 26–29, 48, 50, 52, 51, 61, 123). At low scanning speeds, a higher irradiation time is produced, which results in overheating and degradation of the polymers and, consequently, a lower joint strength. However, increasing the welding speed above threshold value results in a lower irradiation time (Ref. 112), thus causing a low heat input and incomplete joint penetration (Ref. 105), which decreases the joint strength (Ref. 22). During TTLW of polymers, it has been concluded that the velocity has a negative effect on the joint strength (Refs. 22, 27, 28), while the weld width and joint cost decrease with the welding speed. The velocity has a significant effect on the joint cost. The productivity rate can be increased by increasing velocity with acceptable joint strength and joint width (Ref. 27).

Experiments of carbon fiber reinforced thermoplastic (CFRTP)/stainless steel laser direct joining have been carried out by Jiao et al. (Ref. 28). They have concluded that the joining speed has a great effect on the thermal defect zone size and the joint strength. The weld soundness of polymers depends on several factors like the nonisothermal crystallization, the germs growth rate, and the dimensions of the HAZ induced by recrystallization. Increasing the welding speed caused reduction in the maximum temperature, consequently resulting in a faster cooling rate and vice versa (Ref. 61). During the welding process, the polymer is heated up to the tem-

perature range of crystallization that is between the glass-transition temperature and the melting temperature. Crystallinity is strongly dependent on the heating/cooling rates of the polymers (Ref. 48). Casalino and Ghorbel (Ref. 50) investigated the effect of welding speed on the keyhole depth of CO₂ laser welding of PP in butt and lap joint configurations of 4 mm thickness. They observed the keyhole depth decreases with the welding speed due to a decrease in the line energy. The depth-to-width (D/W) ratio of the molten pool has a significant influence on the shear strength of TTLW of PET and PP. The weld width and depth increase with lower welding speed. However, the shear strength gradually increases first and then rapidly decreases with the increase of the D/W ratio (Ref. 52). Transmission laser welding of 0.5-mm-thick PET plate using TWIST mode and conventional contour welding mode was investigated by Wang et al. (Ref. 109). They have found that the welding speed has a negative effect on shear strength in TWIST mode, while there was a small change in the shear strength values of the weld seams obtained through conventional contour welding. This is because, in conventional contour welding, the effect of crystallization is counteracting the diffusion at a lower welding speed, while the sharp decrease in the melted and fused area decreases the shear strength in TWIST mode (Ref. 39). In the case of QS welding, when compensated with the number of passes, an increase in scanning speed was observed to reduce total weld time and in turn reduce total meltdown (Ref. 123).

Standoff Distance

Kumar et al. (Ref. 19) studied the influence of standoff distance (30–34 mm) on diode laser TTLW of acrylics. They found that with an increase in the standoff distance, weld width and joint strength decreases. It may indicate that the laser spot diameter decreases with increasing standoff distance and the weld width becomes narrower. Due to the decrease in weld width, a lesser amount of material is fused. Further, heat conduction between the materials is not sufficient (Ref. 106). Thus, joint strength is decreased. In the work of Acharjee et al. (Ref. 22), diode laser TTLW of acrylics was conducted at varying standoff distances (6–15 mm). They found that joint strength increases with an increase in the focal distance up to 9 mm, and then it starts to decrease as the focal distance increases beyond this point. This is because the beam spot area was controlled by varying the focal distance of the beam. It can be observed from the perturbation plot in Ref. 25 that the weld-seam width varies positively with the standoff distance. Increasing standoff distance increases the laser beam spot size at the weld interface, which results in spreading the beam energy onto a wide area. Consequently, the base material of the weld zone being melted leads to an increase in weld-seam width. In the work of Wang et al. (Ref. 26), a statistical technique was applied to correlate the standoff distance and output variables, such as maximum temperature at the weld interface (T_{max}), the maximum temperature at the top surface of the transparent PET (T_{top}), weld width (WW), weld depth in the transparent PET (DT), etc. Also, the model was validated with the confirmatory tests. Wang et al. (Ref. 52) studied the effect of standoff distance on the depth of penetration of TTLW of PET and PP. It has been concluded that molten depths in-

crease as standoff distance decreases. This is because a decrease in standoff distance leads to an increase in localized laser energy density and also the molten depths.

Clamping Pressure

Clamping pressure is required to decrease the opening between two polymer plates/sheets, because heat conduction between the two plates is more important in the TTLW process. With an increase in the clamping pressure, the weld width increases (Ref. 27). This may be due to an increase in effectiveness of the intimate contact between the two plates. Kumar et al. (Ref. 19) found that clamping pressure has the most influencing effect on the weld width but no significant effect on joint strength or the joint cost of TTLW of PC, as mentioned by Wang et al. (Ref. 27). The effect of clamping pressure (0–0.8 MPa) on the joint strength of fiber laser welding of CFRTP and stainless steel was studied by Jiao et al. (Ref. 28). It was found that the polyphenylene sulfide (PPS) matrix melted adequately when the clamping pressure was in the range of 0.1–0.2 MPa. The melted PPS squeezed out from the CFRTP/stainless steel interface, and the melted PPS for bonding reduced when the clamping pressure was greater than 0.2 MPa. Consequently, the joint strength decreased slowly when the clamping pressure was greater than 0.2 MPa, and the highest shear stress was obtained at the clamping pressure of 0.15 MPa. A similar trend was obtained in the studies presented by Huang et al. (Ref. 106) and Liu et al. (Ref. 107), where the joint strength first increases and then decreases with the increase of clamping pressure in the diode TTLW process. The response surface plot for the failure force as a function of laser power (10–20 W) and clamping pressure (0.4–0.55 MPa) indicated that the optimal zone has to be searched toward low laser power and high pressure (Ref. 61). The meltdown rate did not change with pressure. However, the total meltdown increased with pressure (Refs. 105, 112) in TTLW using a T-shaped test assembly. It is possible to form faultless welds using a dual clamping device by the use of proper welding parameters and, therefore, prevent the risk of downtime or poor weld seam quality due to contaminated clamping devices or improper clamped joining partners (Ref. 110). Clamping pressure was also observed to reduce induction time in QS welding (Ref. 123).

Summary

The basic concept and the technical aspects of the TTLW process have been overviewed. Different variants of TTLW processes have been briefly discussed. Four welding parameters — namely power, scanning speed, standoff distance, and clamping pressure — were chosen as the most significant for the present study and have been reviewed.

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