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Hole Drilling of High Density Polyethylene using Nd:YAG Pulsed Laser

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Abstract: This paper presents the theoretical and experimental results of drilling high density polyethylene sheet with thickness of 1 mm using millisecond Nd:YAG pulsed laser. Effects of laser parameters including laser energy, pulse duration and peak power were investigated. To describe and understand the mechanism of the drilling process Comsol multiphysics package version 4.3b was used to simulate the process. Both of the computational and experimental results indicated that the drilling process has been carried out successfully and there are two phases introduced in the drilling process, vaporization and melting. Each portion of these phases depend on the laser parameters used in the drilling process.

Keywords: Laser drilling, High density polyethylene, Hole drilling.

Introduction

Laser drilling covers a wide variety of applications and deal with numerous materials types [1].The process could be performed by continuous or pulsed laser mode. Nd:YAG and CO_2 are typical types of laser systems used in hole drilling process [2]. Generally, laser drilling is an accurate, non-contact, has small heat affected zone and also high aspect ratio up to 1:20 could be achieved [3, 4].

In laser drilling process, drilling mechanism is occurred via conversion of the photon energy into thermal energy. The hole formation starts, when the material temperature exceeds the melting and/ or vaporization temperature, where two mechanism take place depending on the temperature of the material. If the laser radiation is below a certain value (typically 10^6 W/cm^2 for steels) melting occurs without vaporization, then melted material is ejected using an assist gas jet to achieve the drilling process. If the laser radiation is above the threshold value, drilling operation occurs by evaporation [5,6].

High density polyethylene (HDPE) is used in many forms like bottles for liquid foods , household and industrial chemicals, motor oil, pharmaceuticals, and cosmetics. Other major outlets include drums, fuel tanks, and housewares.

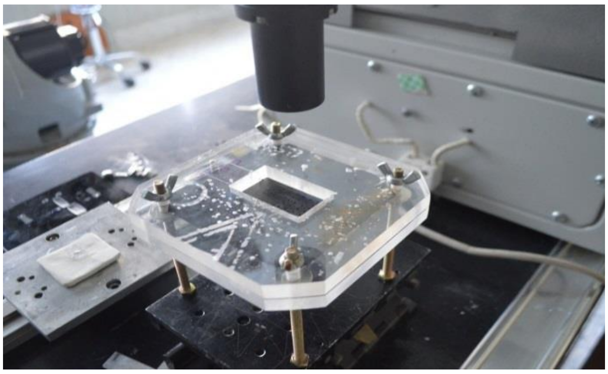
Approximately 33% of extruded high density polyethylene goes into pipe. Sheet is another major outlet, representing for almost 20% of extruded polyethylene.

High density polyethylene is converted into a variety of products that are used in packaging and transport applications such as food containers, crates, pallets, and pails. Other products include toys, housewares, and drinking cups [7].

In this work a millisecond pulsed Nd:YAG laser are used which represent an inexpensive laser system comparing with short and ultra-short laser systems. We are dealing with a cheap thermoplastic material like the high density polyethylene (HDPE) [8] , it will be unlikely to use expensive laser system in the drilling process.

Experimental work

In this study, laser drilling of high density polyethylene with thickness of 1mm (black color) has been carried out using model Pb80 laser system (from HANS laser), this system includes Nd:YAG laser that has 0.1-50 ms pulse duration and maximum pulse repetition rate of 100 Hz with an average power of 80 W. Laser output power is delivered through an optical fiber with 400 µm diameter that connected to the focus workstation. Figure.1 shows the experimental set-up for the drilling process. Four different levels of energy (3-6) joule were used from this 1064 nm laser. The work was done in the ambient air and the focus of the laser beam was on the surface of the sample since the literature available shows that the focal plane position only effective for thick sheets [9]. The spot size of the laser beam was 0.6 mm.



(a)

(b)

Fig.1 (a) Experimental setup for laser drilling (b) pulse shape of the Pb80 Nd:YAG laser used in the drilling process.

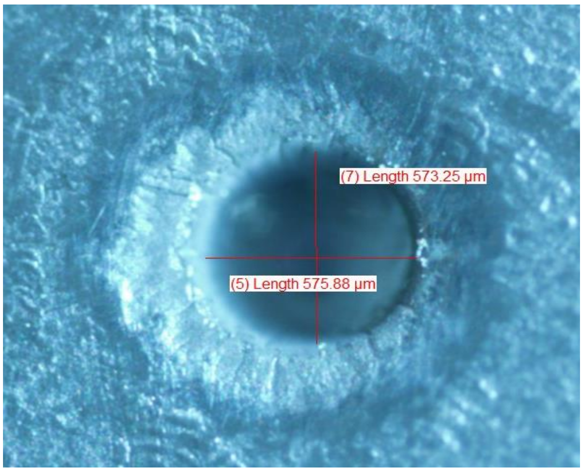
Simulation work

Comsol multiphysics 4.3b package was used to simulate the process. The effects of laser energy, peak power and pulse duration on the drilling process were investigated for a single shot. The simulation results gave us the temperature distribution from which can get the dimensions of the hole and compared it with the experimental results. Moreover the simulation results provided a better understanding for the mechanism occurred during the drilling process.

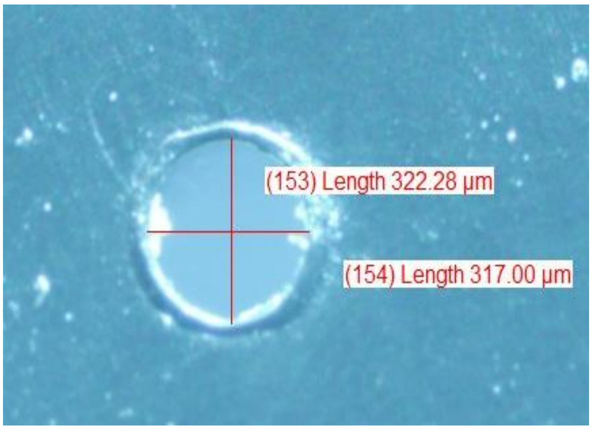
Results and discussion

The most important parameter in laser drilling process is the peak power. The value of the laser peak power is directly proportional to the heat transferred to the material in the case of IR lasers via the photon energy which is totally convert to heat in the material that absorb the laser light. A sample of optical image of the drilled polymer is depicted in Figure. 2.(a,b). It is obvious from the Figure.2 that the circularity is almost optimum for the entrance and the exit of the hole. The simulation of the same sample is shown in Figure.3.The high density polyethylene like most thermoplastics material has very low conductivity (0.38 W/m.K) [7] and the melting temperature is within the range of (130-140) ^{0}C [10] while the decomposition temperature range is between 340-390 ^{0}C [11]. From these two figures of experimental and simulation results the mechanism of the process could be understood.

The drilling starts from the top surface of the sample and the temperature exceeds the vaporization temperature as it is shown in Figure.3 which represent the simulation prediction (the maximum temperature on the center of the laser beam is 477 ^{0}C). This result coincides with the experimental outcome in Figure 2(a). The appearance of the hole entrance in this figure indicates a full vaporization process (no spatter occurred around the crater) but due the low thermal conductivity of the HDPE and the high temperature on the surface of the sample a thermal expansion on the surface can observed around the hole (the rim of the hole) in a uniform circle shape. The reason of the edge of the hole entrance come from the fact that when the polymer reach's the decomposing temperature it convert to gases and will not solidified again such as in metals. For the exit of the hole the simulation results obtained indicated that the drilling process is mostly done by melting rather than vaporization since the temperature at the bottom of the sample in Figure.3 is between the melting and decomposing temperature (around 183 ^{0}C) and that result also coincided with the experimental result in Figure.2 (b) which shows a debris and re-solidified material at the exit of the hole.



(a)



(b)

Fig. 2. Optical image of drilled holes at 3J energy, 5.45 ms pulse duration and 0.55kW peak power: (a) Entrance of the hole; (b) Exit of the hole.

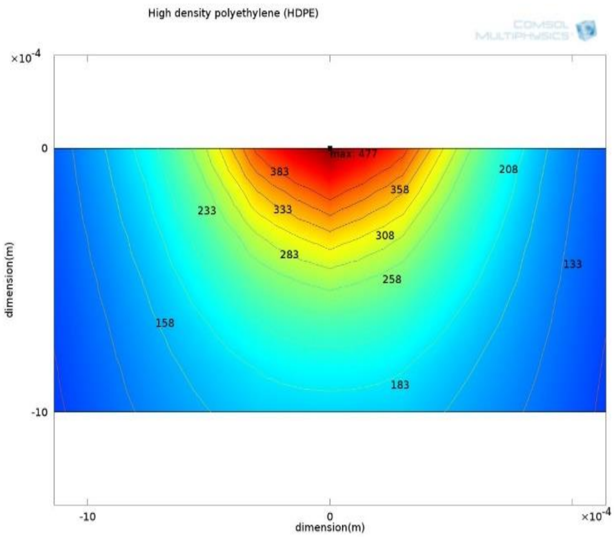


Fig.3. Temperature distribution simulated at 3J energy, pulse duration 5.45 ms and 0.55 kW peak power.

The effect of increasing the peak power on the entrance diameter of the hole is presented in Figures (4,5,6,7). These figures also include the comparison between the experimental and simulation results as well. When the peak power increases the hole entrance increases too and the same tendency has been obtained for the simulation results. The reason for such behavior can be summarized as follows. Further increases of the peak power produces excessive polymer vaporization due to the higher temperatures occurred on the surface of the work piece which leads to increase the value of entrance hole dimension in spite of the low thermal conductivity of the HDPE.

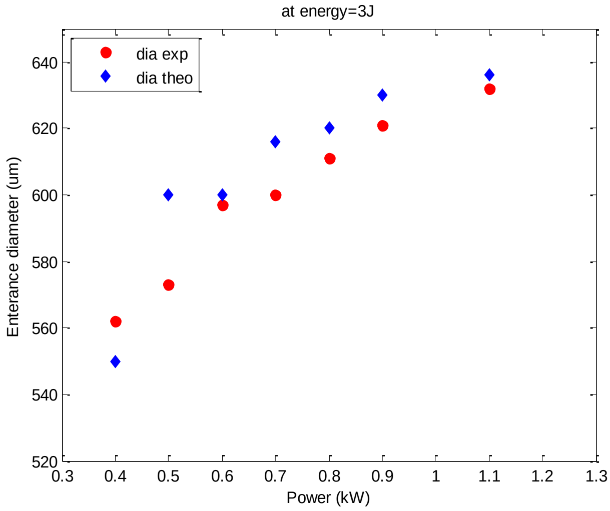


Fig.4. Comparison between experimental and theoretical results of the Entrance diameter as a function of peak power when the energy is fixed at 3J.

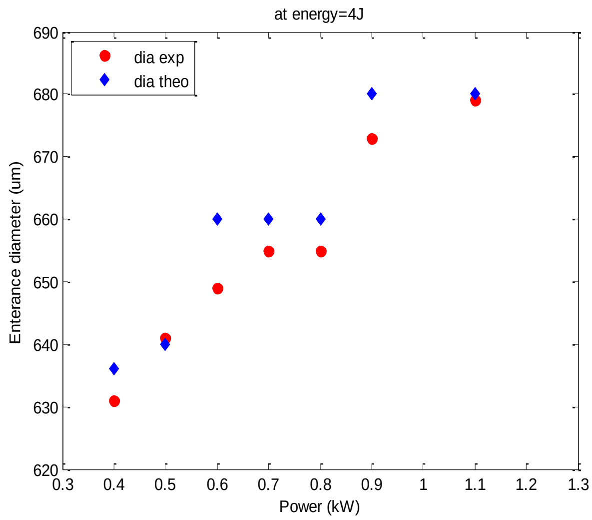


Fig.5. Comparison between experimental and theoretical results of the Entrance diameter as a function of peak power when the energy is fixed at 4J.

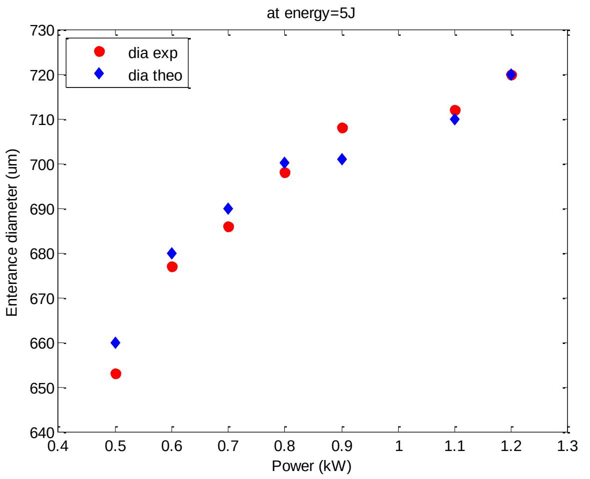


Fig.6. Comparison between experimental and theoretical results of the Entrance diameter as a function of peak power when the energy is fixed at 5J.

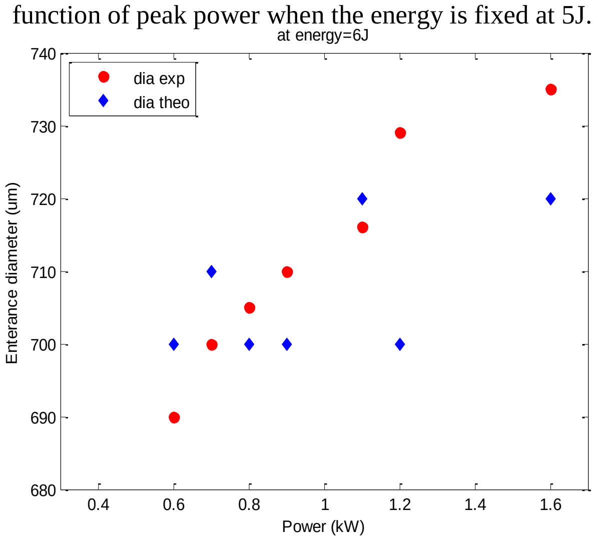


Fig.7. Comparison between experimental and theoretical results of the Entrance diameter as a function of peak power when the energy is fixed at 6J.

To determine the effect of pulse duration on the entrance hole dimension, pulse duration has been increased with fixed peak power (0.6, 0.9, 1.1) kW. The energy of the laser was increased parallel with the pulse duration to keep the peak power constant. When the pulse duration was increased, the hole entrance dimension increases as well, as shown in figures (8, 9, 10).The simulation gives a similar results comparing with the results obtained experimentally. When the laser pulse duration increased with fixed power, it gives the interaction between the laser energy and the work piece sufficient time to interact and to deliver the whole amount of the energy to the work piece which reflected on the dimension of the hole.

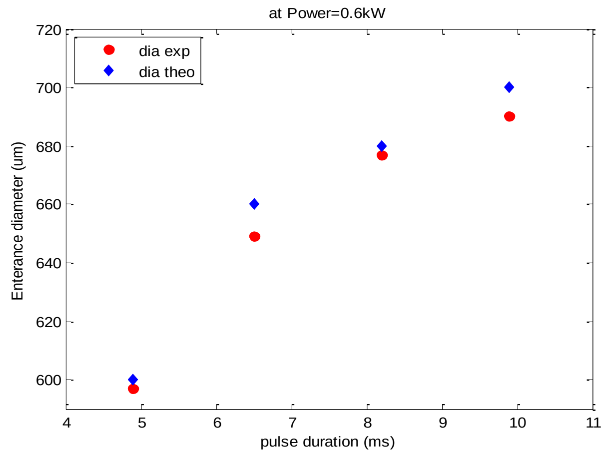


Fig. 8. Comparison between experimental and theoretical results of the Entrance diameter as a function of pulse duration when the peak power is fixed at 0.6 kW.

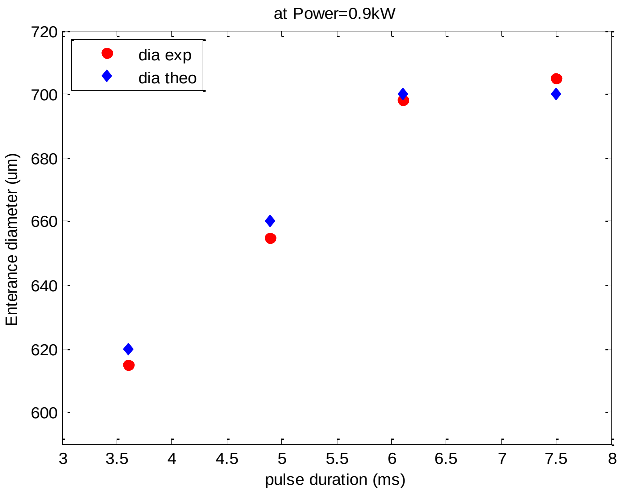


Fig.9. Comparison between experimental and theoretical results of the Entrance diameter as a function of pulse duration when the peak power is fixed at 0.9 kW.

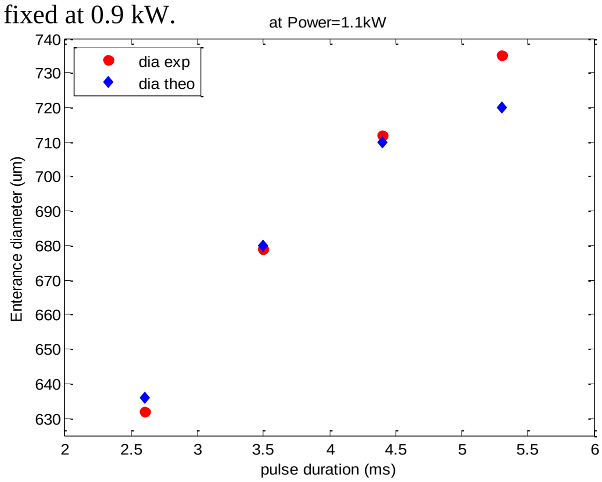


Fig.10. Comparison between experimental and theoretical results of the Entrance diameter as a function of pulse duration when the peak power is fixed at 1.1 kW.

For the influence of the pulse duration on the dimension of the hole exit, the simulation results indicated that when the peak power increased and the pulse duration decreased (to insure that the energy value is fixed) the behavior of the temperature is different on the entrance comparing to the exit temperature. The results indicated a tendency to a temperature decrease in the exit when the hole entrance temperature increased. Figures (11,12,13) give an example for such behavior.

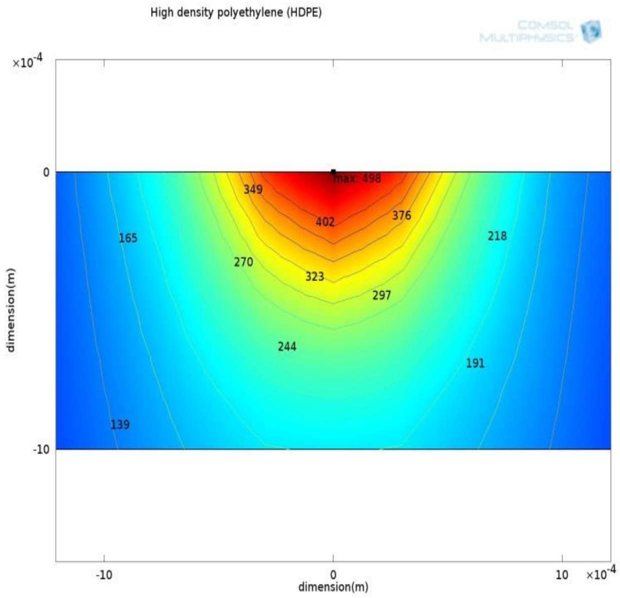


Fig.11 Temperature distribution simulated at 5J energy, pulse duration 9.9 ms, and 0.5 kW peak power.

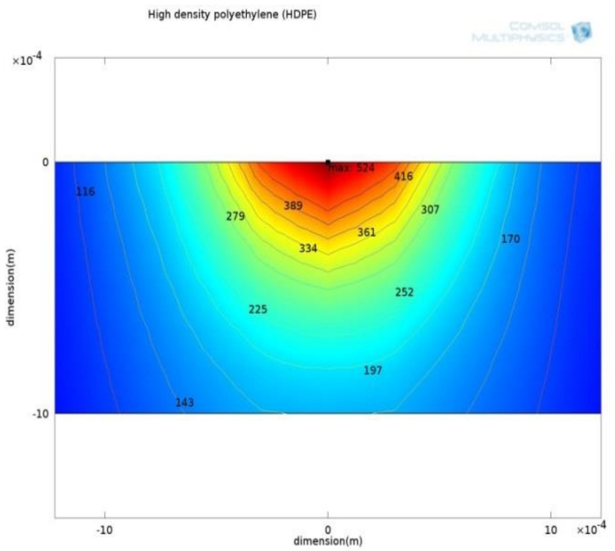


Fig.12 Temperature distribution simulated at 5J energy, pulse duration 5.4 ms and 0.9 kW peak power

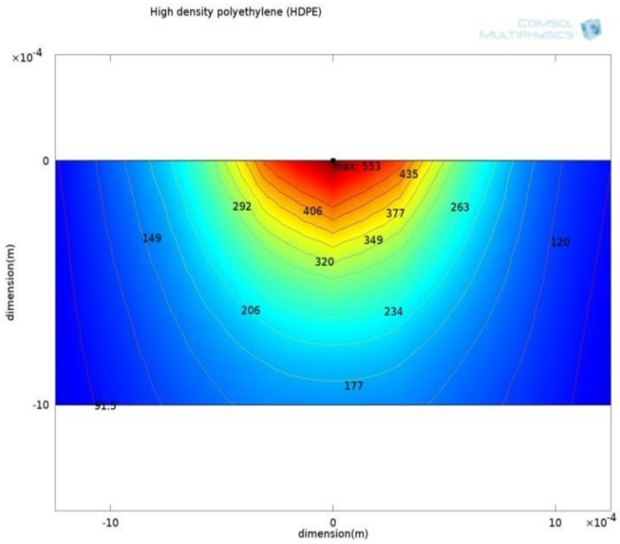


Fig 13 Temperature distribution simulated at 5J energy, pulse duration 4 ms and 1.2 kW peak power.

In Figure.11 the maximum temperature at the entrance is 498^0C and 218^0C at the exit, the pulse duration was 9.9 ms. The temperature in Figure.12 is 524^0C at the entrance and 197^0C at the exit of the hole when the pulse duration was 5.5 ms. For Figure.13 the entrance temperature reaches 553^0C and the 177^0C at the exit while the pulse duration was 4 ms. These results could be explained due to the fact that HDPE has low thermal conductivity and as a result of this property conductive heat transfer from the surface of the work piece to the bottom is very slow . That means a sufficient amount of heat conduction to the exit side requires longer pulse duration and that the mechanism occurred in the drilling process has two phases, the first is the vaporization phase that start from the top of the work piece for a specific depth inside the material as shown in simulation figures (3, 11-13). The second phase is the melting phase which is taken place at the bottom part of the work piece as it is shown in these figures. The taper ratio for the holes produced is affected strongly by the period of the pulse duration. For small taper ratio values longer pulse duration is preferable since it ensures that the maximum portion is for the vaporization phase which leads to minimum values for the taper of the hole.

Conclusions

The laser hole drilling for high density polyethylene using pulsed Nd:YAG laser has been performed. The effects of different laser parameters including laser peak power, pulse duration and laser energy on the dimension of the hole were examined. The results showed that when the peak power increased, this leads to increase of the hole entrance dimension when the energy is fixed. The results showed that the effect of the pulse duration is very significant in determining the hole dimension and the phases occurred in drilling process mechanism whether it is a vaporization or melting phase. The simulation of the drilling process could be used as a predictive tool for selecting best laser parameters for the drilling process and to understand the mechanism of the interaction between the laser beam and the material during the process.

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References

[1] W.M.Steen, J.Mazumder, fourth edition "Laser Material Processing", Springer-Verlag, London limited, UK, (2010).
[2] J.D.Majumdar, I.Manna, "Laser Assisted Fabrication of Materials", Springer-Verlag, Berlin, (2013).
[3] G. Chryssolouris , "Laser machining: theory and practice".Springer (1991).
[4] J.F.Ready, "LIA, Handbook of laser materials processing". Laser Institute of America, Magnolia Publishing Inc., USA (2001).
[5] K. Salonitis , A. Stournaras , G. Tsoukantas , P. Stavropoulos , G.Chryssolouris . A theoretical and experimental investigation on limitations of pulsed laser drilling. Journal of Materials Processing Technology ;183:96–103(2007).
[6] M.M.Hanon et al. Experimental and theoretical investigation of the drilling of alumina ceramic using Nd:YAG pulsed laser, Optics & Laser Technology 44 , 913–922(2012).
[7] A.J.Peacock, "Handbook of polyethylene", Marcel Dekker, NewYork, (2000).
[8] M.F.Ashby, D.R.H.Jones, "Engineering material vol 1" Elesvier, Oxford, (2005).
[9] R.Goyal, A.K.Dubey, Modeling and optimization of geometrical characteristics in laser trepan drilling of titanium alloy. Journal of Mechanical Science and Technology, springer, 30 (3) 1281-1293l ,(2016).
[10] Data sheet of HDPE, www.senova.com.
[11] F.G.Bachmamm, U.A.Russek. "laser welding of polymers using high power diode lasers", Photonics west conference, San Jose, CA, USA, (2002).

تثقيب البولي أثيلين عالي الكثافة باستخدام ليزر النديميوم ياك النبضي

زياد اياد طه

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الخلاصة :هذا البحث يقدم النتائج النظرية والعملية لتثقيب البولي أثيلين عالي الكثافة بسمك 1 ملم باستعمال ليزر النديميوم ياك النبضي ذو مدى نبضي في حدود الملي ثانية. تم التحقق من تاثير معاملات الليزر مثل طاقة الليزر, أمد النبضة والقدرة العظمى على عملية التثقيب. لفهم ووصف ألية عملية التثقيب تم استخدام برنامج الكومسل 4.3b لمحاكاة عملية التثقيب. أن كلا من النتائج العملية والحسابية اعطت مؤشراعلى تحقق عملية التثقيب بنجاح وان هنالك طورين قد ظهرا خلال هذه العملية, الاول هوالتبخير والثاني هو الذوبان وان كل جزء من هذين الطورين يعتمد على معاملات الليزر المستخدمة في عملية التثقيب.