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WELDING OF THERMOPLASTIC MATERIALS USING CO_2 LASER

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ABSTRACT:- The welding of thermoplastics using CO2 laser achieved, two different types of thermoplastic materials used which are; Perspex (PMMA) which is the abbreviation of polymethyl methacrylate and (HDPE) which is the abbreviation of high density polyethylene. Similar or different materials can be welded together by laser beam but in this work similar polymers have been welded (i.e PMMA tube to PMMA tube and HDPE plate to HDPE plate). Mechanical properties for these materials measured after welding, two CW CO2 lasers were used in the welding process have the wavelength of 10.6µm. The maximum power of the 1st one is 16W, and for the 2nd one is 25W. The experimental result showed that the penetration depth increases with increasing laser output when the welding speed is constant. Also a relation between spot width and depth calculated using MATLAB software program version 6.5 taken into account the effect of the following parameters, power used in welding, melting temperature of the materials, welding speed and the spot diameter of the laser beam.

Keywords: CO2, HDPE, PMMA, MATLAB software, power, welding.

1. INTRODUCTION

As laser welding of plastics becomes more widely used it becomes correspondingly important to know what is happening – or what should be happening – in the weld. Laser welding of thermoplastic offers distinct advantages and performance capabilities such us speed, localised heat and fine spot size over the traditional plastics welding methods. Laser welding is popular in industrial applications that require rapid processes, good aesthetics and fine weld lines. To transmit the laser beam to the weld region, the top polymer layer needs to be transparent or translucent to the wavelength of the laser beam used. Heating the interface is further localised by designing the lower layer material to be laser absorbing. The fine laser beam size localises the heat at the weld interface without altering the material surfaces or damaging the adjacent materials. These unique characteristics make laser welding especially suitable for medical, automotive and electronic applications.

Laser welding can be applied to a wide range of thermoplastic polymers. It is also possible to weld materials with different melting temperatures, when there is molecular compatibility between two polymers. [1]

A number of studies have focused on the influence of the process parameters (e.g., weld pressure, laser beam power, and scanning speed) on the weld quality and mechanical performance of polymers. Kagan and Pinho [2] investigated the mechanical performance (i.e., tensile strength) of welded PA as a function of process parameters at room temperature. The main purpose of this study was to promote the use of PA in LTW applications. Abed et al. [3] used a diode laser with PP specimens to observe the weld seam micro-structure. They investigated how the micro-structure is affected by the variation of laser speed and power as well as carbon black concentration in the laser-absorbing part. Woosman et al. [4] used the Clearweld® technique and measured the weld strengths for several thermoplastics (e.g., PC, PMMA, LDPE, PVC, PSU, and PETG) that were butt-joint-welded. Analytically Grewell et al. [5] presented a 1D thermal model to investigate the LTW technique for thermoplastics. They adopted the power flux for the weld to occur using Stokes approach and chose PC, ABS, Acrylic, and PS samples for their studies.

2. LASER WELDING CONCEPT

In laser welding of thermoplastics, sometimes referred to as "laser transmission welding" or "through transmission IR welding (TTIr), compatible thermoplastic materials are bonded together. The laser beam penetrates the top laser-transmissive thermoplastic and is converted into heat by either a bottom laser absorbent thermoplastic or by a laser absorbent dye at the weld interface. [6]

The two parts are put under pressure while the laser beam moves along the joining line. During the welding process an external force is applied which clamps together both thermoplastic parts allowing for a conduction of heat from the laser-absorbent thermoplastic to the laser-transmissive thermoplastic, melting both parts and creating a bond. Thermal expansion in the welding zone creates an internal pressure and leads to a strong weld between the parts. [6]

The beam passes through the first part and is absorbed by the other one or the coating to generate enough heat to soften the interface creating a permanent weld. Power levels from less than 1W to 100W are needed depending on the materials, thickness and desired process speed.

The laser energy is passed through an "infrared" transmitting part and is absorbed at the surface of a second "infrared" absorbing part as shown in figure (1). This is enabled by the use of "infrared" additives. Energy sufficient to cause a temperature rise above the melting point of the polymer is supplied to the joint interface. Parameters such as laser power, laser beam width, and laser speed are used to optimize joint strength. [7]

Desirable characteristics of the laser welding process:

- Excellent joint strength
- Excellent welded joint aesthetics
- No flashes or particulate created by the welding process
- No chemical attack
- Very short weld cycle time
- No cure time requirement

3. CALCULATION OF THE WELD TEMPERATURE AND WELD DEPTH

3.1 Temperature calculation

It is currently difficult to routinely measure the temperature at the interface where the weld takes place. In contrast, the weld depth can be measured after the welding process by microscopic examination of sectioned specimens.

The measured weld depth is used to verify the calculated weld depth and provide confidence for determination of weld temperature that was also calculated using a modified theory by Shercliff and Ashby [8].

In the Shercliff and Ashby model, the following dimensionless variables for temperature, laser power, speed and depth are defined:

$$T^* = \frac{(T - T_0)}{(T_m - T_0)} \quad (1)$$

$$q^* = \frac{Aq}{r_B \lambda (T_m - T_0)} \quad (2)$$

$$v^* = \frac{Vr_B}{a} \quad (3)$$

$$t^* = \frac{t}{t_0} \quad (4)$$

$$z^* = \frac{z}{r_B} \ , \quad z_0^* = \frac{z_0}{r_B} \quad (5)$$

Where

Where T, T_0, T_m, T^* are temperature (K), room temperature (K), melting temperature of the substrate (K), is the dimensionless temperature rise (normalized temperature) respectively.

q^*, A, q, r_B, λ are dimensionless beam power, dye absorption %, laser beam power (watts), beam radius (m) and laser wavelength (μm) respectively.

v^*, Vr_B, a are dimensionless speed, beam speed (m/s) and thermal diffusivity of the substrate (m^2/s) respectively.

t^*, t, t_o are dimensionless time , time (s) and heat flow time constant(s) respectively.

z^*, z are dimensionless co-ordinate, depth co-ordinate (mm) respectively.

r_B is the laser beam radius (mm).

The temperature field at the center of the beam is[8] :

$$T^* = \frac{(2/\pi)(q^*/v^*)}{[t^*(t^*+1)]^{1/2}} \exp - [\frac{(z^* + z_0^*)^2}{t^*}] \quad (6)$$

The maximum temperature and weld depth occurs at the beam centre. The dimensionless time to peak temperature is determined by differentiating (6) with respect to time [8].

$$t_p^* = \frac{1}{4}\left[2(z^* + z_0^*)^2 - 1 + \left[4(z^* + z_0^*)^4 + 12(z^* + z_0^*)^2 + 1\right]^{1/2}\right] \quad (7)$$

The dimensionless peak temperature is obtained by substituting t_p^* from the equation (7) into (6). In these equations, z_0^* is used as an adjustable parameter for calibrating equation (6) to a known surface peak temperature.

3.2 Surface (weld) temperature calculation

When a beam of uniform intensity is applied to the surface, at $z^*=0$, for a time equal to the interaction time, it produces a surface peak temperature in a dimensionless from [8]:

$$(T_p^*)_{z^* \to 0} = (\frac{2}{\pi})^{3/2} (\frac{q^*}{v^*})^{1/2} \quad (8)$$

The adjustable variable of z_0^* in equation (6) is introduced to minimize the difference between T_p^* that is calculated from equations (8) and (6). In practice a difference less than 0.003 is found to be satisfactory.

3.3 Calculation of the melt depth

The temperature inside the substrate is calculated stepwise as the value of z^* is increased until the temperature is higher than the glass transition or the melt temperature of the substrate. [1]

According to P.Okon and etal (10) the penetration depth of a laser spot welding is

$$z_m=1.12(2)^{0.5}(a)^{0.5}[((r_B)^{0.5}/(V_{rB})^{0.5})-(\pi T_m L r_B^2/P)] \quad (9)$$

in which z_m is the depth at which temperature reaches melting point

4. EXPERIMENTAL SETUP

4.1 Using 16W CO_2 laser

This setup is shown in figure (2) which is used to weld two pieces of PMMA tube and in figure (3) to weld two pieces of HDPE plate.

Two methods for HDPE welding were used here; the first was butt weld joint, and the second was spot / lap weld joint.

4.2 Using 25W CO_2 laser

Figure (4) shows another setup of CO_2 laser used to weld the same materials mentioned above. This setup consists of,

- a power supply
- 25W CO_2 laser with repetition rate of 5 kHz, pulse duration of 100µs and beam diameter of 10mm.
- Beam delivery system: the laser beam will be focused through this system so that laser beam diameter that reaches the material will be 5mm.
- CNC positioning system was used to position and rotate the specimen under the laser during welding.
- Eye protect.

5. PRACTICAL PART AND RESULTS

In order to investigate the quality and strength of CO_2 laser welded thermoplastics materials, different types of materials (PMMA and HDPE), different joints of welding (i.e. butt and spot joints), different laser power (i.e. 16W and 25W) and different geometries (tube and plate) were used.

5.1 Using 16W CO_2 laser

The thermal properties of both PMMA and HDPE thermoplastics (9) and CO_2 laser welding process parameters used in this work are shown in table (1). Using 16W CO_2 laser device three welding joints (butt welded PMMA tubes, butt welded HDPE plates and spot welded HDPE plates with lap joint) are investigated as shown in figures below.

For the first time when the PMMA tube was butt welded with the laser parameter shown in table (1), the two pieces were separated after about 24 hours because the weld zone was very thin as shown in figure (5) and this is because full depth penetration wasn't achieved in laser welding. So the PMMA welding was repeated one more time as shown in figure (6) but this time the weld zone has a good thickness enough to keep the joint pieces together and achieving full depth penetration. In figure (7) the results indicate that the welding speed and focused position are the most important factors 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 base metal being melted, consequently the width of the welded zone decreases. Moreover, defocused beam, which mean wide laser beam results in spreading the laser power onto wide area. Therefore, wide area of the base metal will melt leading to an increase in welded zone width or vice versa. The results show also that laser power contribute secondary effect in the weld zone width dimensions. An increase in laser power results in slightly increase 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. This heat will conduct from the fusion zone to the bulk metal through HAZ making it wider and coarser. Figure (8) shows laser welding of HDPE plates which was much easier than PMMA welding because the melting temperature for HDPE is less than that of PMMA so it needs less power, and the second reason here is that the control of welding in HDPE plates can be achieved more than that of PMMA tubes. In figure (8a) the welding joint wasn't good because of high laser power used (13W), after that another trail with less laser power of (8W) was used which gives a good HDPE welded joint as shown in figure (8b) and this result prove that the laser power has a significant effect on welding quality.

5.2 Using 25W CO2 laser

The thermal properties of both PMMA and HDPE thermoplastics [(9)] and CO_2 laser welding process parameters used in this work are shown in table (2). Using 25W CO_2 laser device four welding joints (butt welded PMMA tubes, butt welded HDPE plates and spot welded HDPE plates with lap joint) are investigated as shown in figures below.

Different laser powers were used as shown in table (2), the high power (5W) results in bad PMMA and HDPE welded joints as shown in figures (9&10). In order to get more good weldments (i.e. without defects) the laser power was decreased (i.e. 2W & 1.6W) and this behavior gives good results specifically for tee joints as shown in figures (11&12).

6. PENETRATION DEPTH OF LASER SPOT WELDING

Equation (9) is used to predict semi-quantitative variation of penetration depth with spot radius in a CO_2 laser welding process. The welding parameters shown in table (1) for 16W CO_2 laser device was used as input to equation (9). Figure (13&14) shows the result of a simulation using values, $P=9W$, $v = 0.042cm/s$ for PMMA and $P=8W$, $v = 0.034cm/s$ for HDPE and K, Tm and α remaining constant as seen in the table. What is important here is the penetration depth/spot radius variation. These figures gives in indication that a significantly greater amount of energy is required to vaporise the metal liquid at boiling point than is required to melt the solid metal at melting point. Therefore most of the additional heat absorbed at the boiling point will be utilized in boiling the liquid metal rather than cause vaporisation in the conduction mode regime.

This phenomenon is only observable at relatively low welding speeds. Thus the choice of welding speed is critical depending on the type of laser and the laser power involved. At greater speeds the reduced interaction time results in a relatively lower heat absorption by the work piece.

Using welding parameters in table (2) for both PMMA and HDPE the same analysis was done. A semi-quantitative variation of penetration depth with spot radius in a CO_2 laser welding process was plotted (figures 15, 16, 17 and 18) with different laser powers and different welding velocity.

In all cases it was found that the aspect ratios (penetration depth divided by weld width) of the welds were less than one. Penetration depth/spot radius curves plotted showed an increase (up to a maximum) and then a decrease of penetration depth with increase in spot radius in the conduction weld regime. This can be attributed to the interplay between decreasing power density and increasing interaction time, as the spot radius becomes larger.

7. CONCLUSIONS

1. The PMMA welding was failed for the first time. To obtain a Permanent welding; an additional PMMA material should be welded around the weld zone to give it precision and permanent welding.
2. HDPE welding was much easier than PMMA welding
3. Semi-quantitative analysis of the LW process shows that the penetration depth increases with increase in spot radius when the surface temperature remains at boiling temperature. This trend is reversed when the boiling temperature is no longer sustained due to a further increase in the spot radius. This confirms that the penetration depth/spot radius variation occurs well within the conduction-welding regime, as ideally there should be no vaporisation during LW.
4. Strong, efficient and low-cost weld joints could be achieved using the optimum welding conditions
5. In the welding process a suitable laser power must be used to melt the part that is wanted to be welded.

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Table(1): Thermoplastic materials, their thermo-physical properties and typical welding parameters used.

Thermoplastics / Parameter	PMMA tube	HDPE using Butt weld joint	HDPE using Spot/ Lap weld joint
Thermal Conductivity (J/msK)	0.19	0.38	0.38
Thermal Diffusivity (m^2s^{-1})	$1.1e^{-7}$	$2.64e^{-7}$	$2.64e^{-7}$
Density	$1.19e^{3}$	$0.95e^{3}$	$0.95e^{3}$
Melting Temperature (°C)	140	130	130
Current of Laser (mA)	6	5	5
Laser Power (W)	9	8	8
Welding Time (s)	240	35	60
Welding Speed (cm/s)	0.042	0.034	0.093
Beam Diameter (mm)	5	5	5
Thickness (mm)	4	1	1
Input percentage of power of upper layer (%)	50	50	50
Input percentage of power of lower layer (%)	50	50	50
Absorbitivity (%)	50	50	50

Table (2): Thermoplastic materials, their thermo-physical properties and typical welding parameters used.

Thermoplastics / Parameter	PMMA	HDPE (1)	HDPE (2)	HDPE (3)
Thermal Conductivity (J/msK)	0.19	0.38	0.38	0.38
Thermal Diffusivity (m^2s^{-1})	$1.1e^{-7}$	$2.64e^{-7}$	$2.64e^{-7}$	$2.64e^{-7}$
Density	$1.19e^{3}$	$0.95e^{3}$	$0.95e^{3}$	$0.95e^{3}$
Melting Temperature (°C)	140	130	130	130
Laser Power (W)	5	5	2	1.6
Welding Time (s)	90	20	30	60
Welding Speed (cm/s)	0.388	0.07	0.066	0.0283
Beam Diameter (mm)	5	5	5	5
Thickness (mm)	4	1	1	1
Input percentage of power of upper layer (%)	50	50	50	50
Input percentage of power of lower layer (%)	50	50	50	50
Absorbitivity (%)	50	50	50	50

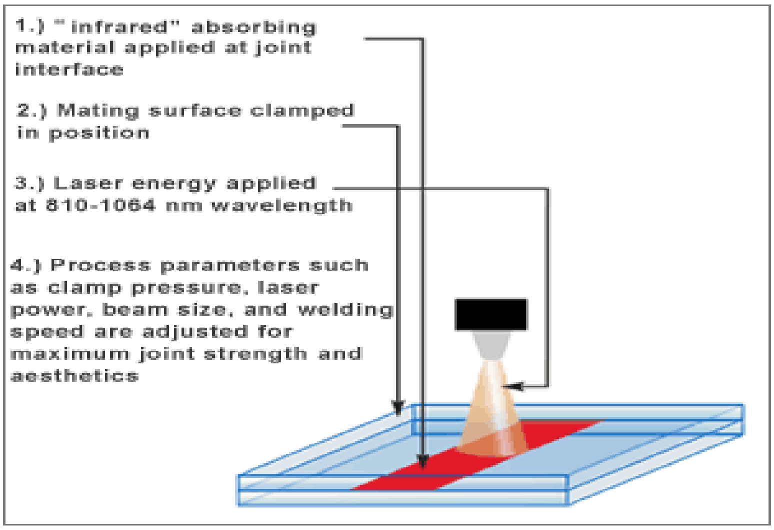


Fig.(1): laser welding process.

PMMA Specimen

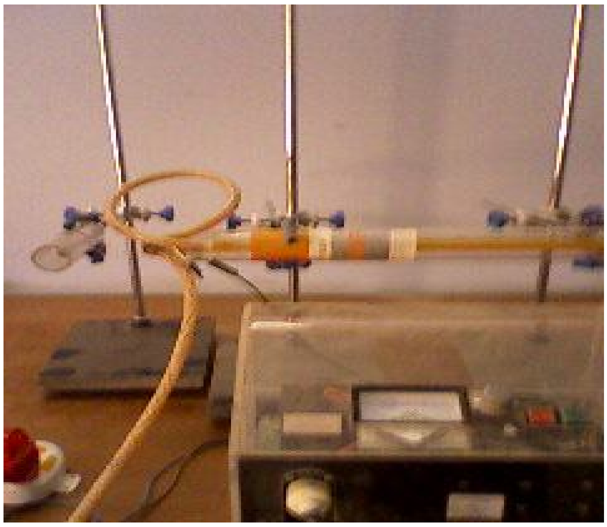


Fig.(2): setup used for PMMA tube welding.

HDPE Specimen

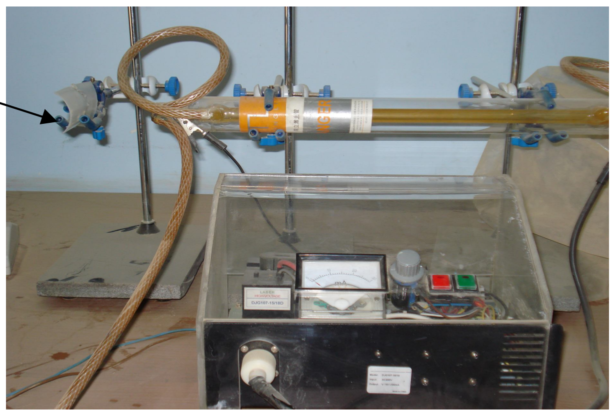


Fig.(3): setup used for HDPE plate welding.

Fig.(4): 2nd setup used for CO_2 laser welding.

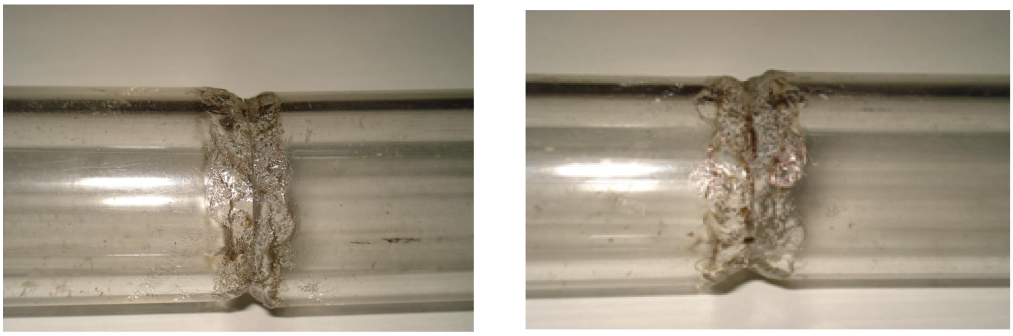
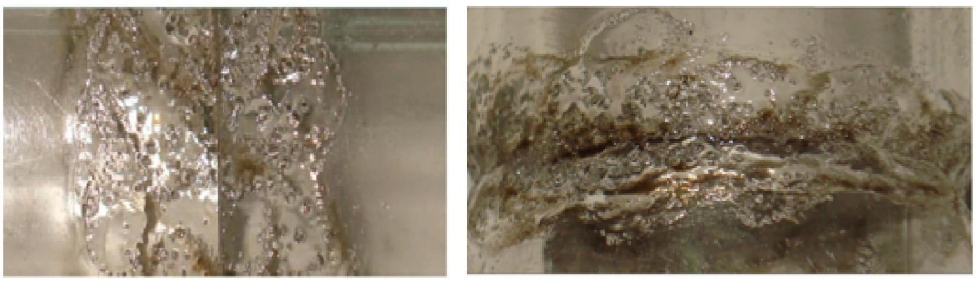


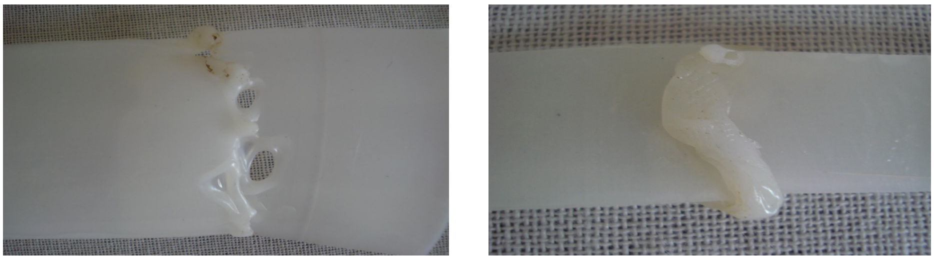
Fig.(5): PMMA welded for the first time.

Fig.(6): PMMA welding for the second time.



(a) **(b)**

Fig.(7): a- represents PMMA welded with high welding speed.
b- represents PMMA welded with low welding speed.



(a) **(b)**

Fig.(8) : HDPE welded using 16W CO2 Laser.

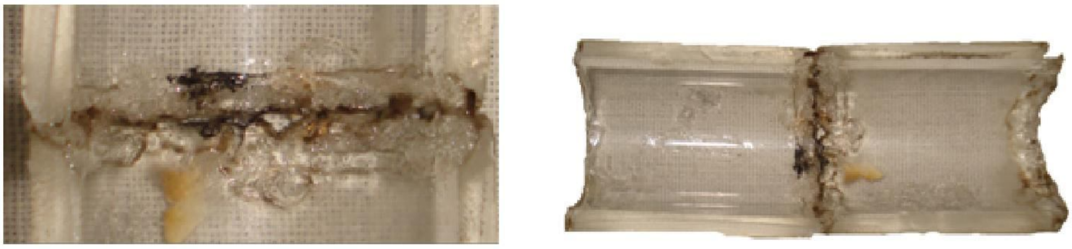


Fig.(9): PMMA welded using 25W CO2 Laser.

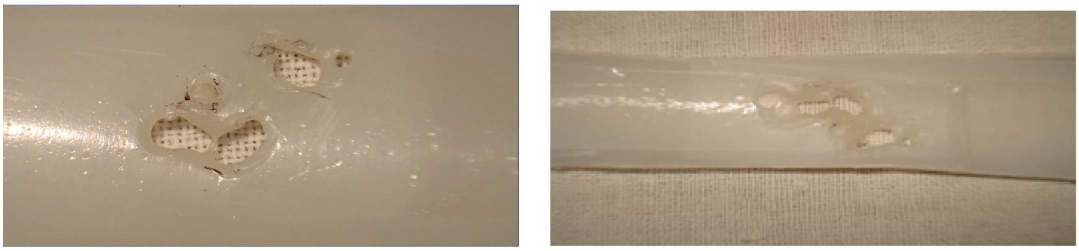


Fig.(10): HDPE (1) welded using 25W CO_2 Laser.

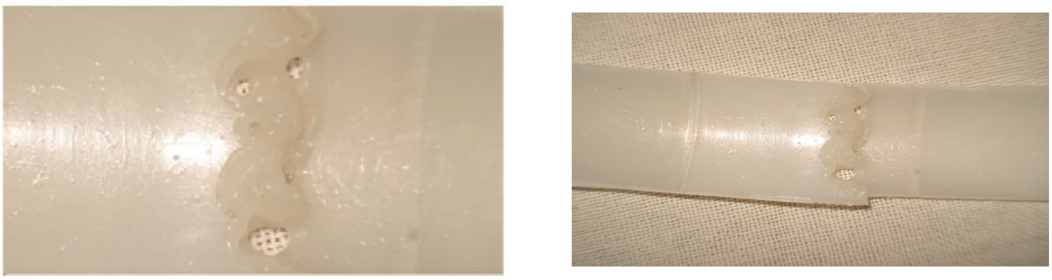


Fig.(11): HDPE (2) welded using 25W CO_2 Laser.

Fig.(12): HDPE (3) Tee weld joint welded using 25W CO_2 Laser.

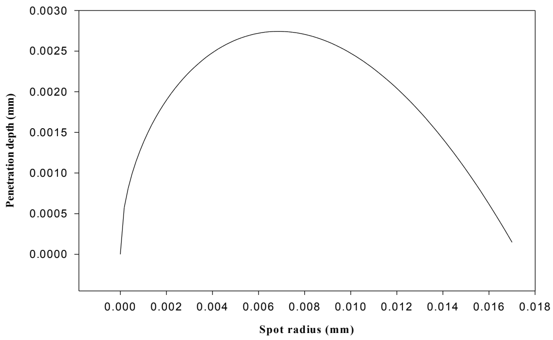


Fig. (13): Depth against spot width for PMMA using 16W CO_2 laser.

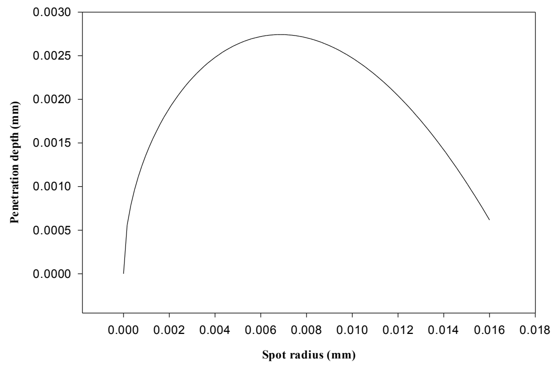


Fig.(14): Depth against spot width for HDPE using 16W CO_2 laser.

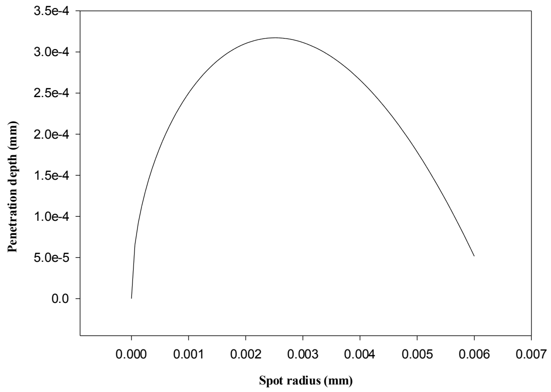


Fig.(16): Depth against spot width for HDPE1 using 25W CO_2 laser.

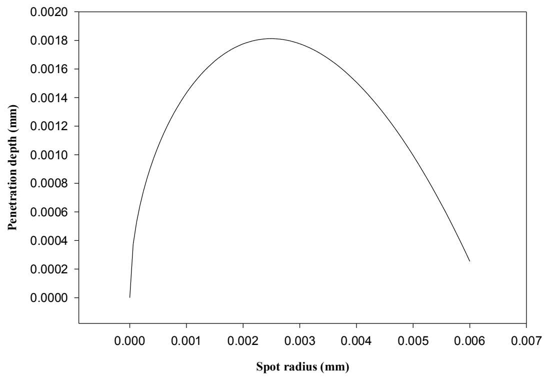


Fig.(15): Depth against spot width for PMMA using 25W CO_2 laser.

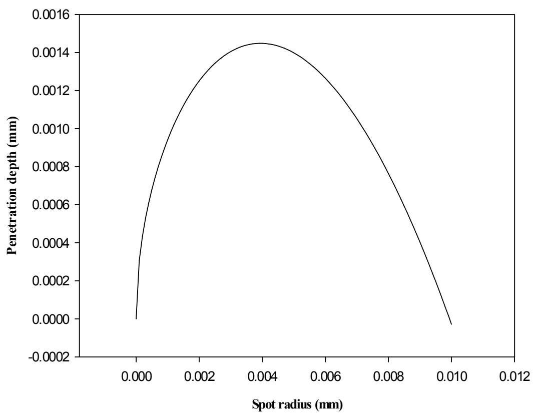


Fig. (17): Depth against spot width for HDPE2 using 25W CO_2 laser.

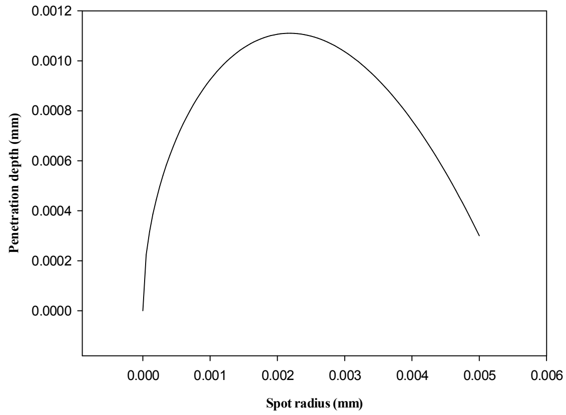


Fig.(18): Depth against spot width for HDPE3 using 25W CO_2 laser.

لحيم البلاستك الحراري باستخدام ليزر ثنائي اوكسيد الكربون (CO2)

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الخلاصة

تم لحام المواد البلاستك باستخدام CO2 ليزر، تم استخدام نوعين مختلفين من البلاستك; Perspex (PMMA)وهو اختصاراً لـ polymethyl methacrylate و(HDPE)وهو اختصاراً لـ بولي اثيلين عالي الكثافة. يمكن لحام مواد متشابهه او مختلفة بواسطة شعاع الليزر لكن في هذا العمل تم لحام مواد بوليمر متشابهه. المواصفات الميكانيكية لهذه المواد قيست بعد عملية اللحام، استخدم جهازي CO2 ليزر بطول موجي 10.6μm، اقصى قدرة للجهاز الاول 16W وللثاني 25W. عمق الاختراق يزداد بزيادة قوة شعاع الليزر عند ثبوت سرعة اللحام. كذلك العلاقة بين عرض البقعة والعمق حسبت ووجدت باستخدام برنامج MATLAB الـ ٦.٥ بالاعتماد على القدرة المستخدمة في اللحام، درجة حرارة ذوبان المواد المستخدمة، سرعة اللحام وقطر بقعة شعاع الليزر.