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# Laser Transmission Welding Of Polycarbonate: Geometrical and Microstructure Characterisation of the Weld

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**ABSTRACT:** This paper investigates the effect of the laser welding parameters such as laser power, welding speed on weld formation and mechanical resistance of the weld joints. A welding experiment has been set up using a 200W YAG laser with wavelength 1064nm to weld the transparent and absorbing Polycarbonate (PC) in lap weld configuration. An Universal testing machine was used to assess the force at break of the lap welds, microscopic characterization of the top and cross sections of the joining were carried out to study the corresponding weld seam such as weld widths and weld depth. A trend between the maximum tensile strength and the variation of the weld seam was observed, at the other hand, the increase of the laser power lead to degradation or burning of the weld joint area. Consequently, the high levels of the laser power caused degradation of the material at the center of the weld seam, reducing mechanical performance of the joint.

KEYWORDS: laser transmission welding, plastic welding, weld strength, Polycarbonate

## I. INTRODUCTION

The efficiency of laser transmission welding strongly depends on the optical properties of the plastic parts to be joined and the process parameters. Chen et al. (2006) investigated transmittance of polycarbonate specimens with carbon black concentration varied from 0 to 0.2 wt%. Laser absorption coefficient was observed to rise linearly with an increase in the absorber content. Chen et al. (2007) evaluated the line energy (power divided by laser scan speed) required to cause degradation on the surface of uncolored polycarbonate. This work demonstrated that, despite high transparency of polycarbonate, there is a particular level of line energy absorption at the surface of the transparent part is high enough to cause burning. Also, it was observed that contamination or ejector pin marks on the surface of the part facilitate the onset of degradation. Burrell et al. (2007) studied dependence of the joint strength on absorbent concentration, specimen thickness and energy density. These tests were conducted using lap welding of polycarbonate specimens. The tests revealed that the weld strength increased with increase of the absorber concentration and/or energy density, reached its maximum, and then began to decrease. This is believed to be due to



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degradation of the overheated polymer. An increase of the specimen thickness also resulted in increase of the weld strength. It is possible that better performance of the thicker specimens is due to higher rigidity, which reduces bending of the lap joint during the tensile test. Potente et al. (2002) investigated optimal process parameters for quasi-simultaneous welding of PMMA and polycarbonate parts. T-joint specimen geometry was used for PMMA samples and both T-joint and butt-joint geometries were used for polycarbonate samples. It was found that weld strength increased with increase of the power intensity and joining displacement, reached its peak, and then decreased again. For some cases the weld strength increased with increased power intensity, scanning velocity and joining displacement, but never decreased at higher power intensity values. It is believed that this is due to limited range of tested powers which does not represent the whole range of the weld strength variation from cold weld to strong polymer degradation. Wang et al. (2010) worked on laser transmission joint between PET and titanium for biomedical application due to the fact that dissimilar materials had the potential for application in biomedical and their encapsulation process. The work was devoted to laser transmission joint between 0.1 mm thick PET films and 0.1 mm thick Titanium using near-infrared diode lasers. The PET/titanium interfaces thus obtained were studied by X-ray photoelectron spectroscopy (XPS), scanning electron microscopy coupled with energy dispersive spectroscopy (SEM/EDS) and microscopy techniques which gave evidence for the formation of Ti-C chemical bonds in a sharp interfacial region between the two sides. These chemical bonds were believed to be responsible for the observed mechanical strength of the joints. Pal et al. (2013) studied and carried out investigations to analyze the effects of process parameters on joint strength in through transmission laser welding of acrylic plastics where current, stand off distance and clamping pressure were selected as input parameters. Experiments were conducted as per L27 orthogonal array of Taguchi method and statistical techniques, analysis of variance and then signal to noise-ratio had been applied on experimental data to identify the significant process parameters influencing the joint strength. Parametric condition for maximization of joint strength was obtained by Taguchi method. Confirmatory experiment was conducted at optimum condition to validate the proposed methodology. Coelho et al. (2000) carried out welding of white and transparent thin film of polypropylene and polyethylene of low and high density at high speed using a carbon-dioxide laser and observed that plastic with high absorption had lower values of critical specific energy. Kagan et al. (2002) studied the effect of moisture content on mechanical performance of a diode laser welded polyamide 6 (PA6) and concluded that the shear strength of a diode laser welded lap joint depended on the amount of moisture that the polyamide had been exposed to and did not depend on the content of fibre-glass reinforcement.

However, no comprehensive research work has been reported on the effect laser transmission welding parameter and transparent part thickness on weld microstructure. In the present research, an experimental investigation into laser welding of polycarbonate (PC) has been carried out. The force at break of the lap welds was assessed on the Universal testing machine, weld fracture surfaces and weld cross-sections were also analyzed under microscope using reflected polarized light to qualitatively assess the weld quality.



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## **II. EXPERIMENTAL WORK**

In order to investigate the influence of the process parameter on the formation of welding defects and mechanical properties of laser welded Polycarbonate (PC), a welding experiment were carried out using 200W Nd:YAG laser operating at 1064nm wavelength equipped with a 3-axes CNC work table, coordinated with the motion system and computer interface. A lap joint configuration was considered in the experiments, the laser-transparent part and the laser-absorbent part are welded together with a fixed overlap distance. The laser beam scans over the assembly at the specified power and speed to join the two parts together. Fig.1 shows the lap welding process of PC and welded samples. The effects of laser power, and welding speed on weld strength and microstructure were assessed. A shear lap tensile test with the weld line arranged perpendicular to the test pull direction was used to evaluate the weld quality of specimens.



Figure 1: Laser welding process and welded samples

## **III. EFFECT OF PARAMETERS ON WELD STRENGTH**

## 1) Weld strength as a function of line energy

The effects of laser power and welding speed in terms of line energy on weld strength are presented in Fig. 2. The line energy is directly proportional to the laser power and inversely varies with the welding speed, at various laser powers the energy densities are not equivalent; an energy density of 1J/mm2 did not produce similar weld strengths at 20W, 30W, 40W or 50W. High weld strengths were achieved with 40W. For each power level, there is a threshold line energy value at which the tensile strength reaches maximum. The threshold line energy and maximum weld strength values increase with the power until a threshold power level is reached (threshold power 40W), then the strength started to decrease for further increase of laser power.



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Figure 2: Transparent part thickness1mm, weld strength as a function of line energy

## 2) Weld strength as a function of Laser Power

The investigation showed that when the laser power was varied between 20 W and 40 W, with welding speeds kept constant, there was a corresponding increase in the fracture loads of the joints up to a specific level, which was followed by a decrease beyond this point, shown in Fig. 3.

Figure 3 shows the force at break as a function of power for PC, at welding speed of 40mm/s. It is observed that, the load-at-break increases with power and then starts to levels off or decrease as power is increased further. This is due to polymer degradation at the weld because of too high temperature caused by high laser power.

For PC, with a laser power P < 20 W no welding, a minimum laser power of approximately 20 W is required for the two parts to bond together. Once the crystalline melting temperature is reached, the black part starts to melt and the welding process starts. At this power setting, due to insufficient heating and limited molecular diffusion between the two parts, the load-at-break is very low.

For the applied laser power range 20 W $\sim$ 30 W, the beam do not possess enough energy to cause strong welding, At this power setting, the load-at-break is low, these lower load are caused by low temperatures the weld zone.

For the applied laser power range 30 W $\sim$ 40 W, the load approaches a maximum 0.9 $\sim$ 1.3 KN, these increase in load with power are caused by higher temperatures and wider heated zone at the weld seam. The microstructure of the weld joint at this power setting shows no defects are found on the weld seam (see table 1, micrograph M1).

For the applied laser power range 40 W $\sim$ 60 W, the maximum load then starts to decrease as power is increased further. These changes in maximum load with power are caused by higher temperatures at the weld seam. This higher temperature caused by high laser power lead to polymer degradation at the weld zone. The microstructure of the weld joint at this power setting shows some voids or burning found on the weld seam.



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Figure 3: Influence of Laser Power on Weld Strength

## 3) Weld Microstructure Analysis

In an attempt to understand, the physical nature and mechanism of formation of strong and stable laser bonds, the joints were characterized by optical microscopy. Table 1-3 shows representative weld seam micrographs, the table provide a good comparison of the bonds, bond widths, and all micrograph pictures were taken with a similar magnification 20 X. In general, the top view of bond surface shows a darkened zone which is created by a change in color of the polymer and represents the bonded area.

By visual inspection of the optical micrographs, high quality weld seams are characterized by a uniform melt pool profile without bubbles or pores, or defects (see micrograph M1, M4, M5, M7 and M8. The damaged area can be identified by the gradually widening dark region with laser power. The very dark area of the weld in the micrograph M2, M3, M6 and M9 indicate the degradation zone. It can be seen from the micrograph that the weld width increased with higher laser power. However, the damaged area in the centre of the weld also increases with power.

As can be noted in the table, welds formed at high laser power such as 60 W resulting in decomposition whatever at low or high welds velocity. Welds formed at high laser power and low weld velocity such as 50 W and 40 mm/s, also resulting in decomposition. At the other end, welds formed at low laser power and high weld velocity, such as 40 W and 80 mm/s, resulting in thin or tapering welds.

It was observed that an increase in laser power brings about a corresponding increase in weld width, which influences positively on the fracture load, illustrated in Table 1, 2 and 3.



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**Table 1:** Influence of laser power on joint appearance, bubbles or porosity formation or polymer degradation, and weld width at fixed welding speed 40mm/s, transparent part thickness 1mm.

Laser power	40 W	50 W	60 W
Weld seam micrograph (welding speed 40mm /s)	M1	M2	M3
Weld width			

**Table 2:** Influence of laser power on joint appearance, bubbles or porosity formation or polymer degradation, and weld width at fixed welding speed 60mm/s, transparent part thickness 1mm.

Laser power	40 W	50 W	60 W
Weld seam micrograph (welding speed 60mm /s)	M4	M5	M6
Weld width			

**Table 3:** Influence of laser power on joint appearance, bubbles or porosity formation or polymer degradation, and weld width at fixed welding speed 80mm/s, transparent part thickness 1mm.

Laser power	40 W	50 W	60 W
Weld seam micrograph (welding speed 80mm /s)	M7	M8	M9
Weld width			



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Analysis of the melt pool profile was carried out to estimate the fusion zone and, hence, the seam depth. Fig.4 shows the effects of welding speeds on the weld geometry. From the micrograph, it is clear that lower welding speed result in greater weld width and depth.



(d) 60 mm/s

(f) 100 mm/s

Figure 4 molten depths in the transparent and absorbing PC obtained in welding experiment; magnification of 50 X.

(e) 80 mm/s

## **IV. DISCUSSION**

In laser transmission welding of polymers, one of the polymers, typically the top polymer, needs to be transparent to the laser beam while the other polymer absorbs the laser beam. The bottom, laser-absorbent polymer heats up and consequently melts. The heat transfers by conduction from the bottom polymer to the top transparent polymer, which melts, and the two parts are subsequently pressed together for eventual joint formation.

The physical phenomena occurring in the welding process are summarized as:

-The polymer -to-polymer joint interface is heated up by the laser beam, and melting temperature is attained in the plastic material in a narrow region adjacent to the interface;

- The resulting high temperature initiates the formation of bubbles in the melted plastic close to the interface;

- Bubbles spread and diffuse into the molten phase and consequently increase seam dimension;

- bonding results in the molten-solid interface between the two plastics.

Laser transmission welding experiments were conducted to explore the effect of the welding parameters (welding speed and laser power) on the quality and integrity of the weld seams. This effect was analyzed based on standard methods: Visual inspection by optical microscopy and tensile strength analysis.



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#### Influence of the process parameters on weld strength

Fig. 2 presents the effects of laser power and welding speed in terms of line energy on tensile strength. Line energy is the ratio of power to welding speed, defined as laser input energy per unit length, by varying the levels of laser power and welding speed within the range of present experimental domain. The increase of laser power with decrease of welding speed results in increase of line energy. Too low line energy results in lack of penetration, poor heat transfer and poor mixing of materials, thus causing an unacceptable weld. On the other hand, too high line energy may cause degradation of the base material. The maximum tensile force occurs at about LE=1J/mm, for line energy beyond 1J/ mm, the tensile force decreases with increasing line energy. The optimum weld strength can be achieved at a favorable value of line energy value at which the tensile strength reaches maximum. The threshold line energy and maximum weld strength values increase with the power until a threshold power level is reached, then the strength started to decrease for further increase of laser power. The weld strength is restricted at very high power density, which causes material decomposition and a very low power density results in lack of fusion.

#### Influence of the process parameter on weld seam microstructure

The shape of the weld joint remained elliptic for all welding speed. The influence of the irradiation time on the seam dimensions and its morphology is shown in Fig. 4. It can be observed that increasing the irradiation time, through decreasing the scanning speed, induced larger and deeper weld seams due to a higher energy deposit and enhanced diffusion phenomena.

Fig. 1, fig.2, fig.3, fig.4, table 1, table 2 and table 3 shows that the laser power, welding speed are the most important welding process parameters for the weld pool geometry, (particularly, the width of weld seam) and the resulting mechanical properties (particularly, tensile strength) of laser-welded lap joints. Table 1, table 2 and table 3 show the effect of the laser power on the final weld formation and surface integrity. Increasing the power density or reducing the welding speed induced an increase of the weld zone dimensions as well as the thermal degradation. By increasing the power density or by reducing the welding speed, voids are observed on weld seam. The very dark area of the weld seam in micrograph M2, M3, M6 and M9 show that the polymer undergoes thermal degradation under excessive heating above the degradation temperature of PC. For laser power 60W, the weld width is wide but the tensile strength is low due to degradation. The tensile strength of laser welded lap joints depends mainly on the width of weld seam, the depth of penetration as well as the quality of weld for example if no degradation or burning occurred.

There is an increase in maximum failure load with increasing power until it reaches a peak and then drops even with increasing power. The extend of weld seam defect such as weld seam surface burning or voids were at maximum value when laser power was at its highest, 60 W. On the other hand, as the laser power decreased slightly, typically to 50 W and 40 W, there was a corresponding decrease in weld seam defect and joints reached the highest fracture load. At lower laser powers, 20 W, the laser power was not great enough to completely melt the polymer part.

Based on observation of the joining process, the extend of weld seam defect such as weld seam surface burning or voids play a vital role in the joining process. When the number/ size of voids increase, a negative effect is dominant and the strength of the joint decreases. On the other hand, as the number and size of voids decreases, the positive effect is



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dominant and the joint strength increases, especially at laser power 50 W and 40 W.

## V. CONCLUSIONS

When the weld interface receives excess laser power than required, polymer degradation takes place. Surface burning of the laser transparent part, which also affects the visual appeal of the welded sample, is one of the signs that the sample receives excess power. Bubbles or voids at the bottom surface of the laser transparent part and the top surface of the laser absorbent part also indicate polymer degradation. The bubbles are simply voids in the weld area are due to polymer degradation, which reduce weld strength.

In order to achieve a successful weld through laser transmission welding, a good understanding of the issues associated with the welding process is required. Polymer degradation and surface burning are the two key issues which affect the strength and the visual appeal of the weld respectively.

The polymer degradation starts at a line energy, for example when the threshold line energy is exceeded. If the line energy is kept between 0.5 and 1J/mm, polymer degradation could be avoided and stronger welds could be achieved.

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