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Drilling of FR-4 Composite Materials Using Single Pulse of Nd:YAG Laser

Osamah F. Abdulateef* **Enas A. Khalid**** **Amer G. Hoss*****

,,***Department of Automated Manufacturing Engineering/ AL-Khwarizmi College of Engineering/ University of Baghdad*

*Email: drosamah@kecbu.uobaghdad.edu.iq

**Email: enaslaser77@yahoo.com

***Email: amer_gazee@yahoo.com

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Abstract

Laser drilling is capable of producing small, precisely positioned holes with high degree of reproductively. In this paper , IR millisecond Nd:YAG single pulsed laser was used to determine the effect of laser parameters on the drilled hole of the glass - fiber reinforced epoxy composite FR-4 sample of 2 mm in thickness . The type of laser source was GSI lumonics JK760TR Series laser 1.064μm system in a CNC cabin. The JK760TR series has a 0.3-50ms pulse length and a maximum repetition rate 500Hz with an average power of 600W. The investigation of single pulse laser drilling in this paper was based on theoretical and experimental solutions. In single pulse technique, the investigation included focal plane position *fpp*, pulse shape, laser peak power, and pulse duration. It was found that (-1) was the best fpp due to less taper for the drilled holes made by this level (Entrance hole =0.68, Exit hole = 0.27). To predict pulse shape effects; three types were : rectangular , rump-up and cool down, it were examined found that rectangular pulse was efficient more than the other types due to its ability to produce holes with less tapering as compared with others types. Also its found that all pulse shapes had the same effect on the materials microstructure . Laser peak power and pulse duration had the predominant affects on the hole dimensions and edge quality without any defect except hole tapering.

Keywords: *Nd:YAG Laser, FR-4 Composite materials, Laser Drilling.*

1. Introduction

FR-4 composite material is a fiber reinforced epoxy resin made from an epoxy resin matrix reinforced by fine glass. They have attracted a significant amount of attention from both industry and academia. The excellent tensile strength of glass fibers, however, may deteriorate when loads are applied for long periods of time. Laser hole drilling in composite materials has been applied widely in industry and became an essential tool for micro-drilling in many components used in the technologically advanced industries. Basic material removal mechanism in laser drilling is based on the absorption of laser energy from a series of laser pulses at the same spot. As a result of which, material gets melted and ejected to form a hole [1, 2]. Laser micro-drilling does not need expensive cutting tools and does not produce mechanical forces that can damage delicate work pieces. The use of laser micro-drilling or micromachining in manufacturing industry can be attributed to its flexibility and ability to process variable quantities and qualities of materials in a very short time with very high surface finish, accuracy, and minimum amount of wastage. Laser machining could drill a hole in very small diameter size, but it will require well controlled laser parameters in order to produce a high quality of hole. Defects that could occur due to inappropriate parameters setting are like overheating, fiber swelling, large heat affected zone HAZ and air plasma spraying APS. Most of the defects are caused by the rapid heating of the laser beam. The material removal rate MRR for laser machining is not limited by constraints such as maximum tool force, built-up edge formation, or tool chatter. However, due to the presence of thermal effects, the spatial resolution available from conventional, wider pulse lasers operating at visible and infrared wavelengths of the spectrum is limited. Since the absorption coefficient of different materials is highly wavelength dependent, by selecting the laser beam wavelength from deep ultra-violet (UV) to infrared (IR), one can precisely control the material processing [3].

Many researches deal with the micro drilling of composite materials. M.M.Noor, T.T.Mon, K.Kadirgama, 2009 , [4] , non-traditional machining method was employed by using CO2 laser to drill the fiber-glass composite sheet of 2 mm in thickness having four layers of glass-fiber with orientation <0, 90, 0, 90>. The machining parameters under consideration were laser power and pulse duration. Hole quality were then compared for each parameter combination. It was found that the laser power had predominantly affected the quality of the hole in fibre-glass composite material during laser-drilling. A. Demir, L. Candan, T. Canel, V. Gunay, and T. Sınmazcelik, 2009[5], predicted and evaluated the effect of pulse duration and peak power of Nd:YAG laser to find optimum laser parameter in the drilling operation. The average hole diameters and the average taper angles are examined as a function of the laser pulse duration and the laser peak power. The experimental results indicated the diameters of the craters show approximately linear proportion with the pulse duration and the peak power. Avanish, K. D. & Vinod Y., 2007, [6], predicted and evaluated the effect of laser parameter in the drilling of composite material using Nd:YAG laser. This study concluded that HAZ was directly proportional to laser power, where an increase in power would result in an increase in HAZ and it works in the opposite for the cutting speed. *W*.S.O. Rodden, S.S. Kudesia, D.P. Hand, J.D.C. Jones, 2002, [7], the results of an extensive experimental study of the free running Nd:YAG laser drilling of a multi-layer carbon fiber composite, where adjacent layers had differently orientated fibers. For holes drilled with the laser operating in fixed-Q mode at 1064 nm, parallel sections of blind holes illustrated discontinuities in the hole size along a given section direction Detailed single pulse drilling characteristics presented illustrating the exit hole diameter as a function of pulse energy and material thickness. *Zheng* Hongyu , Eric Gan Kok Wah 2000 [3], presented the experimental investigation of drilling FR4 , polyimide and alumina substrates using the RF and TEA CO2, 3rd-harmonic Nd: YAG, and KrF excimer lasers, respectively. Both blind and through-vias were drilled and evaluated for taper, wall-angle and smoothness through optical microscope, SEM and cross sectional analyses.

In this paper we *identifying* the most significant parameters governing the quality of the holes in FR-4 composite materials drilled by millisecond Nd:YAG laser by varying the laser parameters pulse peak power, pulse energy , pulse duration, focal plane position(fpp) , and pulse shape to produces a high quality hole with minimal residue and consistent edge quality from entry to exit point. And studying the effects of varying laser beam parameters on the hole dimensions (diameter and depth) and hole quality.

2. One-Dimensional Model for Laser Drilling

Drilling can be divided into two stages: heating and material removal, as shown in Figure1. In the heating stage, the temperature of the work piece surface, T_s, is increased up to the phase transition temperature, T_m, by the laser beam. The heating stage is usually very short because the laser beam intensity is very high. In the material removal stage, the hole depth is increased through molten material removal.

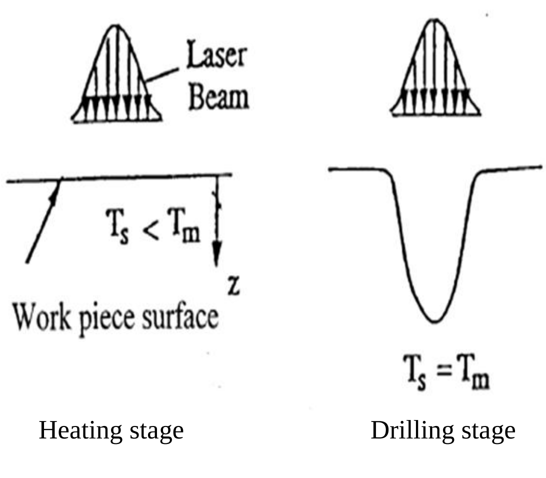


Fig. 1. Heating and Material Removal Stages of Laser Drilling [9].

During the heating stage, the work piece surface is not thermally eroded. It is difficult to obtain a simple analytical solution for drilling as a non steady process with three-dimensional heat transfer characteristics. Thus, it is assumed that drilling is a one dimensional process and that the laser beam intensity is uniform.
The boundary conditions are:

At $z = 0 \rightarrow I = -\kappa\,(dT/dz)_{z=0}$ …(1)
and
At $z \rightarrow \infty$, $T = T0$

where I_0 is the laser beam intensity(W/m^2), and T_0 is the initial temperature(^{o}K). The temperature distribution inside the workpiece can be derived, to be [8]

$$T-T_0 = \frac{2I_0}{K}\left(\frac{Kt}{\pi}\right)^{1/2} e^{\frac{-z^2}{4kt}} - \frac{I_{0z}}{k} \quad ...(2)$$

where κ is the thermal diffusivity (cm^{-2}s^{-1}) and I_0 is the laser beam intensity. The temperature distribution given by Eq. 2 is valid under the condition that $(\kappa t)^{1/2} < \omega$ [8], which can be achieved either through low diffusivities or short drilling times. The time for the workpiece surface to reach the solid-liquid phase transition temperature T_m can be determined from Eq.2. Applying Ts = T at z = 0, the following relation can be obtained [8]

$$T - T_0 = \frac{2I_0}{k}\left(\frac{kt}{\pi}\right)^{1/2} \quad …(3)$$

The duration of the heating stage, t_h in second, can be calculated as [8]

$$t_h = \frac{\pi}{k}\left(\frac{k(Tm - T0)}{2I_0}\right)^2 \quad …(4)$$

where T_m is a melting temperature(^{o}K). During the heating stage, a hole is not made because phase transition does not occur. After the surface temperature reaches the melting point, drilling starts. In order to determine the hole depth as a function of time and process variables, a one-dimensional analysis is considered, Figure 2 a laser beam is assumed to have a uniform intensity distribution I_0 defined as [8]

$$I_0 = \frac{P}{\pi w^2} \quad …(5)$$

where P is the laser power (N/m^2) and w is laser beam radius at the surface of a workpiece (mm).

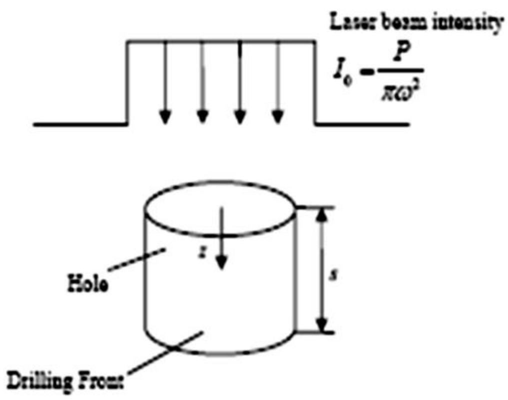


Fig. 2. One-Dimensional Drilling [8].

3. Experimental Work

In this paper, FR-4 sheet of 2 mm in thickness was drilled by using millisecond pulsed Nd:YAG laser. The schematic diagram of the experimental setup is shown in Figure 3 .Machining is done on the FR-4 composite material samples by changing the laser parameters. The type of laser source was GSI lumonics JK760TR Series Laser (Class 4) (IR) wavelength 1.064λ system in a CNC cabin sees Figure.4. It has a 0.3-50ms pulse length and a maximum repetition rate 500Hz with an average power of 600W.Laser output power is delivered via a 600 μm radius fiber optic cable to the focus head at the work station for processing. The laser beam was focused on to the FR-4 sheet using 160mm focal length Plano convex lens investigate the drilling process of composite materials . glass fiber/epoxy composites sheet type 2116 FR-4 having twelve layers of glass-fiber with orientation <0, 90 respectively > .Single pulse laser drilling method was used. Crater investigations such as crater diameter, depth were performed at five laser peak powers, six pulse duration, four *f*pp, and three pulse shapes. The laser beam mode is TEM_{00}. The spot size of the laser beam on the composite materials substrate is 480 μm. The applied parameters in the experiments are given in Table 1.

Table 1,
Laser Parameter in Single Pulse Technique Applied During Experimental.

Wave length 1.064µm Nd:YAG pulsed laser				
Peak power	**Pulse duration**	**Pulse energy**	**Pulse shape**	***Fpp***
From 3kw to 9kw with 1.5 kw increment	From 1ms to 4ms with 1ms increment	From 3j to 36j	Rup-up Cool down Rectangular	from +1 to -2 mm with 1 mm steps

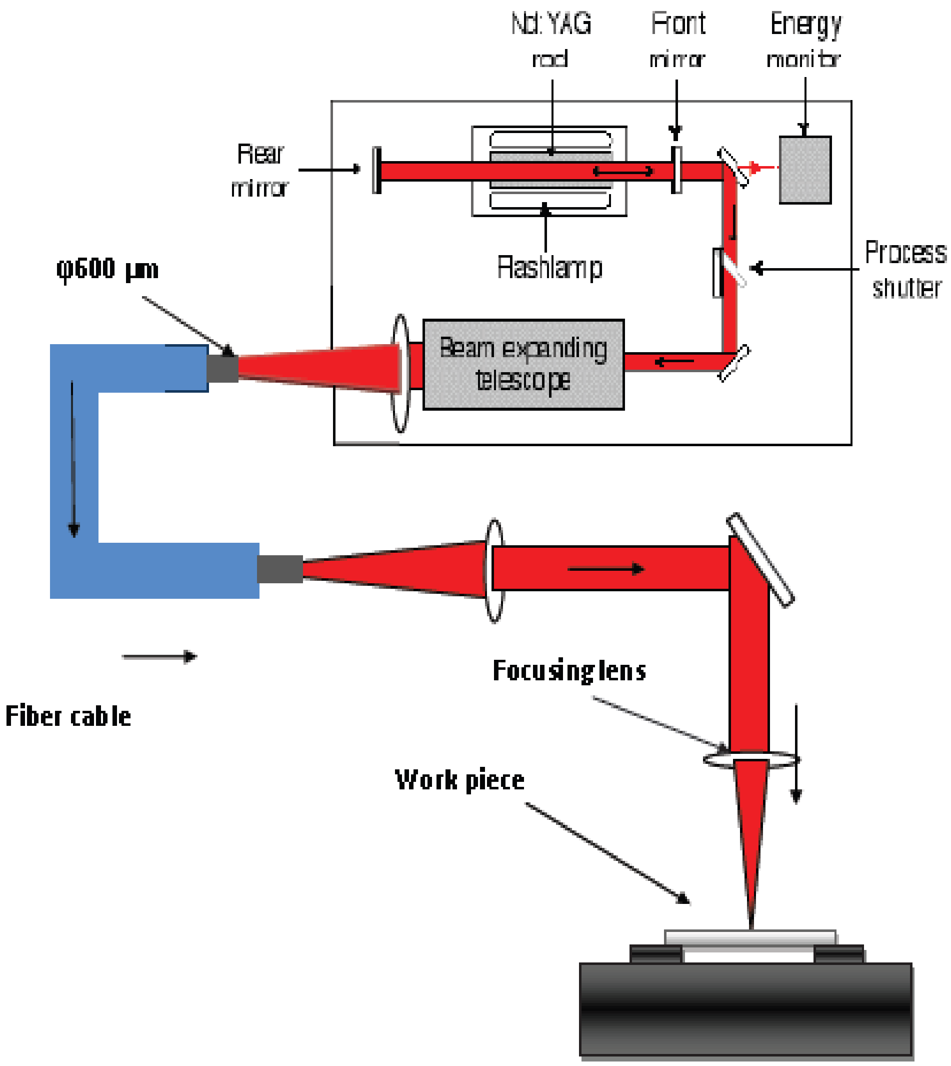


Fig. 3. Experimental Setup for Nd-YAG JK760TR.

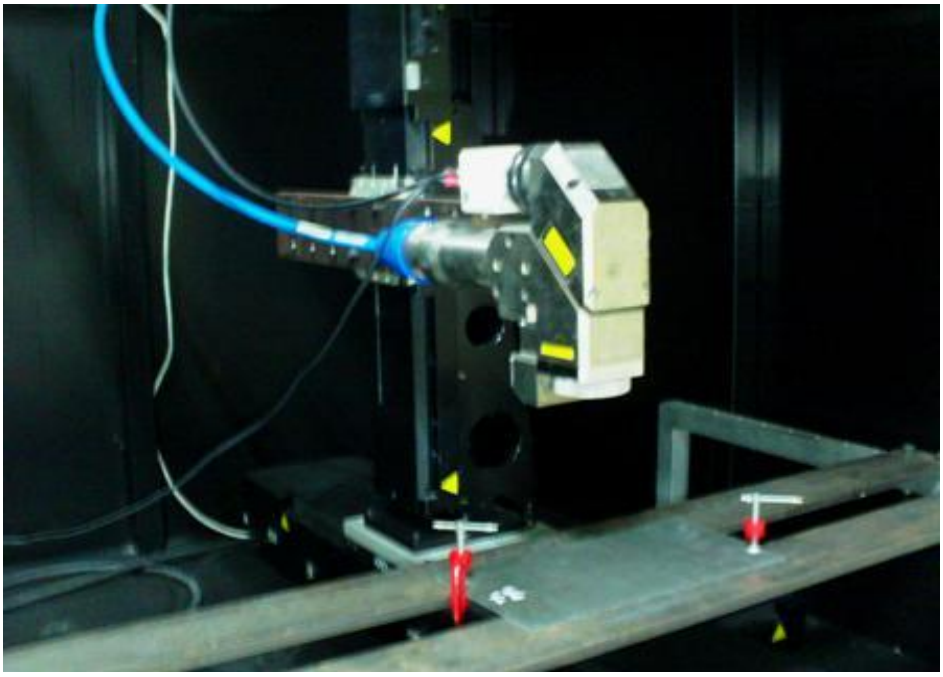


Fig. 4. Millisecond Pulsed Nd:YAG Laser Head.

The minimum spot size is calculated as follows [8]:

$$\textbf{spot size} = \frac{\textbf{lense focal length}}{\textbf{collimator optics focal length} + \textbf{beam expansion factor}} * \textbf{fiber diameter}$$

$$= (160\ \text{mm} / 200\text{mm}) * 600\mu\text{m} = 480\mu\text{m} \qquad \ldots(6)$$

The glass fiber used in this paper is made from an epoxy glass laminate, which employs a resin based on BT/epoxy with 12-layer woven fabrics of glass fiber and epoxy resin that has orientation (90^o, 0^o) “E-glass” reinforcement (see Figure 5). The relatively low dielectric constant and low manufacturing cost of the glass-epoxy system make it ideal for many printed circuit applications. 52-56% silicon oxide, 12-16% aluminum oxide and 16-25% calcium oxide [2].The elemental analysis of the selected materials at the specific point was tested by using Energy-dispersive X-ray spectroscopy connected to a scanning electron microscopy (SEM) .The mechanical and physical properties of the FR-4 are listed in Table.2.

The experimental procedures are as follows:

1. Fixing the workpiece and identifying the lines of drilling.
2. Drilling the workpiece.
3. Cutting and coating the workpiece.
4. 4. Taking images by the scanning electron microscopy (SEM) and optical microscope for analysis purpose.

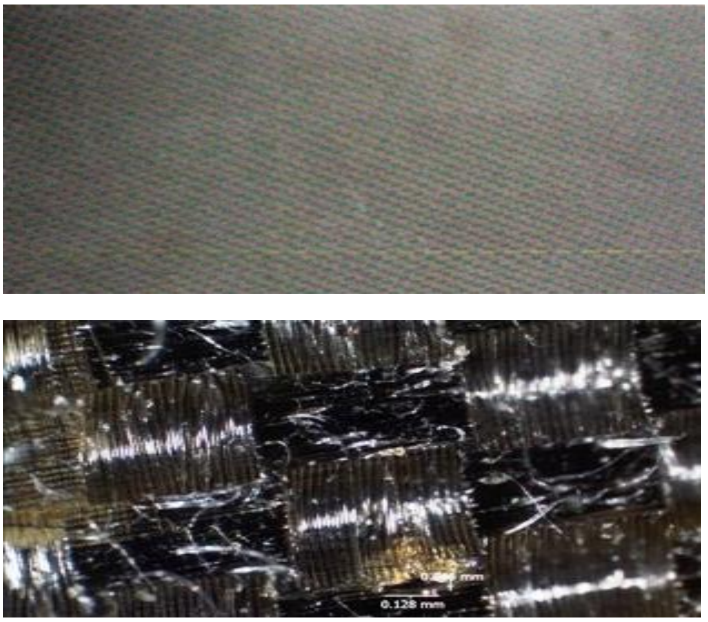


Fig. 5. A: 2116 Glass Fiber Composite FR-4 Work Piece: B: High Magnification (16x) Showing Glass Fiber.

Table 2,
Mechanical and Physical Properties of the FR-4 [11].

Tensile strength MPa	1,770
Rockwell Hardness	110 M scale
Temperature Limit (^oC)	Up to 120
Glass Melting temperature (^oC)	Above 1590
Resin	Not Applicable
Density (g/cm^3)	1.85
Specific heat (J/kg ^{0}k)	960
Heat Capacity(J/m3-K)	$1.703*10^{-6}$
Thermal Conductivity (W/m-°C)	0.16 – 0.20
Permittivity-A	4.8
Thermal expansion coefficient 10^{-6} $1/^0k$	$0.9 - 1.5 \times 10^{-5}$

4. Results and Discussion

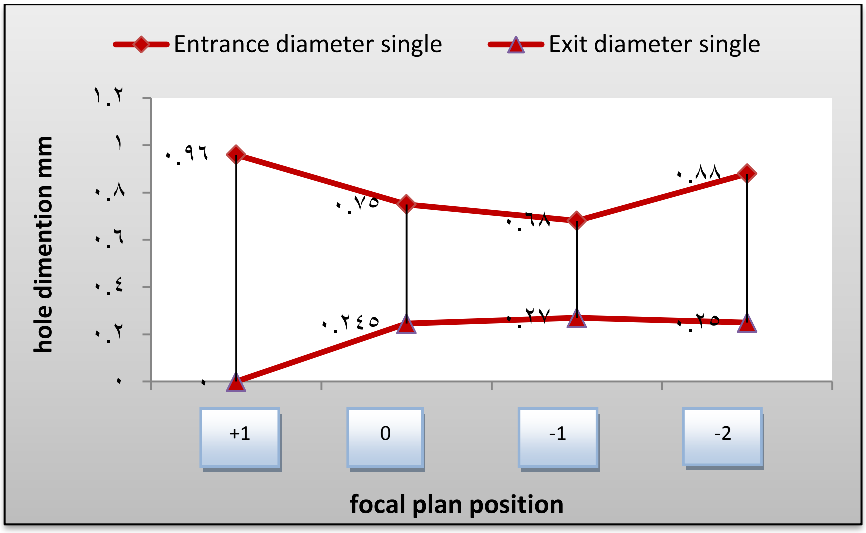
Laser macro drilling on the FR-4 sheets are presented and discussed for the study of the effect of laser parameters on micro drilling results. There are a total of 24 holes in the final actual experiment based on the parameter range under consideration. Prior to this, trial holes were drilled in order to acquire minimum amount of laser power, pulse duration, and pulse shape that can penetrate the composite specimen of 2mm thickness and to see the effects on the materials microstructure.

To determine the effects of the laser parameters; starting reference parameters were first been determined as; 2 ms pulse width, 3 kW peak power, 10 Hz repetition rate, and -1 focal position. All experiments were applied at 160 mm focal length. These parameters have were changed systematically to investigate these effects on macro drilling results. The holes were drilled by unique pulse, first fpp was changed to obtain the optimum surface level for drilling operation, and then the laser parameters (peak power, pulse duration) were changed to obtain ties effects on macro drilling results.

4.1. Effect of Focal Plane Position (fpp)

In laser processing, intensity (power per unit area) of the laser beam at the material surface is of prime importance. Intensity is great enough to melt or vaporize any material generated by focusing a laser beam. The maximum irradiance is obtained at the focal point of a lens, where the beam is at its smallest diameter. Intensity values of billion of Watts per square centimeter can be obtained at the focal spot. During this experiment the fpp is considered zero on the workpiece surface and above or below the surface is considered positive or negative, respectively. The fpp was changed from +1 to -2 in a single drilling. As shown in Figure 6 the hole not drilled at +1 fpp and the entrance diameter of the hole was maximum value 0.955, so +1 fpp is already eliminated, but it did not change much at -1 and -2 mm focal plane positions when compared to the other positions. Circularity of the hole for -1mm focal position was better than the one with -2 mm. It is possible to say that -1 mm focal position was a more suitable position for single drilling due to minimum entrance hole and maximum exit hole (less tapering).

1



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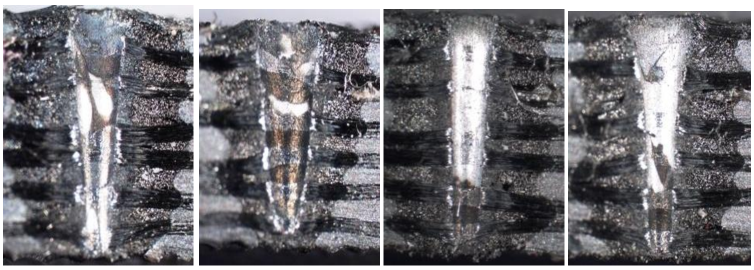

Fig. 6. (1) Effect of fpp on the Dimensions of Laser Drilled Microholes (f = 10 Hz), (2) Optical Picture Showing Changing Crater Dimensions for Different Fpp.

4.2. Heating Stage

When a laser pulse interacts with a solid target, the electrons are heated to a high temperature by the absorption of laser energy. By the electron-photon interactions, the hot electrons transfer energy to the lattice on a few picoseconds time scale for most materials [9–10]. The equilibrium between these two energies depends on the laser pulse duration. The energies transformation occur in the stage before hole beginning to drill by very short time and this stage is called heating time .

The theoretical calculation for heating time that was gathered according to Equation (4) showed high reduction in heating time with increase in laser peak power (see Fig.7). A significant decrease in the heating time as peak power was increased from 3kW to 6kW, and the heating time is decreased slightly from 6kW to 9kW, the heating time relationship is inversive with laser power. This decrease continues until it reaches to the lowest value before drilling process starts as shown in the values from 3-6(kW), after 6kW and due to high power transfer to the surface, the time is very close to the minimum value for start of the drilling process. So any increase in laser power even if a sudden it will be accompanied by a small decrease in the heating time. Another observation is that heating time was increased as pulse width increased as shawn in Figure 2.

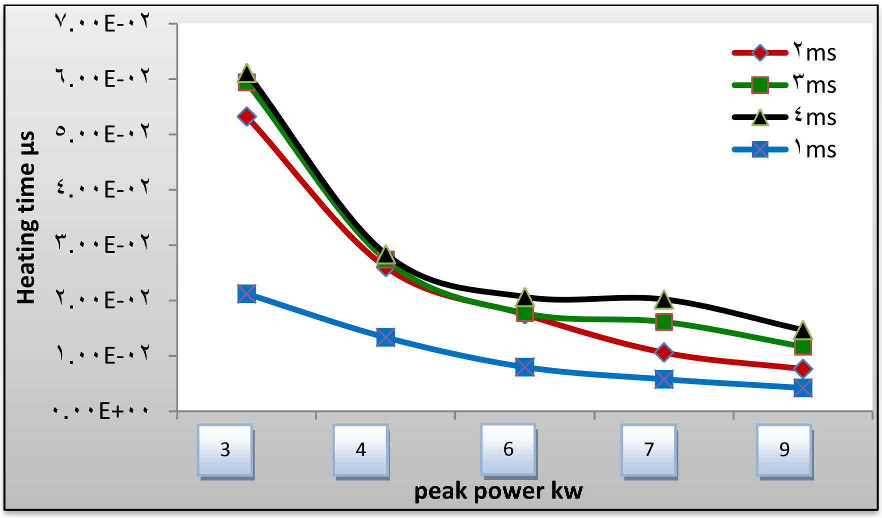

Fig. 7. Effect of Laser Power on the Heating Stage.

4.3. Effect of Laser Parameters

After predicting the best *f*pp for single pulse methods (-1) , hole dimensions were examined under different laser parameters and the results show that crater diameter was influenced strongly by changing laser parameter as shown in Figure 8. It was found that Laser power is the predominant effect on the hole size, burn mark and edge quality.

At 1ms pulse width the laser didn’t reach to the back side of the FR-4 sample even at high peak power of 9 kW due to less interaction time between the material and the workpiece. For other pulse widths from 3kW to 6 kW the crater dimension was increased slightly and from 6 kW to 9kW the crater dimension was increased significantly. The holes made by a single pulse drilling had more tapering (see Fig.9).

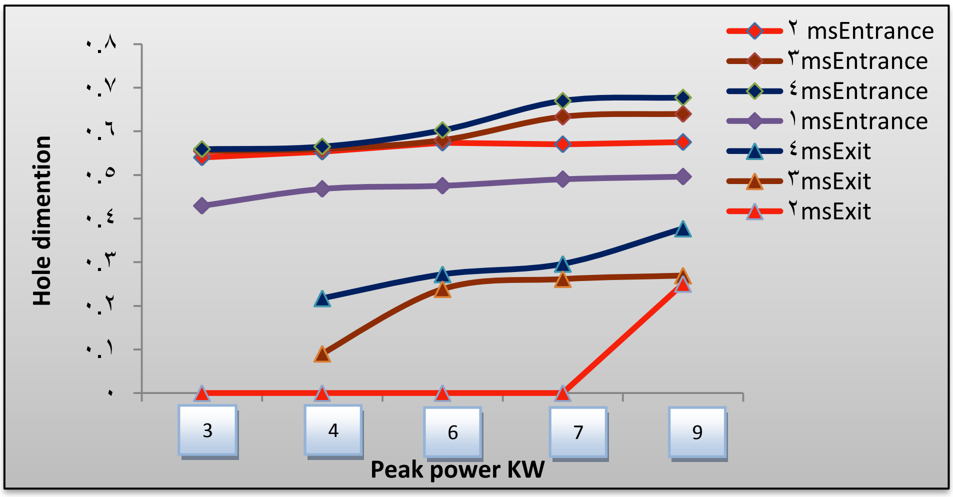

Fig. 8. Effect of Laser (Peak Power, Pulse Duration) on the Dimensions of Laser Drilled Micro Holes in FR-4, (f = 10 Hz , and fpp = -1).

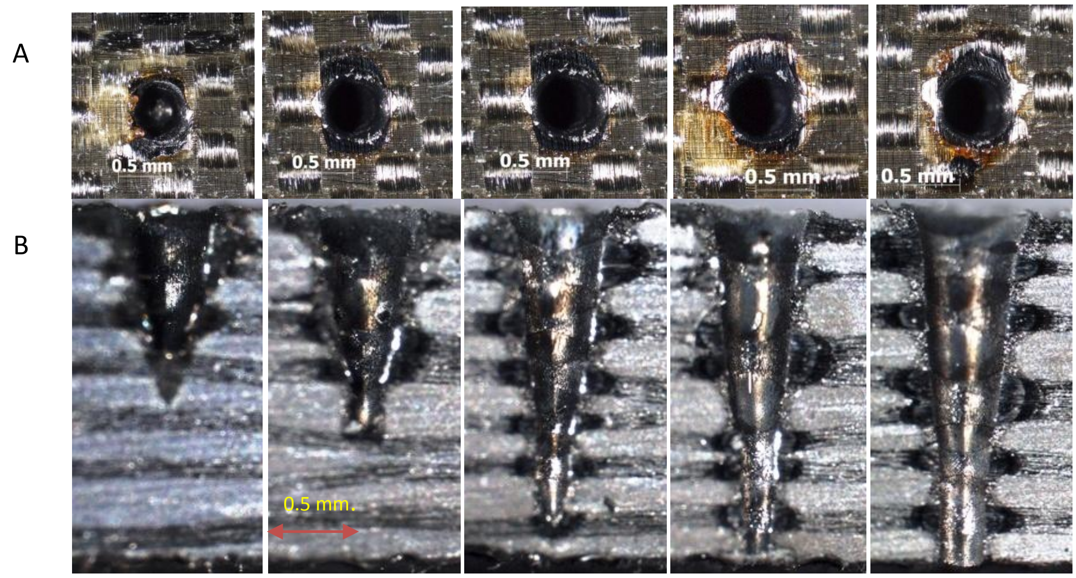

Fig. 9. A- Optical Images of the Cross-Section of FR-4 Drilled Hole at 2 ms Pulse Width. B- Effect of Peak Power at 2ms Pulse Width on the Hole Dimension.

5. Conclusions

The effect of the four variables on micro-hole drilling in the IR millisecond Nd:YAG laser ablation regimes were investigated theoretically and experimentally in single method. Changes in the pulse length, pulse peak power, and pulse shape were correlated for holes depths and diameters on FR-4 composite materials. The results show:

1- (-1) fpp was the best level to accomplish drilling operation, due to less tapering produced.
2- Heating time increases as pulse width increases while its decrease as peak power increase.
3- In all cases of this experimental work, high laser power density affects the hole in two ways; depth and width, it also increase melt. This implies imparting energy quicker and maintaining higher temperatures within the hole makes the process more efficient.
4- Increased ablation times have two effects on hole creation, first, the removal rate is increased, and second, the hole quality experiences degradation. For holes requiring high removal rates yet not as perfect hole quality, longer pulses become ideal.

6. Acknowledgment

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تثقيب المادة المركبة (فايبر كلاس) باستخدام النبضة المفردة لليزر النيدميوم – ياك

اسامة فاضل عبد اللطيف*   ايناس عبد الكريم خالد   عامر غازي هوس*****

**، **، ***قسم هندسة التصنيع المؤتمت/ كلية الهندسة الخوارزمي/ جامعة بغداد*

*البريد الالكتروني: drosamah@kecbu.uobaghdad.edu.iq

**البريد الالكتروني: enaslaser_77@yahoo.com

***البريد الالكتروني: amer_gazee@yahoo.com

الخلاصـــــة

عملية التثقيب بالليزر لها القدرة على إنتاج ثقوب صغيرة، عالية الدقة . في هذا البحث استخدم ليزر النيدميوم- ياك النبضي بالملي ثانية لدراسة تغير خصائص الليزر على أبعاد الثقوب وعلى البنية المجهرية لعينات المادة المركبة (المادة الأساس والألياف) بسمك ٢ مليمتر عند تثقيبها باستخدام تقنية النبضة المفردة . نوع الليزر المستخدم كان GSI lumonics JK760TR بطول موجي ٣.٠-٥٠ ملي ثانية بمعدل قدرة ٦٠٠ واط وأعلى مستوى تردد يصل الى ٥٠٠ هيرتز. في حالة النبضة المفردة فان خصائص الليزر التي تم تغييرها هي موقع المستوى البؤري ،وشكل النبضة، وقدرة النبضة، وطول النبضة ولقد وجد انه في حالة التثقيب بالنبضة المفردة فان افضل مستوى للتثقيب هو (-١) من بين اربع مستويات تم استخدامها وهي بالتسلسل (+١ ، ٠ ، -١، -٢) وذلك لاعطائه ثقوب اقل استدقاقا مقارنة بالمستويات الاخرى حيث كان قطر الثقب في منطقة الدخول = ٠.٨٦ اما في نقطة الخروج فكان = ٠.٢٧. لاختبار تأثير شكل النبضة، فقد استخدمت ثلاث اشكال وتم ملاحظة أن النبضة المستطيلة أكثر كفاءة وذلك لقابليتها على إنتاج ثقوب اقل استدقاقا مقار نة بالأشكال الأخرى اما تأثيرها على البنية المجهرية للمادة فكان متشابها . إن طاقة الليزر ومدة النبضة لها التأثير السائد على أبعاد وحجم الثقوب وكذلك على المنطقة المتأثرة بالحرارة بدون أي عيوب ماعدا استدقاق الثقب الذي كان صفة ملازمة لكل الثقوب التي أجريت بهذه الطريقة .