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

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Abstract

The efficiency of laser transmission welding strongly depends on the optical properties of the plastic parts to be joined and the process parameters. This paper investigates the effect of the laser welding parameters such as laser power, welding speed on weld strength. A 200 W YAG laser with wavelength 1064 nm has been used to weld transparent and absorbing polycarbonate (PC) in lap weld configuration. 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.

Keywords: Laser transmission welding; Plastic welding; Weld strength; Polycarbonate

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 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 [1]. Chen evaluated the line energy (power divided by laser scan speed) required to cause degradation on the surface of uncolored polycarbonate [2]. This work demonstrated that, despite high transparency of polycarbonate, there is a particular level of line energy at which 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 studied dependence of the joint strength on absorbent concentration, specimen thickness and energy density [3]. 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 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 investigated optimal process parameters for quasi-simultaneous welding of PMMA and polycarbonate parts [4]. 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. Vegte performed comparative measurements of transmittance of different plastics [5]. They tested specimens of the same thickness made of PC, PA 6, PA 46, and PBT. These materials are listed in the sequence from the highest to the lowest measured transmittance. The magnitude of the beam scattering was higher for a material with lower transparency. In other words, PC showed the best transmittance and the lowest scattering and transparency of PBT was the lowest with the highest magnitude of scattering. Additionally, authors observed a reduction of transmission with an increased amount of glass fibers in the material.

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.

Experimental Work

In order to study the effect of part thickness on weld quality, different thickness for transparent part was selected. The part thickness for transparent part varied between 1 mm to 3.5 mm, and for absorbent part, a part thickness of 3 mm was selected. In order to manufacture both transparent part and absorbent part, a mold with different mold inserts was fabricated. The mould insert was used in an existing mould cavity in an injection moulding machine to produce the polycarbonate (PC) absorbent part and transparent part with different thickness, as shown in Figure 1. Figure 2 shows the injection molded of transparent and absorbent parts.

The welding experiment were carried out using 200 W Nd:YAG laser operating at 1064 nm 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. Figure 3 shows the lap welding process of PC and welded

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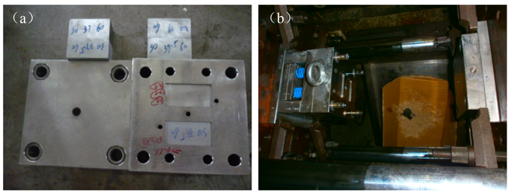

Figure 1: (a) Mold with different mold insert; (b) Injection machine.

Figure 2: Injection molded of transparent and absorbent parts.

Figure 3: Laser welding process and welded samples.

Thickness of transparent part (mm)	Transmission (%)
1	94.5
1.5	94
2	93
2.5	92
3	91.7
3.5	91

Table 1: Transmission for different thickness of transparent part.

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.

Effect of Parameters on Weld Strength

Optical properties of transmitting part

In this section, the optical properties of the PC materials are investigated; the transmission measurement results are summarized in Table 1. The data shows that the transmittance varied with material thickness, which is approximately between 91%~94.5%. A 1 mm thick polycarbonate (PC) part has a transmittance of 94.5, and 3.5 mm thick PC has a transmittance of 91%. These results shows that for laser-transparent parts made of amorphous polymers such as PC, the part thickness usually has little influence on transmittance.

Influence of welding speed on weld strength

Figures 4 and 5 show the degradation of the weld at low welding speed. At welding speed 10 mm/s, and laser power 40 W, and transparent part thickness 1~1.5 mm range, serious overheating degradation of the weld is observed. At low welding speed, longer laser irradiation time cause overheating degradation of the plastic part, thereby damaging the surface of the weld and plastic parts. Figure 4 shows the deterioration of the weld joint at low welding speed (10 mm/s) and laser power 40 W.

At welding speed between 20~30 mm/s, laser power 40 W, and transparent part thickness 1~1.5 mm range, the PC welding process may be subject to thermal stress effect and lead to lower relative molecular diffusion, causing slight degradation or decomposition, thereby affecting performance of plastic parts and surface quality, as consequences shortened service life expectancy of the welded part (Figure 5). Figure 5 shows the degradation of the weld joint at low welding speed (20~30 mm/s) and laser power 40 W.

Figure 6 shows the weld width as function of weld speed, at laser power of 40 W. In Figure 7 the results indicate that the welding speed is the most important factor affecting the welded zone width. An increase in welding speed leads to a decrease in welded zone width. This is due to the laser beam travelling at high speed over the welding line when welding speed is increased. Therefore the heat input decreases leading to less volume of the material being melted, consequently the width of

Figure 4: Welding 10 mm/s, laser power 40 W, overheating degradation of the weld joint occur.

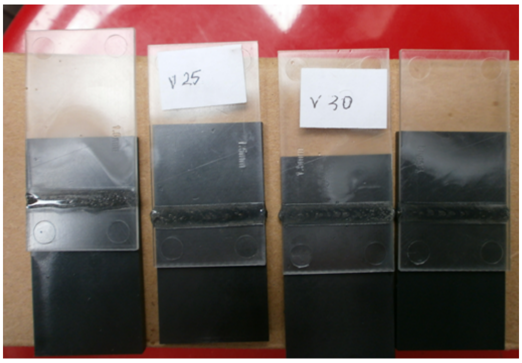

Figure 5: Welding 20~30 mm/s, laser power 40 W, slight degradation of the weld joint occur.

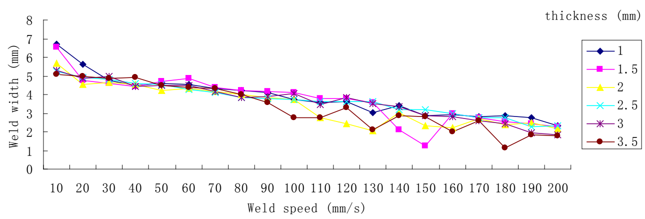

Figure 6: Laser power 40 W, weld width as function of weld speed.

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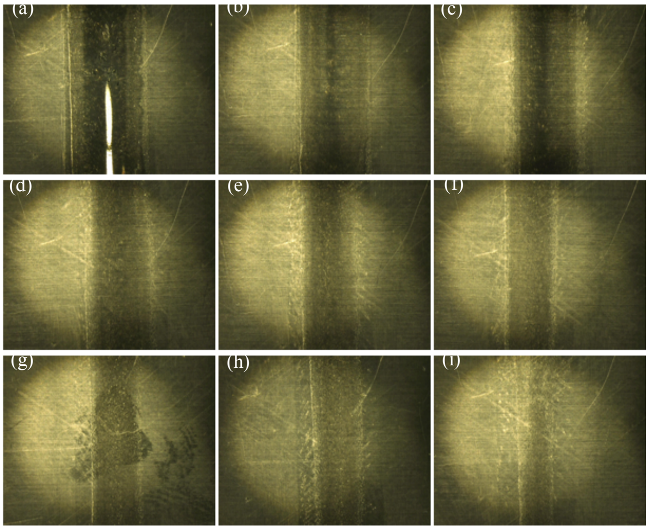

Figure 7: Effect of welding speed to weld width, laser power 40 W, transparent part thickness 1 mm; (a) 40 mm/s; (b) 50 mm/s; (c) 60 mm/s; (d) 70 mm/s; (e) 80 mm/s; (f) 100 mm/s; (g)110 mm/s; (h)120 mm/s; (i)160 mm/s.

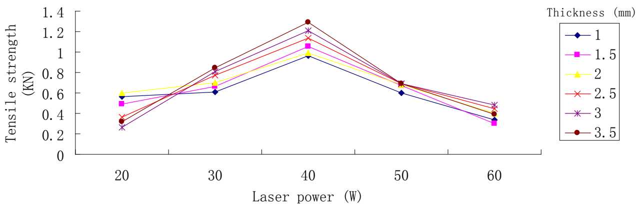

Figure 8: Influence of laser power on weld strength.

the welded zone decreases. Moreover, the results shows also that laser power contribute secondary effect in the weld zone width dimensions. An increase in laser power results in slightly increases in the weld zone width, because of the increase in the power density. The main factor influencing the width of HAZ is the welding speed as the results indicated. This is due to the fact that at low welding speed the heat input will be greater.

Influence of laser power on weld strength

Figure 8 shows the force at break as a function of power for PC, at welding speed of 40 mm/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~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~40 W, the load approaches a maximum 0.9~1.3 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 (Figure 9).

For the applied laser power range 40 W~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.

Figure 9 shows the force at break as a function of welding speed, at laser power of 40 W. 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.

Figures 10-12 show the effect of laser power on weld microstructure. From Figures 11 and 12 it can be clearly seen that further 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

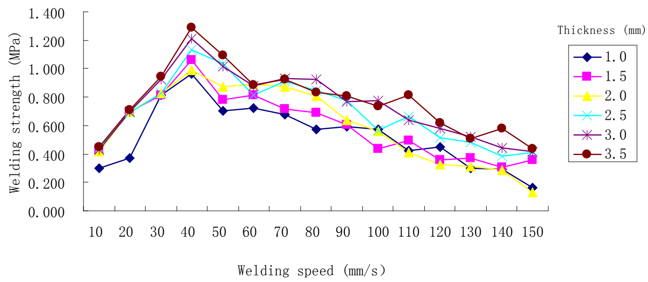

Figure 9: The maximum load as a function of welding speed, laser power=40W.

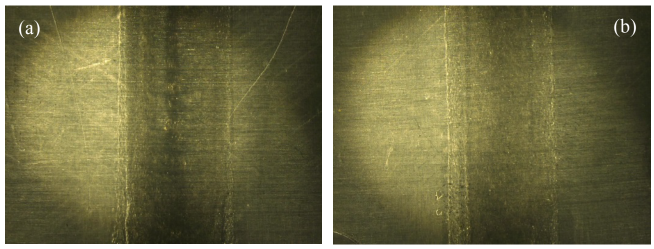

Figure 10: Weld interface for PC with laser power 40 W, welding speed of 40 mm/s (a) transparent thickness 1 mm; magnification 20X; (b) transparent thickness 1.5 mm; magnification 20X.

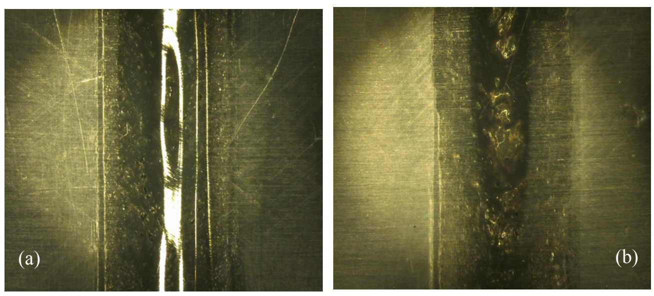

Figure 11: Weld interface for PC with laser power 50 W, welding speed of 40 mm/s; magnification 20X (a) transparent thickness 1 mm and (b) transparent thickness 1.5 mm; magnification 20X.

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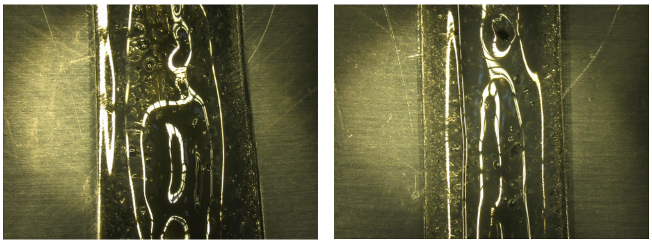

Figure 12: Laser power 50W, welding speed 40 mm/s; (a) transparent part thickness 1 mm; (b) transparent part thickness 1.5 mm.

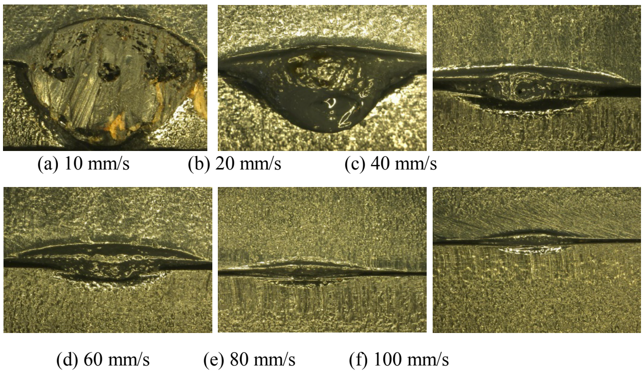

Figure 13: Molten depths in the transparent and absorbing PC obtained in welding experiment; magnification of 50X.

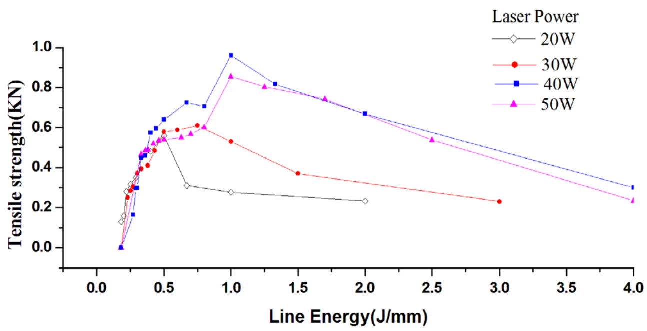

Figure 14: Transparent part thickness 1 mm, weld strength as a function of line energy.

of the material at the center of the weld seam, reducing mechanical performance of the joint.

Figure 13 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. The effects of laser power and welding speed in terms of line energy on weld strength are presented in Figure 14. 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/mm^2 did not produce similar weld strengths at 20 W, 30 W, 40 W or 50 W. High weld strengths were achieved with 40 W. 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 40 W), then the strength started to decrease for further increase of laser power.

Discussion

Influence of the process parameters on weld strength

Figure 14 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 optimum weld strength can be achieved at a favorable value of line energy with an appropriate combination of laser power and welding speed. 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 40 W), 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 dimension

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 Figure 13. 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.

Figures 7-12 shows that the process parameter affects the weld seam dimension as well as the weld strength. 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 Figures 11a, 11b 12a and 12b show that the polymer undergoes thermal degradation under excessive heating above the degradation temperature of PC.

Conclusions

We can conclude that the weld strength is limited by very high welding speed in one hand, in the other hands the weld strength is limited by very high heat input, which causes overheating and partial decomposition of the material, and a very low heat input results in lack of fusion. As the results indicate, it is not recommended that too high or too low laser power and velocity be used.

Acknowledgement

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