Laser Transmission Welding is a promising joining technology technique – A Recent Review

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Abstract. Laser transmission welding (LTW) is one of the latest evolutions in joining technology. Simply, it involves joining two similar or dissimilar materials by melting and fusing two parts at their interface using laser radiation. The upper material is transparent in order to allow the laser radiation to pass and heat the second material which is in this case an absorbent material. This technique is also known with other names such as Laser Plastic Welding, Through-Transmission Welding and Laser Assisted Metal to Polymer Joining. The developments occurred in this field have also enabled LTW to approach different Lasers like Diode Laser, CO2 Laser, Nd: YAG Laser and Fiber Laser. This review aims to explain LTW process, working procedures, effect of Laser types and process parameters on this approach. It especially clarifies using LTW to weld thermoplastics materials together or with metals. It also attempts to help scholars to have an overview on LTW technique and achieve their answers related to this topic.

Keywords: Polymer Welding, Thermoplastics, Polymer-Metal Joining, Lap Joints, Lasers.

1. Introduction

Laser took a place in industrial application in 1972, it was dealing with metals only. As a result, metals processing such as cutting and welding become easier and well established. By this time LTW was not developed yet [1]. LTW was firstly proposed as a metal-polymer joining method at the Joining and Welding Research Institute of Osaka University by Katayama et al. [2].

The first two lasers used to weld plastic were CO2 and Nd:YAG. But they were not capable of economical industrial application owing to their high investment costs. This problem was solved when high-power diode lasers entered the industrial field and raised its production. In 1997, the earliest product that entered the market in the field of industrial applications for laser welding plastic components was an electronic car key. This was produced for the new Mercedes Benz type 190 [1].

Laser transmission welding is a non-contact technique that uses laser to join two materials together and relies significantly on the transmission and absorption principles. It has the advantages of fast processing speed, design flexibility, better welding strength and excellent reliability. Furthermore, even if there is no physical contact, laser energy is still able to be directed precisely to the welding site. According to these advantages LTW process becomes an alternative to joining conventional means such as mechanical fastening or adhesive bonding [2,3,4]. Laser transmission welding plays an important role in the fields of
automotive, electronics, medical and household goods industries. It was used to manufacture connectors, rear lights, liquid containers, bumpers, dashboards, liquid tanks, floodlights, camshaft sensors, pump or turbine housings, sensors and switches, dialysis components, large dowels and polymeric windows, shavers and plastic dishes, filter cases of motor vehicles, electronic engine oil sensors and finally for micro-fluidic devices which is used for DNA analysis and clinical diagnostics [5,6].

The necessity to join plastic with other metals is obviously increasing, as the use of plastics in modern technologies and devices expanded. Thus, finding a new method to create hybrid combination from polymer and metals becomes necessary. Laser transmission welding is capable of joining these two materials in a strong lap joint [7].

Plastics are categorized into thermoplastics and thermosetting. Nevertheless, only thermoplastics can be used in LTW since they melt or soften at relatively low temperatures [8]. Most thermoplastics are naturally transparent to the laser radiation, so in order to achieve best absorptive properties additives can be used. Additives are pigmentations that dyed the absorbing layer to increase its absorption to the laser like Carbon Black and Titanium Dioxide (TiO₂) [9]. Table 1 displays a number of thermoplastics that are mentioned in this paper with some of their characteristics.

Accordingly, this paper attempts to comprehensively review the research of LTW technology in the case where one of the material layers at least is thermoplastic. The following part of this review illustrates the procedures of LTW process in details. While, lasers that have been used in this technology is discussed in the final section.

| Acronym | Chemical Name                  | Chemical Structure | Melting Point |
|---------|--------------------------------|--------------------|---------------|
| PETG    | Polyethylene Terephthalate Glycol | ![PETG Structure]  | 260°C         |
| PMMA    | Polymethylmethacrylate          | ![PMMA Structure]  | 160°C         |
| PET     | Polyethylene Terephthalate      | ![PET Structure]   | 264°C         |
| PA66    | Polyamide 6,6                   | ![PA66 Structure] | 264°C         |
Polyethylene Vinyl Acetate (PEVA) 190 °C

Polycarbonate (PC) 145–150 °C

Polypropylene (PP) 171 °C

Polyethylene low-density (PE-LD) 105–115 °C

Acrylonitrile Butadiene Styrene (ABS) 230 °C

Source: The content of the table is based on these references [1,10,11,12,13,14,15,16,17,18,19]

2. Working procedures
Laser transmission welding involves passing laser radiation through an upper transmissive layer down to the surface of a lower absorbing layer, so the energy is absorbed at the interface. As a result, heat is created to allow the polymer to be molten and that molten polymer creates a weld [20].

Process main factors
Laser transmission welding process has been classified into three main factors. Each factor has its essential role in this process. These factors are: transmissive upper layer, absorbing lower layer, and contact [21]. The main property of transmissive upper layer factor has the ability to transmit laser radiation. Laser radiation used in LTW falls into the infrared spectrum [22].
The major characteristic of absorbing lower layer factor has ability to absorb the same laser radiation which the upper layer transmitted. This absorption creates heat at the interface between the two layers and that heat allows the upper layer to be molten and create a weld [21]. Finally, the contact factor joins the two materials at the interface. The main purpose of this factor is to ensure the conduction which transfers heat energy from the lower layer to the upper layer in order to melt the upper layer and create a weld. Additionally, to guarantee perfect contact clamping device is used throughout the process [23,24]. Figure (1) shows a schematic illustration of the laser transmission welding process. Firstly, a laser beam incident on the top layer. This layer transmitted the incident beam to the bottom layer. Secondly, the bottom layer absorbed the laser beam energy. Then heat is generated at the interface between the two layers. Because of the heat conduction the top layer is heated and melted too. Finally, the melted layer solidifies to create the weld seam.

![Figure 1. Laser transmission welding process [6]](image)

3. Lasers used for welding
There are four lasers demonstrated on LTW technique such as Diode, Nd:YAG, Fiber and CO₂ laser. These lasers share the same infrared spectrum. However, they differ in many properties such as wavelength, pumping source and active medium, Table 1 lists the Laser types used in LTW. Furthermore, the first three lasers lie in near infrared region with a spectral range starting from 800 to 2500 nm. Because of that, plastics show a high transmittance to these wavelengths. Therefore, these lasers are capable of penetrate plastics, while CO₂ laser lies in the far infrared region with a wavelength of 10.6 μm. CO₂ is absorbed by most thermoplastics at the surface, due to its low penetration depth. As a result, CO₂ is used for special application such as welding thin plastic films [1].

As shown in Table 2 the wavelength of each laser depends on the type of laser active medium. It also displays the difference of pumping process for lasers [1].

| Laser source      | Active medium | Pumping process   | Wavelength        |
|-------------------|---------------|-------------------|-------------------|
| Diode laser       | Semiconductor | Electric current  | 800 nm to 2000 nm |
| Nd:YAG laser      | Doped crystal | Optical radiation | 1064 nm           |
Transmittance is defined as “the ratio of the light passing through to the light incident on the specimens”, and also defined the reflectance as “the ratio of the light reflected to the light incident.” [25]. While absorbance can be defined as the “Logarithm of the ratio of incident to transmitted radiant power through a sample” [26]. There is a relation between transmission and absorption. This equation (R + T + A = 1) clearly explains this relation, the behavior of the materials with lasers is based on these optical properties [27]. Figure (2) clarifies how transparent polymers deal with different wavelengths which are related to specific lasers like Diode, Nd:YAG and CO₂ lasers. Thus, polymers show a high transmittance and low reflectance near 1000nm wavelengths when diode or Nd:YAG lasers are used. Transmittance may reach 80% at these wavelengths, while reflectance is below 20%.

![Figure 2](image)

**Figure 2.** Reflectance and transmittance percentage of transparent polymers with different wavelengths [2]

On the other hand, at 10000nm with CO₂ laser transmittance and reflectance are both low with percentages under 10%, but transmittance is less than reflectance.
As far as fiber laser is concerned, figure (3) indicates that the polymers have a high transmittance at 1090nm which means low absorbance. As mentioned earlier, that fiber laser lies in the near infrared spectrum as diode and Nd:YAG laser, it is obvious in the figure above that these lasers share the same optical properties.

Optical properties are considered as materials parameters which affect the welding process besides other parameters which falls under the title of light parameters and process parameters. Setting and controlling these parameters lead to an effective laser joining processes. On the other hand, Light parameters are the parameters related to the power sources which are lasers such as beam mode, beam power, pulse duration, pulse repetition rate, pulse shape, spot size and wavelength. While process parameters are the parameters related to the process such as scanning speed, focal spot position, clamping pressure, shielding gas type and shielding gas pressure [28].

In the next section each type of lasers is briefly discussed with parameters that have been measured and recorded.

3.1. Nd:YAG Laser

Nd:YAG laser is a solid-state laser with wavelength of 1064 nm. It is composed of an Nd ions and crystal of yttrium aluminum garnet (YAG). It also operates in both continuous and pulsed modes [29].

Nd:YAG laser enables the overlap joining process successfully because its wavelength penetrates most thermoplastics of several millimeters thickness, while producing only small absorption. Therefore, Nd:YAG lasers have usually been used for welding thermoplastics until the evolution of diode lasers [1]. Research focused on welding by utilizing Nd:YAG laser are as follows:

Tillmann et al. conducted a welding process between stainless steel type 304 and PETG polymer sheets by using continuous Nd:YAG laser. A parametric investigation was made to reach the optimum value of laser power and process speed leading to strong weld strength [30]. Figure (4) views the relation between the laser power, fracture load and bond width. It is obvious that the bond width increased as the power increased. This increase has a positive impact on the fracture load. The fracture load can be defined as the capability of the material to resist failure. [31] Accordingly, the growth of the fracture load brings on a
high weld strength as a result of an adequate melting of the polymer side and wetting on the steel side without decomposing the polymer sheet. It also was mentioned that decreasing the laser speed would lead to the same results [30].

![Figure 4](image1.png)

**Figure 4.** The effect of laser power on fracture load and bond width [30].

In addition, Huang, et al. studied the influence of several process parameters on weld’s strength and recorded the optimum parameters values. Nd:YAG laser was applied once more to weld stainless steel type 304 and polymers, the difference here was that the polymer type that was used is PMMA instead of PETG [31]. Figure (5) shows the experiment set up and the device that was used.

![Figure 5](image2.png)

**Figure 5.** a) the laser system and the experiment equipment and b) illustration image of clamping and laser path [31].

Bauernhuber, et al. joined steel with PMMA using pulsed Nd:YAG laser. Their results displayed a strong joint between the two dissimilar materials. They also explained the gas bubble formation at welding interface [7]. It was reported that these bubbles formed were due to the resin matrix thermal decomposition and it would decrease the joining strength.
Figure 6. Bubbles formed in the PMMA surface [7].

On the contrary, Farazila, et al. mentioned that these bubbles would help the molten polymer to stick onto the metal surface and they were caused by high expansion pressure when the polymer was being heated up during the welding process [32]. Farazila, et al. applied Nd:YAG laser to weld aluminium alloy with PET material. Their research showed that aluminium had a good thermal conductivity and a high reflectivity. As a result, more energy required to weld aluminium and PET than that applied for welding steel and PET [33].

Moreover, two polyethylene partners were welded by Visco, et al. using Nd:YAG laser for this purpose. Carbon nanomaterials were applied as a filler material to increase the absorbance of the lower polyethylene sample. The weld strength was also studied and the relation between laser exposure time and filler concentrations was discussed until the researcher reached the optimal conditions that guaranteed a suitable result [34].

Finally, Shaker et al. achieved joining PMMA samples by using continuous wave green laser (532nm wavelength). The relation between the process parameters (welding speed, spot size, and clamping pressure) and welding width and strength was studied. Taguchi Method was used to determine the optimal values of the process parameters [35].

Because of the reliability process, laser working life, maintenance costs and low plug efficiency, Nd:YAG application started to decrease [1]. Recent developments of diode lasers with wavelength ranging from 800 and 1100 nm and no need for additives creates new possibilities for LTW applications.

3.2. Diode Laser

A diode laser is a semiconductor laser based on the principle of generating the combination of electron-hole [29]. It plays a significant role in industrial applications as a power source with wavelength ranging from UV to IR radiation and power up to several kW [1].

Fiber-coupled diode lasers are diode laser devices where a glass fiber is used to transport the generated laser beam from the diode laser to the focusing unit. The output beam from the fiber has better beam quality than direct coupled diode lasers [1].

Diode laser has the advantage of having high electrical efficiency, high power small size, reliable, easy to handle and low cost. However, it has a poor beam quality thus resulting in a large spot size and low intensity using the focusing unit [20,23,36].

Diode laser took an efficient position in joining dissimilar materials and many researches proved that. For example, Wang et al. applied diode laser to join PET and 316L stainless-steel. A parametric investigation was conducted until they reached the optimum values that gave the highest joints strength. Results indicated that the weldment strength rose when laser power increased. On the contrary, the strength dropped when welding speed increased. For stand-off distance, joint strength increased with stand-off distance increase until it reached a certain value where it started to drop [37]. The writers believe that weldment with thickness of 0.1mm might be useful in small scale parts in micro industrial applications. The increasing demands make the micro parts make them spread widely in fields such as optics, electronics, medicine, biomedical devices, communications, and avionics [38]. Recently, LTW achieve a huge success in joining the micro parts.
Figure 7. the final sample appearance under the microscope [37].

Schricker et al. also used a 1kW fiber-coupled diode laser to join aluminium and polyamide 6.6 (which is also known as PA66). They studied the impact of metal surface’s macroscopic structures on the mechanical joint properties [39].

Further, Gisario et al. employed 1500W diode laser to join aluminium alloy with polyethylene terephthalate (PET). Experiments were carried out on two kinds of polymers were PET 100% and PET-PEVA 15%. Results showed a strong weld joint. Nevertheless, the joint between PET 100% and Al 7075 showed a stronger strength than joints between PET-PEVA 15% and Al 7075 [40].

Figure 8. The setup of the experiment [40].

Likewise, Fortunato et al. implemented an experiment to weld stainless steel type 304 with three types of polymers were PA66, glass fiber reinforced PA66 and carbon fiber reinforced PA66 by utilizing 100W diode laser as a power source. Tensile test was done to evaluate the strength of welding process for the produced samples [41]. The outcome of the latest two experiments ensured the effectiveness of diode laser in welding dissimilar materials.

Moreover, in the case of welding two polymers together Shaker et al, studied the impact of different parameters on welding width and strength between two samples of PMMA (polymethylmethacrylate), one of them opaqueness while the other is transparent, by using diode laser (810µm wavelength). Two thicknesses were tested with several parameters such as laser speed, spot size and force. Optimum process parameter was determined by using Taguchi method. Results exhibited that increasing either the welding speed nor the spot size leading to decrease the welding width, on the other hand increasing the force on the sample increased it [42].

In addition, Kadhim A.Hubeatir, implemented several experiments to weld two samples of PMMA, one is transparent, whereas the other is oblique. Different values of thickness and welding speeds were tested and discussed in each experiment. Results showed how a 2W Diode laser (808nm wavelength) succeeded in creating a lap joint between two polymers despite its low output power, which means that joining two polymers requires less power than joining polymers with metals. [43].

Aden et al. worked on welding PC and PP probs with two diode wavelengths at 1530 and 968 nm, respectively. They discussed the effect of adding titanium dioxide (TiO₂) as an additive material. Optical characteristics of polymer were discussed too. Results indicated that increasing the concentration of the
applying $TiO_2$ colorants increased reflectance of the polymers and scattering coefficients decreased transmittance [44].

Finally, Wang et al. joined samples of PC with a metal absorption layer between the two samples. This metal was a copper film with 0.02mm thickness. A diode laser (980nm) was the suitable choice to be used since copper film has high absorption at short wavelengths. The study focused on examining the residual stress effect and distribution. Results indicated that increasing laser power and copper film width led to increase residual stress, while the laser speed had an opposite effect on residual stress [45].

3.3. Fiber Laser

Fiber lasers are the latest evolution of laser sources in welding thermoplastics field. It is one of the Near Infrared (NIR) lasers family consisting of a wide range of wavelengths. Each wavelength relies on the type of the active medium [1].

Fiber lasers consist of a small diameter single-mode glass fiber with special doped silica core as an active medium, an inner cladding works as a waveguide for pumping radiation, and outer cladding that provides total reflection for pumping radiation. The generated laser radiation wavelength is classified according to the silica core doping type [1,29]. Table 3 displays the type of fiber lasers according to their wavelengths ranging from 990 to 2210nm.

| Laser active doping in glass fiber | Laser wavelengths [nm] |
|----------------------------------|------------------------|
| Er                               | 1500 to 1620           |
| Ho                               | 1900 to 2010           |
| Nd                               | 1060 to 1120           |
| Pr                               | 1300 to 1330           |
| Tm                               | 1820 to 2090           |
|                                 | And 2190 to 2210       |
| Yb                               | 990 to 1200            |

Fiber lasers have the advantages of compactness, excellent beam quality, high plug efficiency up to 30%, small spot sizes and long depth of focus. These features make it commercially alternative to diode and Nd: YAG lasers since it operates with wavelengths ranging from 1.03 to 1.1 \( \mu m \), which are similar to Nd:YAG lasers wavelengths [20,46,47].

This was clear in the study of Klein et al. in which a comparison was carried among fiber, diode and Nd:YAG lasers at the same rated power. Polymers such as Polycarbonate (PC), Polymethylmethacrylate (PMMA) and Polypropylene (PP) were coated at the lower layer by Clearweld Coating and then welded. Tensile test results showed that tensile load values with the same material of different lasers were close together with slightly higher values of the fiber laser [20].

Multiple experiments in welding similar and dissimilar polymers were conducted by Mingareev et al. In their research a 27W thulium fiber laser (2\( \mu m \)) was employed in order to weld four different partners of polymers as follows: PETG/PETG, PMMA/PMMA, PMMA/PP, and PP/PE-LD. All the polymers were
with thickness of 1.6mm. No additives were applied. Results showed a different kind of joining between welded polymers which were material joints in the case of similar polymers and form joints in the case of dissimilar polymers. The joints classification depends on the physical properties of the adopted materials [48].

![Figure 9. The experiment set up [48].](image)

Acherjee pointed that lasers with wavelengths ranging from 1.4 to 2.2 μm were used for absorber-free polymer welding processes. Erbium fiber laser (1.53–1.65 μm) and Thulium fiber laser (1.9–2.05 μm) are examples of fiber lasers which are used in this case [49,50].

Shirgur studied the influence of three parameters on joint strength (laser power, scanning speed and number of passes). Fiber laser with 30W was used to weld natural polypropylene with black polypropylene and natural polypropylene with jute fiber reinforced polypropylene. ANOVA results indicated in the first experiment of natural-black polypropylene joints that scanning speed among other parameters had the greatest effect on the weld strength and the weld width. While in the second experiment of natural-jute fiber reinforced polypropylene joints laser power had the greater effect on the weld strength and the weld width as well [51].

Research expanded to using LTW in medical applications such as welding PET with titanium and its components to produce biocompatible material systems that applied in neural implant devices. Fiber lasers in addition to diode lasers, were one of the suitable choices to weld these two partners [52].

Chan et al. utilized 200W CW fiber laser (1064nm) to join PET and pure titanium (Ti). A parametrical study and analyses were carried out by Taguchi method. It was observed from their results that laser power was the most controlling parameter to the amount of non-contact area at the joint interface, followed by scanning speed and stand-off distance [53].

Ai et al. utilized 16W CW fiber laser to join PET and titanium alloy Ti6Al4V. The relation between the weld geometry, molten pool, fluid flow and porosity formation were studied, analyzed, and discussed. Results showed an effect of the welding processing parameters on the welding joint. [54]

TAN et al. examined the wettability of titanium alloy TC4 with Carbon Fiber Reinforced Thermoplastics (CFRTP) joints. Pulsed fiber (1064nm) with 70W was employed to texture the surface of TC4 samples. A 6000W fiber laser (1070nm) was used for welding process. It was found that wettability of molten CFRP-TC4 joint was remarkably progressed after the texturing of TC4 surface and also the shear force increased [55]. Exposing the metal surface to a pulse laser leads to structural transformations in the surface which harden the surface and enhance its characteristics. Laser pre-treatment is considered the best alternative method in surface heat treatments since it utilizes the properties of self-quenching that cools rapidly the materials without cooling water [56].

Jiao et al. implemented an experiment to join CFRTP with stainless steel by using 500W fiber laser. The impact of the melting width, depth and the process parameters were studied numerically. Results indicated that the depth and the width of the joint had a direct relation with laser power, and inverse relation with welding speed and the laser beam diameter [57]. Figure (11) part a) displays precisely how
The welding depth and width increased with the increase of the power value when the welding speed and the laser diameter are constants. Figure (11) part b) and c) view the welding depth and width behave the opposite with the laser speed and the diameter.

![Figure 10](image1.png)

**Figure 10.** A schematic diagram of LTW process between Stainless steel and CFRTP [57].

![Figure 11](image2.png)

**Figure 11.** The relation between both the melting width and depth with a) laser power b) laser speed and c) the beam diameter [57].

Noh et al. [58] worked on joining stainless steel type 304 with ABS by using CW fiber laser. The effect of laser power and welding speed on weld quality was discussed. The optimal values of the two parameters were determined by ANOVA method. Weld strength was measured by tensile test. It was observed that as the power increased the weld became stronger. Nevertheless, increasing welding speed caused weaker weld.

### 3.4. CO₂ Laser

CO₂ laser is a gas laser consisting of a gas mixture of nitrogen (N2), helium (He) and carbon dioxide (CO₂) at a low gas pressure with wavelength of 10.6 μm [29]. Several types of CO₂ lasers are available for material processing such as waveguide, slow-flow, fast-flow or slab lasers with power up to several 10 kW of laser power. Slow-flow and waveguide CO₂ lasers are favourable to be used for plastic processing with high beam quality and laser power up to 500 W [1]. The procedure of plastic welding with CO₂ laser was improved by J.P. Coelho [59].

Tamrin et al. [60] mentioned in a recent review that the available literature related to the use of CO₂ laser in LTW not adequate due to two causes related to CO₂ large wavelength, especially in dissimilar materials...
joining. The first cause is that CO₂ wavelength is absorbed strongly by plastics. Subsequently, CO₂ laser has a low penetration depth of 10 mm to some 100 mm in thermoplastic materials. This low penetration can drive to material degradation, melt shearing and vaporization. The second cause is that CO₂ laser has the largest beam spot size among other lasers. This leads to large bond width unwanted when laser is applied to heat-sensitive material. Due to these two causes, CO₂ laser was used practically for cutting and drilling more than welding since its interaction with ferrous and non-ferrous metals, and non-metals is more efficient [1,34,36]. However, welding process by CO₂ could be used for special application like welding very thin (micron-thick) materials [61]. There was also a number of research group who employed CO₂ in their experiments and compared it with other lasers.

Tamrin et al. [62] worked on creating a weld between ceramic and thermoplastics by employing CO₂ laser as a power source. The effect of process parameters on the properties of the spot-welded joint was studied. Several experiments were conducted and also a tensile test was measured to determine weld tensile strength. They found that parameters like laser exposure and number of spots had the capability to affect the weld strength. In addition, Park et al. [63] studied the effect of three parameters, such as input power, working time of laser beam and pulse per second, on the lap welding joint of two plastics together. Both CO₂ and Nd:YAG laser were applied and compared. Results showed that Nd:YAG is practically more appropriate than CO₂ laser. The main reason was that CO₂ laser wasn't penetrated through plastic material, but instead its energy was absorbed on the contact surface.

4. Conclusion
This paper reviews LTW process in details and discusses its working procedures, applications and types of lasers used. Knowing the previous welding experiments in this field makes it easier to understand the welding possibilities of each laser. The process parameters play a significant role in controlling the process and its success. The main two parameters affecting the welding strength are laser power and scanning speed. Also, surface conditions such as surface roughness, pre-treatment by laser or dying with pigmentation can influence the interaction leading to better welding results.

Laser sources can be chosen by many various ways, such as Nd:YAG, diode, fibre and CO₂. According to this review high power diode lasers and fiber lasers lead to new generation of developments in similar or dissimilar joining process due to their attractive properties. Different combinations of materials were mentioned to prove that LTW is a successful joining technique in manufacturing micro and complex hybrid components.

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