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HOLE DRILLING IN POLYMETHYL METHACRYLATE (PMMA) USING CO2 LASER

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ABSTRACT: - Laser sources are used in a large variety of applications for material processing. It is mainly used for welding, cutting, drilling, laser annealing, etc. This study narrows the scope down to one of the process, namely, laser drilling.

The hole depth, width and penetration velocity of evaporation depend on different parameters such as power, material, exposure time, distance between drilling tool and the material, the drilling tool, etc. In this paper; the laser beam was used as drilling tool. 16W CO_2 laser (10.6μm) and transparent Perspex (PMMA) which is the abbreviation of polymethyl methacrylate work piece with 8mm thickness were used. The distance between laser beam and the material was 5cm. Different powers for CO_2 laser were used for different exposure time. Hole depth, time required for boiling, heat flow per unit area and penetration velocity of evaporation were calculated. Measured and calculated results were approximately the same. Many figures which representing the relations between laser power, time to reach boiling, hole width, hole depth and exposure time were obtained by using Matlab 2008 software program.

Keywords: Drilling PMMA, laser beam and heat flow.

1. Introduction

Drilling is a cutting process that uses a drill bit to cut or enlarge a hole in solid materials. The drill bit is a multipoint, end cutting tool. It cuts by applying pressure and rotation to the workpiece, which forms chips at the cutting edge.

Drilled holes are characterized by their sharp edge on the entrance side and the presence of burrs on the exit side (unless they have been removed). Also, the inside of the hole usually has helical feed marks [1].

Laser drilling is based on the absorption of the laser energy by the work piece and the conversion of photo energy into thermal energy. This thermal energy forms a large temperature gradient near the surface region of the work piece. When this temperature exceeds that of the melting and/ or vaporization temperature of the work piece, the work piece begins the ablate and a hole geometry is formed. With sufficient time, more material is removed and this hole geometry penetrates deeper into the work piece until the desired hole depth is achieved [2].

Drilling with solid state lasers is a thermal removal process. Due to the strong focused laser beam with high energy density, material is melted and evaporated. As a result of the evaporation and assist gas pressure, the material is thrown out of the hole.

One of the very first industrial uses of the laser was reported in 1965 when a diamond die was drilling using pulse ruby laser. A hole 4.7mm in diameter & 2mm deep was made in about 15 minutes; using a mechanical process this had previously taken 24 hours [3]. Zhang, Yao and Chen reports on experimental and numerical investigation of micromachining of copper using a frequency tripled Nd: YAG laser with 50 ns pulse duration [4]. LAZARE and TOKAREV investigated the micro drilling of polymers with ultraviolet laser beams. The mechanisms of the drilling process have been studied in details and an original analytical model has been constructed recently [5]. Collins and Gremaud presented a mathematical model of laser drilling. Assuming axi-symmetry of the process around the axis of the laser beam, a one-dimensional formulation is obtained after cross-sectional averaging [6].

The energy required to remove material by melting is about 25% of that needed to vaporize the same volume, so a process that removes material by melting is generally favored. Whether melting or vaporization is more dominant in a laser drilling process depends on many factors, with laser pulse duration and energy playing an important role [7].

2- Laser drilling

The laser is actually an intense source of heat. The amount of heat energy absorbed by the work piece is very high which in turn generate high surface temperatures. This high surface temperature can be as high as the boiling point of the work piece. When the work piece reaches boiling point, the localized area starts to eject as gas or vapor from the surface and the surface recedes towards the work piece bulk. Over time, a hole with the required diameter and depth can be achieved [8].

Drilling is the normal area for YAG lasers but CO_2 lasers can also be used on many of these applications. The advantage of the laser is that it can drill holes at an angle to the surface. It is fast and accurate; mechanical drilling is slow and causes extrusions at both ends of the hole which have to be cleaned [9].

Several advantages of using laser are: productivity, cost reducing and residual quality of cutting process are the main factors of laser technology over conventional cutting methods. The laser is also a noncontact tool; nothing touches the part being worked on and there are no saw blades or drill bits to break or keep clean. Other advantages in using laser are a small kerf width and high cut velocities combined with a small HAZ (Heat Affected Zone).Fig.1 shows cutting and drilling of materials using laser. [8]

3- Theoretical calculations

The rate of heat flow per unit area into the surface, is calculated by

$$H= I * (1-R) \quad \ldots. (1)$$

I is the power intensity

R is the reflectivity

The time to reach surface boiling (vaporization) is calculated by

$$t_b= (\pi/4) * (K \rho C/H2) * (T_b)^2 \quad \ldots.(2)$$

Where K is the thermal conductivity

ρ is the density

C is the specific heat capacity

T_b is the boiling point

T_o calculate the maximum depth of penetration of the melting surface (Zm), the following equation is used

$$\mathrm{ierfc}\,(H\, Zm / K\, T_b \sqrt{\pi}) = (Tm / \sqrt{\pi}\, T_b) \quad \ldots.(3)$$

Where H is the rate of heat flow per unit area into the surface

Zm is the depth of melting

Tm is the melting point

And to calculate the penetration velocity of evaporation, the following equation is used [10].

$$\nu_s= H/ \rho\, (C\, T\nu + L_\nu) \quad \ldots.. (4)$$

Where L_ν is the latent heat of vaporization.

4- Experimental setup

Figure (1) shows a setup for drilling PMMA using 16W CO_2 laser (model DJG107-15/18) working in continuous mode as a power source with efficiency

(10-30)%, laser beam diameter is 5 mm, a power of 1, 2, 3 and 4 W were used. The distance between the laser beam and the PMMA sample is 5 cm. PMMA thickness is 8mm. And the drilling process was implemented to drill holes with different time intervals.

Table (1) shows the parameters which were used to calculate the heat flow, time required for boiling, maximum depth of penetration of the melting surface and the penetration velocity of evaporation for PMMA work piece using equations (1), (2), (3) and (4) [11].

Table (2) shows the calculated parameters for drilling PMMA using CO_2 laser, depending on the equations (1- 4), the parameters listed in table (1) and laser parameters.

5- Practical part and results

Figures (2-5) show the holes in PMMA that drilled by CO_2 laser, figure (2) shows the hole drilled by 1W power and for exposure time of 70 sec, figure (3) shows the holes drilled by 2W power and for exposure time of 46 sec, figure (4) shows the hole drilled by 3W power and for exposure time of 37.5 sec and figure (5) shows the hole drilled by 4W power and for exposure time of 20.2 sec.

For the first drilling process (figure (2)), the hole depth was so small even if the exposure time was long; so it is clear in this figure that the laser beam can’t evaporate a lot of layers of PMMA because it was been hit by 1W laser power (maximum measured depth=3mm), and for the other drilling processes (figures (3, 4 & 5)), the depths of holes were increased to 8mm even if the exposure time was decreased because they were been hit by larger laser power so it could evaporate multi layers of PMMA and make deeper holes.

Figures (6-9) show the relations between measured and calculated parameters for PMMA, figure (6) illustrates that decreasing H increasing t_b, it is clear that t_b is inversely proportional to the square value of H for both measured and calculated parameters, for decreasing H the values of Z_m will increased in inversely proportional roughly linearly as shown in figure (7), the results are almost the same for both measured and calculated parameters. Figure (8) shows the relation between hole width and H, and between hole depth and H; this figure illustrates that increasing hole width from about 2.5mm to 6mm will increasing H, this figure also illustrates that the hole depth is increased from 3mm until H= $9.37*10^4$ W/m^2 for 8mm depth and then it fixed to this value for the other values of H. Figure (9) shows that the aspect ratio (hole depth divided by hole width) is proportional to the exposure time until it reaches 46 sec then the aspect ratio began to decrease for increasing exposure time.

Also it appeared from these figures that the hole depth and penetration velocity of evaporation depend on laser power, exposure time, intensity, material density, specific heat capacity, boiling point and latent heat of vaporization as shown in equations 1, 2, 3 & 4.

6- Conclusion

The following points can be concluded from this paper:

1- The aspect ratio depends on both laser power and exposure time.
2- The most suitable power for drilling a hole in a PMMA workpiece with 8mm thickness using a CO_2 laser working in CW mode was 2W where in this value of power, a maximum value of the aspect ratio was achieved.
3- Hole depth remains constant (equal to the material thickness 8mm) after $9.37*10^4$ W/m^2 for different laser power and exposure time.
4- When the power was not sufficient to drill a hole even if the exposure time was increased; the heat was diffused inside the material and not along the depth.
5- The increasing in laser power leads to a significantly increasing in the diameter of the hole until it reaches to a certain value where the increasing in the diameter became slightly.

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Table (1): PMMA parameters used in calculations.

Parameters	PMMA
Thermal Conductivity (J/ms.K)	0.19
Density (Kg/m^3)	1190
Heat capacity (J/Kg.K)	1466
Boiling Temperature (°C)	200
Melting Temperature (°C)	140
latent heat of vaporization(J/g)	1620
Refractive index	1.492

Table (2): Calculated parameters for drilling PMMA by using CO_2 laser.

Power (W)	H (W/m^2)	t_b (sec)	Zm(mm)	v_s (m/sec)
1	$4.685*10^4$	4.74	0.2875	$2.06*10^{-5}$
2	$9.37*10^4$	1.186	0.144	$4.12*10^{-5}$
3	$14.05*10^4$	0.527	0.096	$6.17*10^{-5}$
4	$18.74*10^4$	0.296	0.072	$8.23*10^{-5}$

Figure (1): Setup used for PMMA drilling.

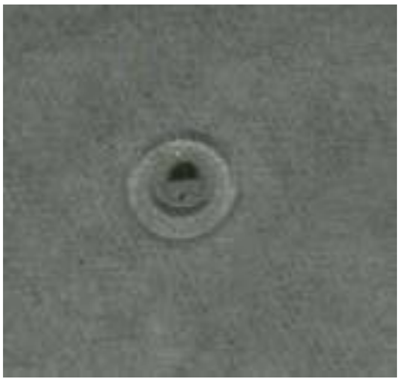


Figure (2): Hole with P=1W, ex. time=70.

Figure (3): Hole with P=2W, ex. time=46 sec

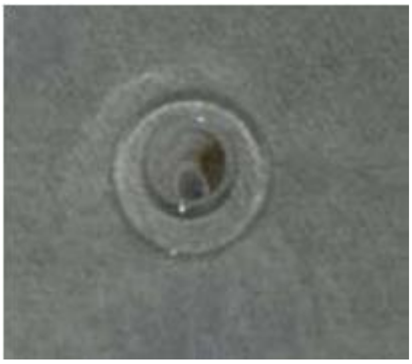


Figure (4): Hole with P=3W, ex. time=37.5 sec

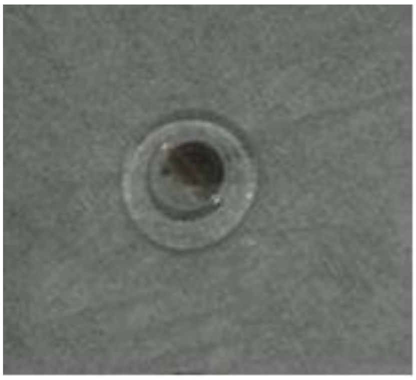


Figure (5): Hole with P=4W, ex. time=20.2 sec.

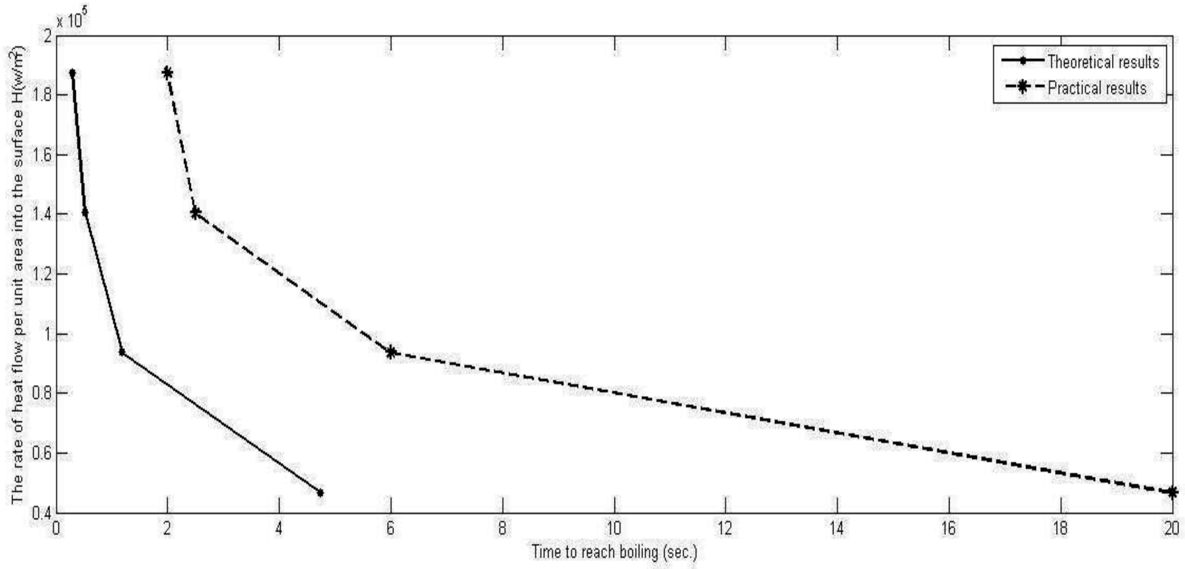


Figure (6): The relation between the rate of heat flow per unit area into the surface H (w/m^2) and the time to reach boiling t_b (sec).

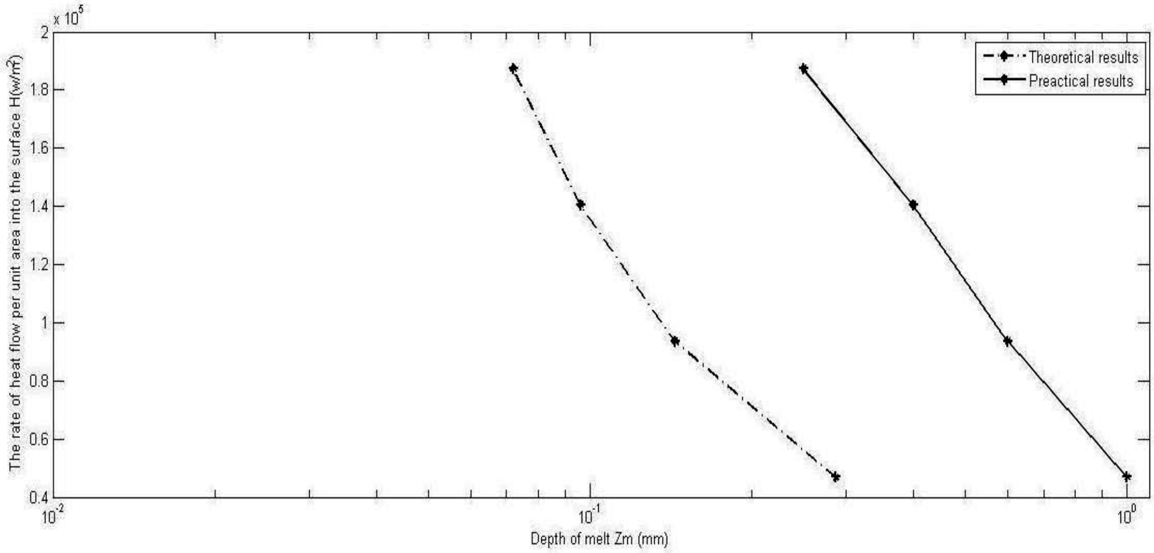


Figure (7): The relation between the rate of heat flow per unit area into the surface H (w/m^2) and the depth of melt Zm (mm).

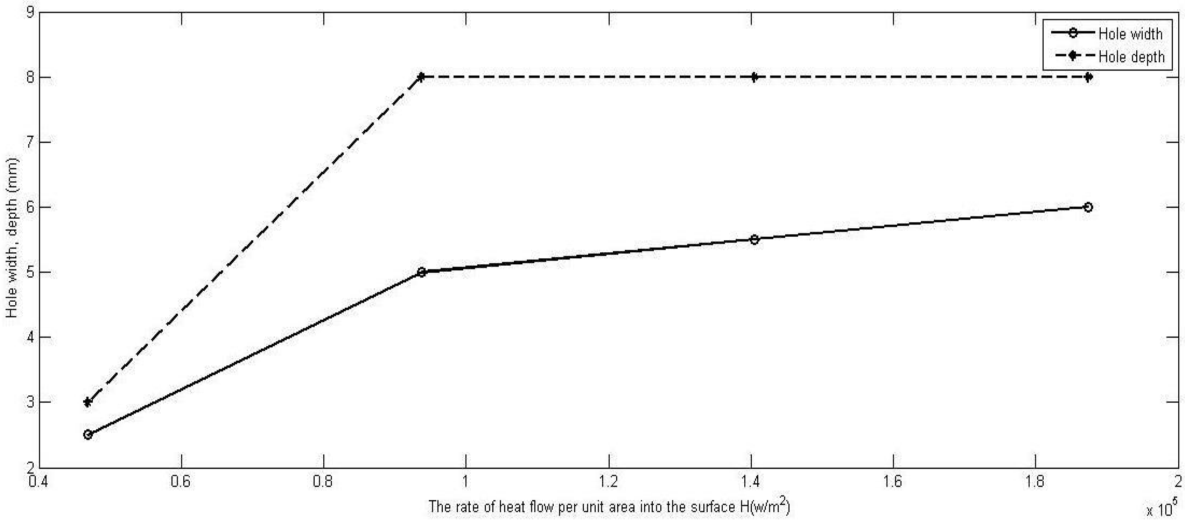
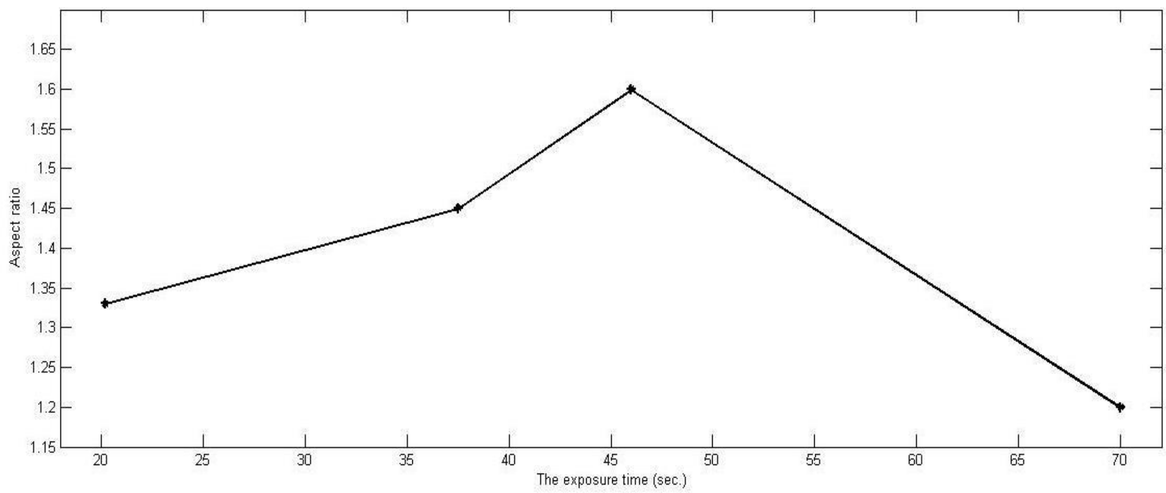


Figure (8): The relation between the rate of heat flow per unit area into the surface H (w/m^2)



and the hole depth, width (mm).

Figure (9): The relation between the aspect ratio A_r and the exposure time (sec).

حفر ثقوب في مادة البيرسبكس باستخدام ليزر ثنائي اوكسيد الكاربون

رنا محمد طه

مدرس مساعد/ قسم هندسة الليزر والالكترونيات البصرية/ جامعة النهرين

الخلاصة:

ان مصادر الليزر تستخدم في العديد من تطبيقات معالجة المواد وبصورة رئيسية في عمليات اللحام، القطع ،الحفر، التصليب، والى اخره من العمليات الاخرى .ان هذه الدراسة تلقي الضوء على واحدة من هذه العمليات والتي تسمى الحفر باستخدام الليزر.

عمق الحفرة, عرضها وسرعة عمق التبخير تعتمد على معاملات مختلفة مثل القدرة, المادة, زمن التعرض, المسافة بين اداة الحفر والمادة, اداة الحفر, الخ. في هذا البحث; شعاع الليزر سيستخدم كأداة حفر. W16 ليزر ثنائي اوكسيد الكربون (10.6 μm) و مادة البيرسبكس والتي هي مختصر لـpolymethyl methacrylate بسمك 8 ملم استخدموا في هذا البحث. المسافة بين شعاع الليزر والمادة 5 mm. تم استخدام قدرات ليزر مختلفة لزمن تعرض مختلف. تم حساب عمق الحفرة, الزمن المطلوب للوصول للغليان, تدفق الحرارة لوحدة المساحة وسرعة عمق التبخير. النتائج المحسوبة والمقاسة تقريباً متشابهة. تم استخدام برنامج Matlab 2008 للحصول على رسوم تمثل العلاقات بين قدرة الليزر, الزمن المطلوب للوصول للغليان, عرض الحفرة, عمق الحفرة وزمن التعرض.

الكلمات المفتاحية: حفر بيرسبيكس (PMMA), شعاع الليزر وتدفق الحرارة.