Theoretical Study of Drilling Process Materials By Laser Pulses (Micro, Nano and Picoseconds)

Ikhlas Jabir Mahmood

Physics Department, College of Education-Kufa University-Iraq

Abstract: ***The time of laser drilling process for(Stainless steel304 and Single crystal silicon) using laser pulses (mico-, nano and picoseconds)) have been calculated at different values of the intensity of these pulses. Many parameters of laser drilling process have been calculated as heating stage time (t_h) , drilling velocity (ds / dt) , temperature gradient(dT / dz) and temperature of material surface (T) at different values of the intensity of the pulses depending on one-dimensional model of laser drilling.We found that the wavelength and the duration of the laser pulse play an important role in laser drilling process where considered very short pulses (picoseconds) is the best in the drilling process. It can be conclusion is that the thermal properties of the material and the degree of melting effect on the drilling process.Matlab program (Matlab 8) were used for the implementation of all programs related to this research.***

Keywords: interaction of laser, pulse duration, laser radiations, solid material, thermal distribution, laser beam intensity

1. Introduction

Laser drilling is an important industrial process by which laser pulses are used to drill holes in hard materials. It presents several advantages over conventional techniques such as low heat input into the material, accuracy, consistency, ease to automate and ability to drill very small holes of the order of 10 microns indiameter(Jeb Collins.2009). This technique is used either with single or multiple pulses(K.T..Voisey.2002). In laser drilling of metals Increasing the pulse intensity increases the ejection velocity and decreases the average particle size, were drawn by(K.T.Voisy et al) (K.T.Voisy2002) .

The effects of process parameters on entrance diameters of drilled holes, shapes of the holes, taper angles of the holesand temperature distributions in the vicinity of the holes were examined quantitatively. In addition, the optimal drilling condition wasestimated to improve the quality of the drilled holes, had been concluded by (Dong-Gyu AHN et al) (Dong-Gyu AHN.2009)

Drilling is one of the most important and successful applications of industrial lasers. Laser drilling emerges as a viable and successful substitute for holes less than 0.25mm indiameter that are otherwise difficult to drill mechanically, especially for hard and brittle materials, such as ceramics and gemstones. Laser drilling of metals is used to produce tinyorifices for nozzles, cooling channels in air turbine blades, etc. For direct hole drilling, the quality of the laser beam, wavelength, intensity, pulse duration, pulse repetition rate areall important parameters. Yet many issues remain to be solvedwhen high quality holes are to be drilled in various material. These include cracks, large taper size, unsatisfactory shapeetc. In the present paper, the technologies, applications and techniques that lead to the solution of aforesaid problems are highlighted, had been proved by (Dhar et al) .(Sushant Dhar2006)

Using Nd-YAG pulsed laser (with minimum pulse duration of 0.5 ms) is in order to determinethe effects of the peak power and the pulse duration on the holes of the alumina ceramicplates. The thicknesses of the alumina ceramic plates drilled by laser are 10mm. Averagehole diameters are measured between 500mand 1000mat different drilling parameters.The morphologies of the drilled materials are analyzed using optical microscope. Effects ofthe laser pulse duration and the peak power on the average taper angles of the holes areinvestigated, had been studied by(E. Kacara et al)(E. Kacara.2009).

A hydrodynamic Physical Modeling of Laserdrilling. 1D hydrodynamic physical model was created based on realistic materialremoval mechanisms (including melt vaporization and vaporization-induced recoilpressure). The effect of O2 gas assist (exothermic reaction) and forced convectivecooling were incorporated in this study – but were proven to be insignificant,had been introduced by(Low et al) (Low 2002).

The ablation rate is substantially affected by the pulse energy during nanosecond ablation. The increase in material removal rate was more than 600% when the pulse energy was increased from 2.3 to 9.2 ìJ by decreasing the frequency from 200 to 50 kHz. Thermal losses have a major effect on the removal rate at irradiances close to the ablation threshold, as greater fraction of the pulse is heating thematerial in the solid and liquid phases instead of evaporating and removing material. Therefore, the dependence between pulse energy and material removal rate can be expected, had been proved by(Henrikki Pantsar1 et al)(Henrikki Pantsar1.2008).

2. Material Removal Mechanism

Laser drilling is a material removal process, which has two major mechanisms ofremoval of material from the beam interaction zone and consequent propagation of themelt front into the metal bulk. They are: (1) melt evaporation (for high-power or short pulse-duration drilling), (2) melt ejection by the vaporization-induced recoil force (forgeneral cutting, welding, and drilling) (Semak and Matsunawa, 1997).For short laser pulses in the micro- and nanosecond range the ablation process is dominated by heat conduction, melting, evaporation and plasma formation(compare Figure 1 a)(B.N. Chichkov.1996, J. König .2011).For ultra-short picosecond laser pulses and the thereby related short timescales these classical descriptions of beam-matter interaction loose their validity.Due to the extreme intensities of ultra-short laser pulses, absorption is increased by nonlinear multi-photon absorption processes. Furthermore, within Pico- and femtosecond timescales the energy cannot be transferred from the electron gas to the ion grid instantly. Here new thermal ascriptions distinguishing between electron and grid temperature, the so called two-temperature model compare Figure 2 b) (, M. Dirscherl.2005, A. Miotello.1999)

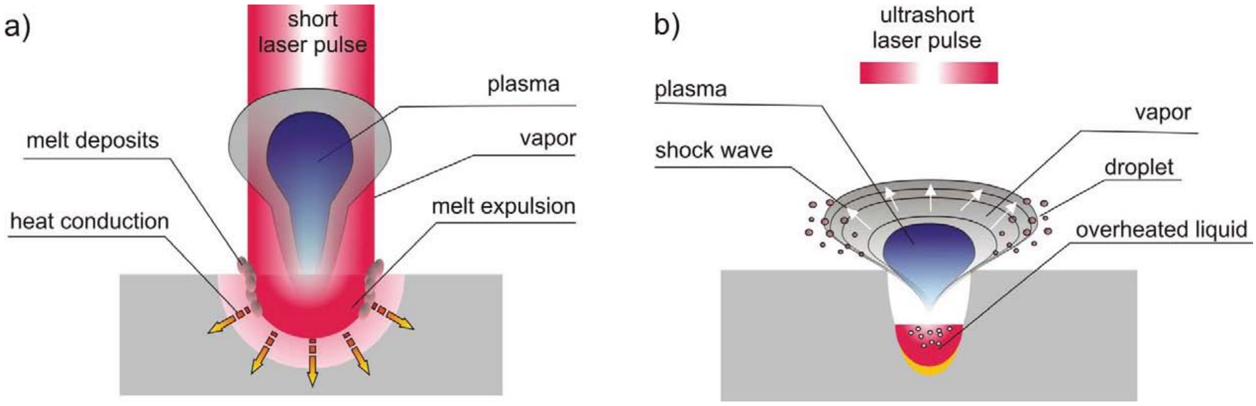


Figure 1: Beam-Matter interaction: a) classical beam-matter interaction; b) ultrafast beam-matter interaction

The vaporizationmechanism of melt removal can be the dominating mechanism for lower laser powersand consequently lower melt-surface temperatures in the case of short laser pulses, forwhich, due to inertia, the melt cannot be ejected from the interaction zone before itssolidification. For higher melt surface temperatures generated either by higher absorbedlaser intensities or by exothermic reaction with a chemically active assisting gas, such asoxygen, the vaporization recoil pressure becomes the primary factor removing melt fromthe interaction zone under the regime of hydrodynamic mechanism.

Among the two material removal mechanisms during laser drilling, that is,material removal via vaporization and physical ejection of molten material, melt ejection is a very efficient way since the latent heat of vaporization does not need to be absorbed when melt ejection occurs. For melt ejection to occur, a molten layer must form and the pressure gradients acting on the surface due to vaporization must be sufficiently large to overcome surface tension forces and expel the molten material from the hole. The energy required to remove material via melt ejection is about one quarter of that required to vaporize the same volume.

Detailed explanation of the melt ejection process in single pulse laser drilling is as following. Immediately after the start of the laser pulse, the substrate starts to heat up. After a time, the surface temperature reaches the melting point and a molten layer is formed. Vaporization produces a recoil pressure that acts on the molten layer, removing molten material from the region ahead of the ablation front. The recoil pressure initially overcomes the threshold required for melt ejection sometime shortly after the start of the pulse. At the initiation of melt ejection, the thermal gradients in the material and the vaporization rate at the surface, and hence the recoil pressure, will be at their highest and the molten layer will be at its thinnest. A large number of small droplets are, therefore, ejected at a relatively high velocity. As the pulse progresses, the molten layer thickens, resulting in a larger average droplet size. The recoil pressure decreases, reducing the ejection velocity, but continues to remove material from the ablation front. The molten material moves along the hole walls in a relatively smooth way, breaking up into discrete droplets under the influence of surface tension on exiting the hole. Surface tension effects may also increase the angle of ejection as the molten material follows the curve ofthe hole entrance on exiting it. Since the recoil pressure plays an important role in laser drilling as shown in fig

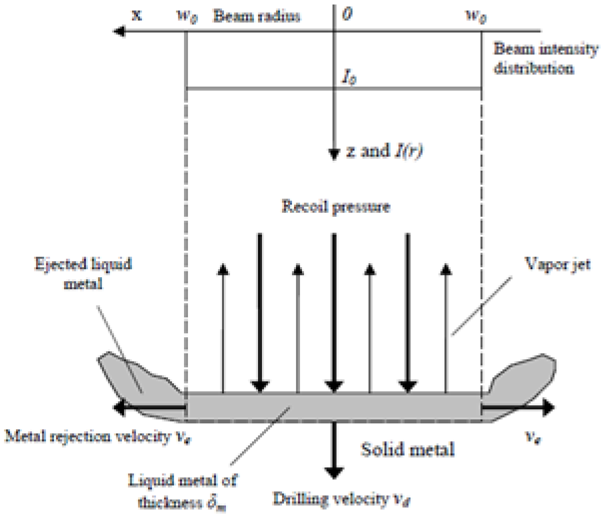


Figure 2: Illustration of melt ejection from the laser-material interaction zone(A. Miotello.1999)

3. One-dimensional Model for Laser Drilling

It is difficult to obtain a simple analytical solution for drilling as anon steady process with three-dimensional heat transfer characteristics. Thus, it is assumed that drilling is a one – dimensional process and that laser beam energy is uniform(p) defined as(Wei Han,2004):

$$P=E/t_0 \quad \text{------------(1)}$$

Where (E) is laser energy ,(t_0) is the Pulse duration . the laser beam intensity is uniform(I_0) defined as :

$$I_0= P/\pi w^2 \quad \text{-----------(2)}$$

Where w is the radius of alaser beam. The temperature distribution inside the work piece is equal to :

$$T - T_0 = \frac{2I_0}{K}\left(\frac{kt}{\pi}\right)^{1/2} e^{\frac{-z^2}{4kt}} - \frac{I_0 z}{K}\left[1 - erf\,\frac{z}{2(kt)^{1/2}}\right] \text{---------(3)}$$

Where (K) is the thermal conductivity ,(erf)is the error function ,(z) is the axial coordinate ,and (k)is thermal diffusivity which is defined as:

$$K = K/\rho\, C \qquad \text{-------------(4)}$$

Where (ρ) ,(C) are the density and the heat capacity of the metal, respectively .the temperature distribution is valid under the condition that $(kt)^{1/2} < w$ which can be achieved either through low diffusivities or short drilling times .the time for the work piece surface to reach the solid –liquid phase transition temperature (t) can be obtained by the following :

$$T_m - T_0 = \frac{2I_0}{K}\left[\frac{kt}{\pi}\right]^{1/2} \qquad \text{--------------------(5)}$$

Where(T_m) is the melting point ,and (T_0) is the ambient temperature. The duration of the heating stage (t_h) can be calculated as:

$$t_h = \frac{\pi}{k}\left[\frac{K(T_m - T_0)}{2I_0}\right]^2 \qquad \text{--------------------(6)}$$

The drilling velocity (ds/dt)can be rewritten as :

$$-\frac{1}{k}\frac{ds}{dt}\frac{dT}{dz} = \frac{d^2T}{dz^2} \text{--------------------------(7)}$$

Then at z=0 $\qquad T=T_m$ ------------(8)

At $z \to \infty$ $\qquad T=T_0$ -------------(9)

By applying the boundary conditions given by eqs. (8 and9) ,eq.(7)can be solved for the temperature distribution inside the solid as:

$$\frac{T - T_0}{T_m - T_0} = exp\left[-\frac{1}{k}\left[\frac{ds}{dt}\right] z_d\right] \qquad \text{-------------------------(10)}$$

Where

$$z_d = 2(kt_0)^{1/2} \qquad \text{----------------------(11)}$$

The temperature gradient at the drilling can be determined using eq. (10) to be :

$$\left[\frac{dT}{dz}\right]_{z=0} = -\frac{1}{k}\left(\frac{ds}{dt}\right)(T_m - T_0) \qquad \text{--------------------(12)}$$

The drilling velocity ds/dt can be expressed as:

$$\frac{ds}{dt} = \frac{I_0}{\rho[L_m + C(T_m - T_0)]} \qquad \text{------------------------(13)}$$

Where L_m is the latent heat of fusion.
The hole depth(s) can be rewritten as:

$$s = \frac{I_0(t - th)}{\rho[L_m + C(T_m - T_0)]} \qquad \text{------------------(14)}$$

Table 1: Experimental parameters of Applied laser systems(Karl-Heinz,2011)

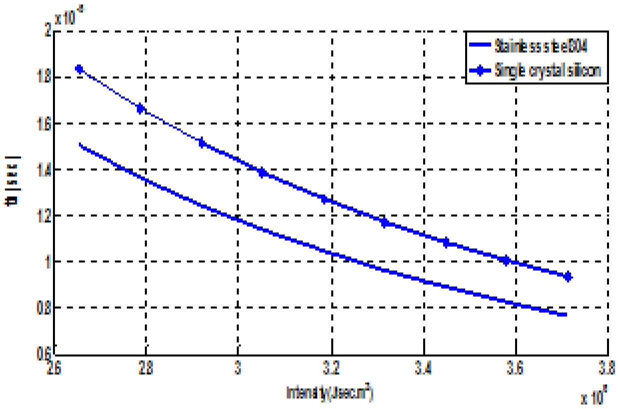
	Microsecond laser system	Nanosecond Laser system	Picosecond laser system
Wave length	1064nm	532nm	1064nm
Pulse duration	80µs	60ns	10ps
Pulse energy E	90mJ	280µJ	150µJ

Table 2:Properties thermal of the materials(EMIS,1988)

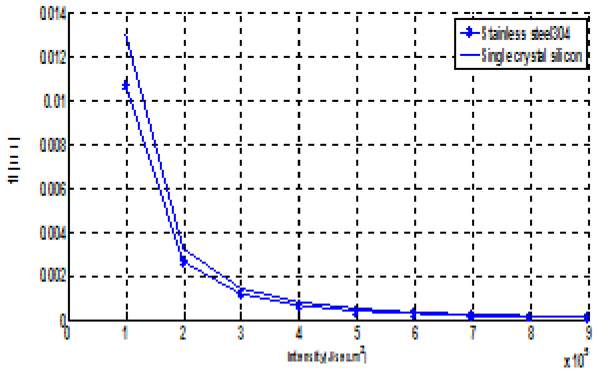
Nomenclature	Stainless steel 304	Single crystal silicon	Units
Density,	$7.93 \cdot 10^3$	$2.33 * 10^3$	$kg \cdot m^{-3}$
Latent heat of fusion	$2.73 \cdot 10^5$	$2.667 * 10^5$	*J/kg*
Thermal conductivity	*21.4*	43	$Wm^{-1}K^{-1}$
Specific heat,	*0.50*	0.70	$kJ \cdot kg^{-1}K^{-1}$
Melting temperature	1685	1683	K^0
Vaporizing temperature	2910	2628	K^0

4. Results and Discussion

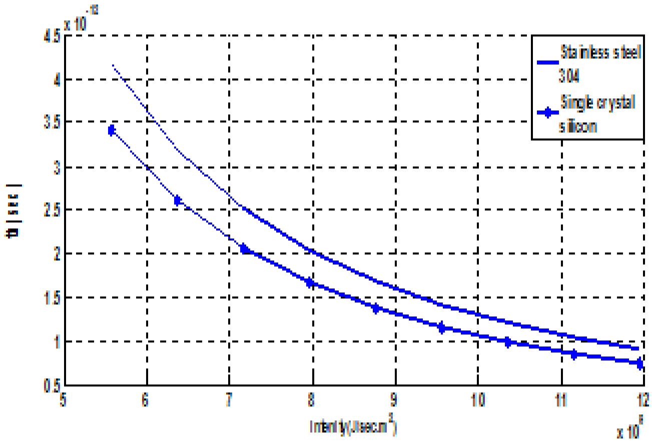
The introduction has been of variable values in the table (1) and (2) in the equations (6), (7), (10), (12), (13), and (14) to calculate all of the heating stage time , the drilling velocity and temperature of material surface, temperature gradient and drilling hole depth and the time of laser drilling process at different values of the intensity of laser pulses, and I've found parameters of laser drilling process (the temperature of material surface ,heating stage time, drilling hole depth , temperature gradient and the time of laser drilling process) decreases when increasing the intensity of laser pulses, especially the decline is large the time of laser drilling process and heating stage time the material and drilling hole depth when the effect of pulse picoseconds and have teams fall between the effect of pulse (micro) and ((Nano less as shown in Figures (1), (2), (3 (while the decline is large in the temperature of material surface and the temperature gradient at the effect of pulse (micro) less than when the effect of pulse ((Nano)and would be very small when the effect of pulse picoseconds and as shown in Figures (4), (5). while we note that the drilling process velocity of increases when you increase the intensity of laser pulses, and this increase is large when the effect of pulse picoseconds and less of them when the effect of pulse ((Nano and would be very small when the effect of pulse (micro) as described in the forms (6) and (7), and this difference that occurs in parameters of laser drilling process due to different lengths wavelengths of the pulse and the duration that caused to different energies and play a role that affect the intensity of the pulses by the relationship (2). When the comparison between articles Stainless steel304 and Single crystal silicon in terms of the effect of laser pulses them we find that the parameters of laser drilling process (the temperature of material surface, heating stage time , drilling hole depth , temperature gradient and the time of laser drilling process) be less reduction in material Stainless steel304 while drilling process velocity increases in Single crystal silicon material more than material Stainless steel304 and that because of the different thermal properties) of the material (thermal conductivity, density, specific heat capacity and the degree of melting.



A

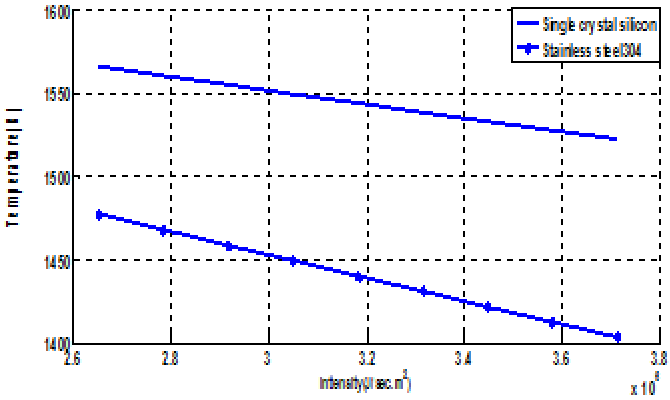


B

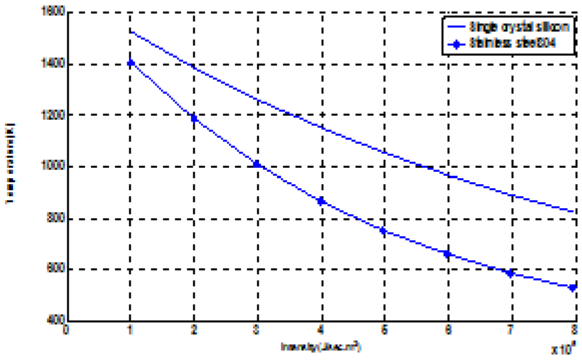


C

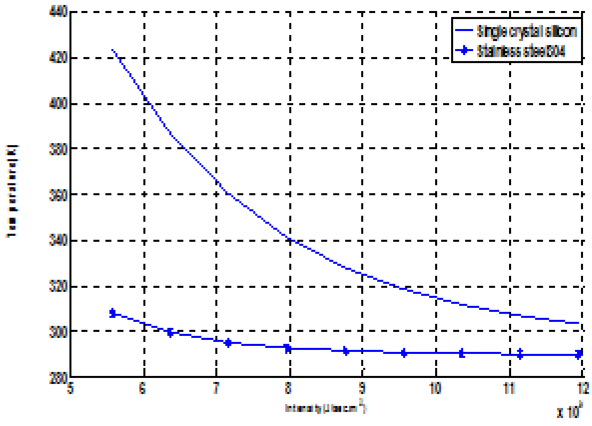
Figure 3: the duration of the heating stage as a function intensity laser pulses (A) effect laser pulses of nanosecond (B) effect laser pulses of microsecond(C) effect laser pulses of picosecond



A

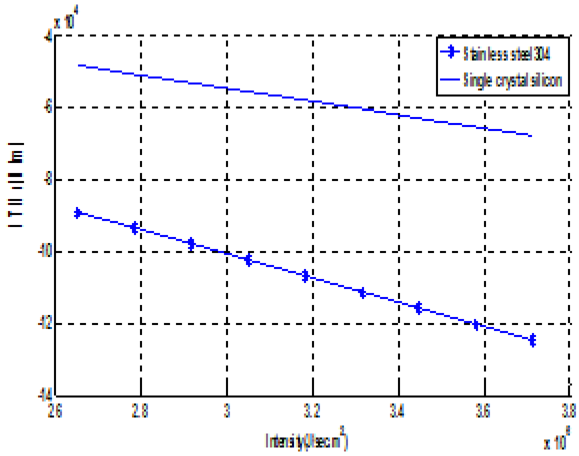


B

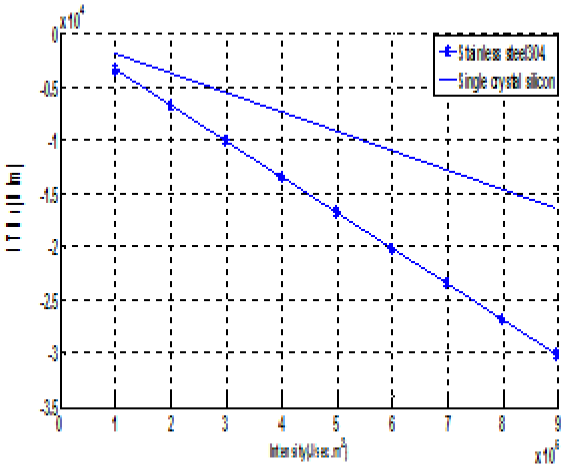


C

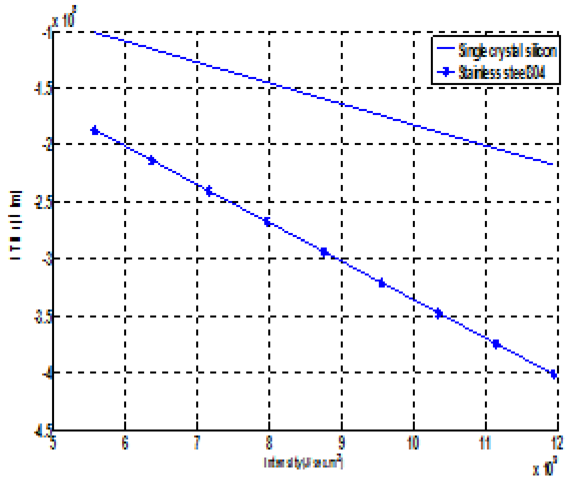
Figure 4: the temperature distribution inside the work piece as a function intensity laser pulses (A) effect laser pulses of nanosecond (B) effect laser pulses of microsecond(C) effect laser pulses of picosecond



A

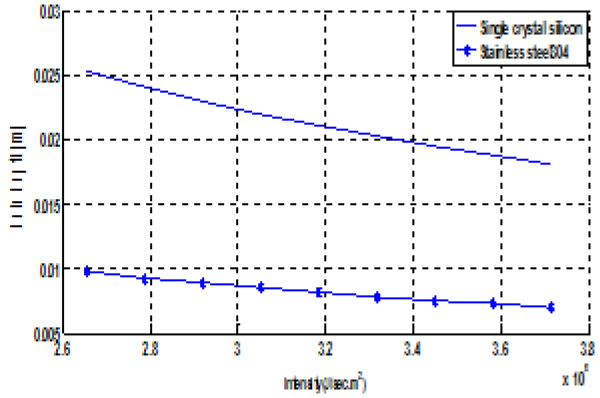


B

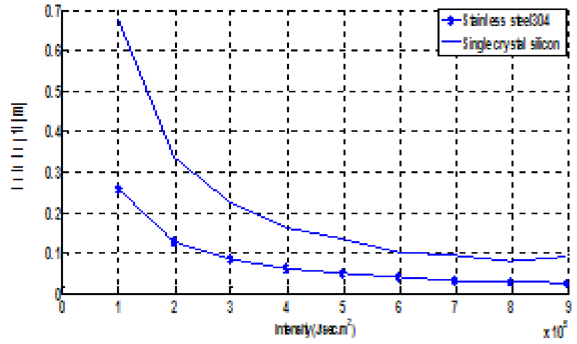


C

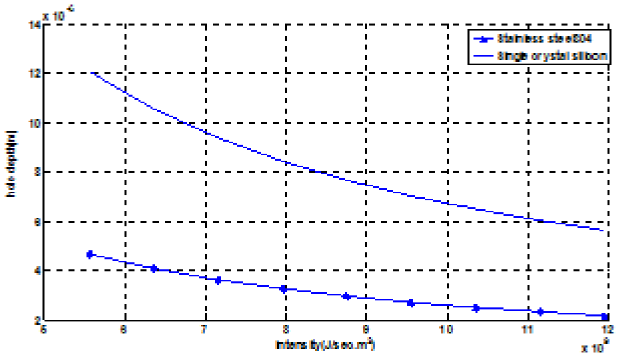
Figure 5: the temperature gradient at the drilling as a function intensity laser pulses (A) effect laser pulses of nanosecond (B) effect laser pulses of microsecond(C) effect laser pulses of picosecond



A

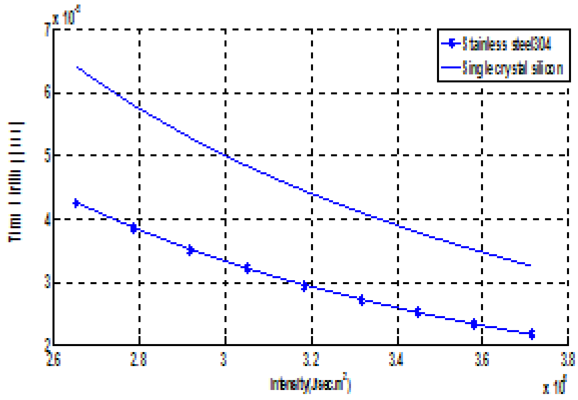


B

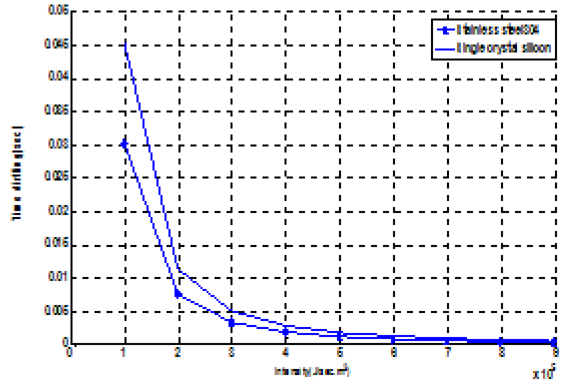


C

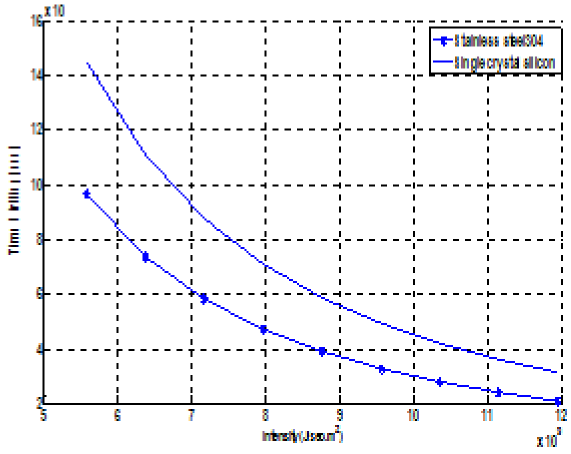
Figure 5: the hole depth as a function intensity laser pulses (A) effect laser pulses of nanosecond (B) effect laser pulses of microsecond(C) effect laser pulses of picosecond



A

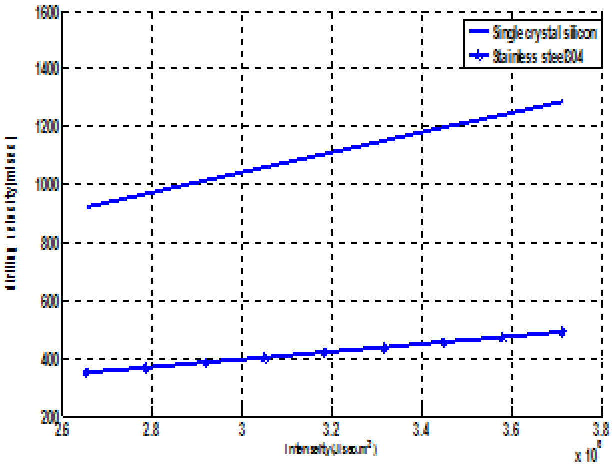


B

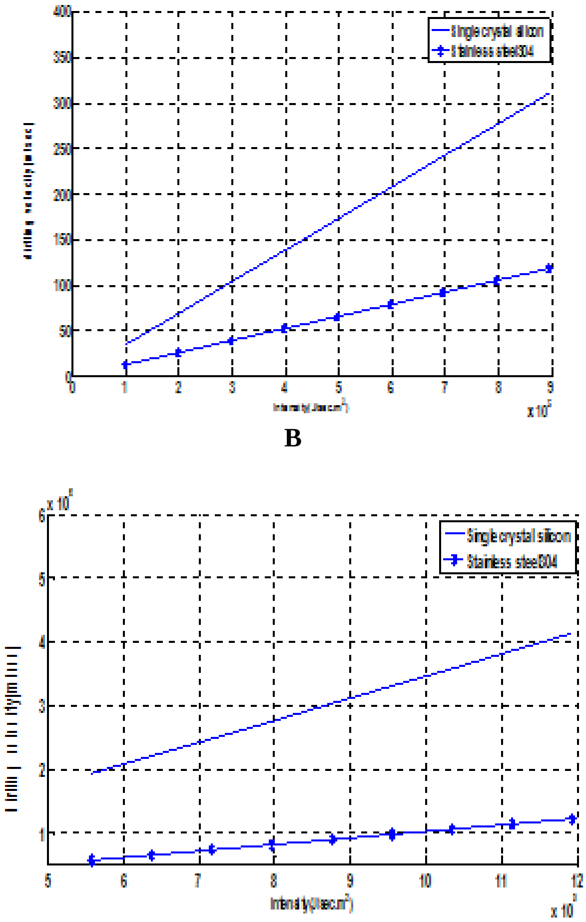


C

Figure 5: the time drilling as a function intensity laser pulses (A) effect laser pulses of nanosecond (B) effect laser pulses of microsecond(C) effect laser pulses of picosecond



A



B

C

Figure 5: the hole depth as a function intensity laser pulses (A) effect laser pulses of nanosecond (B) effect laser pulses of microsecond(C) effect laser pulses of picosecond

5. Conclusions

We conclude from this research that the drilling process depends on the wavelength of each pulse and the pulse duration and ultra-short laser pulses (picoseconds) is the best to use in the drilling process and well conclude that the thermal properties of the material (thermal conductivity, density, specific heat capacity) and the degree of melting material has an important role in the drilling process.

Reference

[1] Jeb Collins, Pierre Gremaud**“A simple model for laser drilling”** Preprint submitted to Mathematics and Computers in Simulation 23 March, 2009.

[2] 2-K.T..Voisey ,S.S.Kudesia , W.S.O.Rodden,”**Melt Ejection During Laser Drilling of Metals”**‘, Submitted to Mat .Sct and Eng .Oct, 2002.

[3] Dong-Gyu AHN, Gwang-Won JUNG,**“Influence of process parameters on drilling characteristics ofAl 1050 sheet with thickness of 0.2 mm using pulsed Nd:YAG laser”** Trans. Nonferrous Met. Soc. China 19,pp157−163,2009

[4] 4-SushantDhar, NishantSaini, R. Purohit NSIT, Delhi, India **“A review on laser drilling and its Techniques”,**Proceedings: International Conference on Advances in Mechanical Engineering-Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, Punjab, India**2006**.

[5] 5-E. Kacara, M. Mutlu, E. Akman, A. Demir, L. Candan,T. Canel, V. Gunay, T. Sınmazcelik.” **Characterization of the drilling alumina ceramic using Nd:YAG pulsed laser”** journal of materials processing technology 2 0 9,pp 2008–2014,2 0 0 9.

[6] 6- Henrikki Pantsar1, Hans Herfurth1, Stefan Heinemann1, Petri Laakso, RaimoPenttila,

[7] Yi Liu3, Golam Newaz4 **“ LaserMicroviaDrillIng AndAblatIon OF SilIicon Using 355 NM Pico And Nanosecond Pulses**” ICALEO® Congress roceedings, Laser Microprocessing Conference ,pp. 278 of 430,2008.

[8] 7- Low, D. K. Y., L. Li, and P. J. Byrd, “**Hydrodynamic physical modeling of laser**

[9] **drilling**” J. Manuf. Scien. and Engin., 124,pp.852-862,2002.

[10] 8-V. Semak, X. Chen, K. Mundra, and J. Zhao, 1997, “**Numerical simulation of hole profile**

[11] **in high beam intensity laser drilling**” Proc. of Laser Materials Processing Conf., 81-90.

[12] 9-J. König, T. Bauer, **“Fundamentals and industrial applications of ultrashort pulsed lasers at Bosch”**, in: Photonics West, San Fransisco, pp. 7925-793,22011.

[13] 10- B.N. Chichkov, C. Momma, S. Nolte, A. Alvensleben, A. Tünnermann**,” Femtosecond, picosecond and nanosecond laser ablation of solids”,**Appl. Phys. A, 63 pp. 109-1151996.

[14] 11- M. Dirscherl,”**Ultrakurzpulslaser”** - Grundlagen und Anwendungen, 2005.

[15] 12- A. Miotello, R. Kelly, “**Laser-induced phase explosion: new physical problems when a condensed phase approaches the thermodynamic**”Critical temperature, Appl. Phys. A, 69 pp.67-73,1999.

[16] 10-Wei Han**“Computational and experimental investigations of laser drilling and welding for microelectronic packaging**”phD. Thesis ,Mechanical Engineering /Worcester Polytechnic Institute,2004**.**

[17] 11- Karl-Heinz Leitz ,Benjamin Redlingshöfer, Yvonne Reg, Andreas Otto andMichael Schmidt .“**Metal Ablation with Short and Ultrashort Laser Pulses**” Physics Procedia,A.12, pp. 230–238,2011.

[18] 12- EMIS, “**Properties of Silicon” ,** An INSPEC The Institute of Electrical Engineers. Data review series No. 4, 1988.