Study of laser drilling mechanism parameters for a Ni-based superalloy

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Abstract

The time of laser drilling process for Hastelloy-x by using hybrid Ti:sapphire/KrF excimer chain laser has been calculated at different values of each (number of shots , distance of sample from lens focus , intensity as well as fluence) according to the establishment results of drill depth .Many parameters of laser drilling process have been calculated as heating stage time (t_h) , drilling velocity (ds/dt) , temperature gradient (dT/dZ) , temperature of metal surface (T) and energy flux absorbed by the surface (φ_{Ea}) at different values of photons intensity and in many different positions;infront of the lens focus and behined it . The laser drilling parameters have been calculated also by variation of ambient temperature ($T_\circ$) according to one dimensional model of laser drilling . We found that ambient temperature ($T_\circ$)was more efficient parameter than laser photons intensity in laser drilling velocity and the metal position in front of the lens focus or behind it was not affect on most drilling parameters. It can be concluded that small divergence laser beam is adequate in laser drilling of metals

الخلاصة :

حسب زمن عملية التثقيب الليزري لسبيكة Hastelloy-X باستخدام ليزر hybrid Ti:sapphire /KrF excimer chain عند قيم مختلفة لكل من عدد مرات القدح والبعد عن بؤرة العدسة والشدة بالإضافة إلى كثافة الفيض الفوتوني بالاعتماد على نتائج عمق الفجوة المنشورة . حسبت عدة معاملات لعملية التثقيب الليزري ومنها زمن مرحلة التسخين (t_h) وسرعة التثقيب (ds/dt) وانحدار درجة الحرارة (dT/dZ) ودرجة حرارة سطح المادة (T) بالإضافة إلى فيض الطاقة الممتص من قبل السطح (φ_{Ea}) عند قيم مختلفة للشدة الفوتونية وعند عدة مواقع مختلفة أمام بؤرة العدسة وخلفها . حسبت المعاملات الليزرية مرة أخرى بتغيير درجة الحرارة الابتدائية ($T_\circ$) بالاعتماد على نموذج التثقيب ذي البعد الواحد. وجد أن درجة الحرارة الابتدائية ($T_\circ$) هي العامل الأكثر أهمية من شدة الفوتونات الليزرية في تحديد سرعة التثقيب الليزري وأن موقع المعدن أمام أو خلف بؤرة العدسة لا يؤثر على معظم معاملات التثقيب . لقد أمكن الاستنتاج أن الحزمة الليزرية ذات الانفراج الصغير هي الأكفأ في عملية التثقيب الليزري للمعادن .

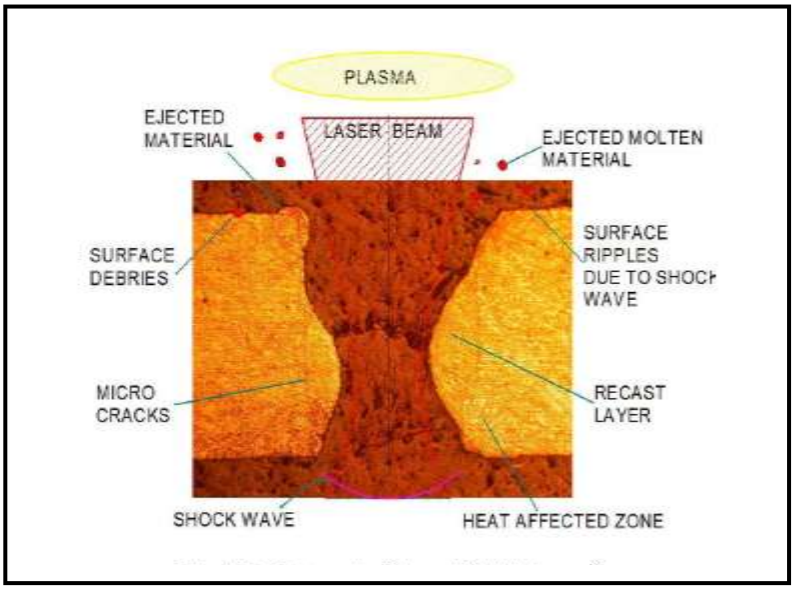
1. Introduction

Laser drilling has become a significant industrial process , because there are many outstanding advantages in using it as the fabrication method of small holes over other techniques . One major application of laser drilling is making holes for combustors and turbines in aircraft jet engines. Many theoretical and experimental attempts have been directed to understand the mechanism of laser drilling and solve the problems which are evolutes during it . The first one-dimensional model show that material exposed to the laser beam is removed via evaporation [1] , but Von Allmen proposed that surface evaporation in the area exposed to a laser beam may be attributed to the recoil pressure which ejects molten material [2]. In 1980 , Mazumder and Steen developed a three-dimensional heat transfer model with a moving Gaussian heat source , by using finite difference numerical techniques , which is solved for temperature and melting profile in the work piece of infinite length but finite width and depth [3]. The experimental studies are introduced a statistical method to investigate the effects of variation a single pulse laser drilling parameters on the hole geometry of Nimonic 75 work piece material [4] and a factorial design to identify the effects of a single pulse drilling on the hole quality , including resolidified material , taper , barreling , inlet cone, exit cone, surface debris and mean hole diameter [5] . A modified model was proposed later to include a more accurate calculation of melt front dynamics , which are usually treated in terms of the "problem of Stefan " [6] , for that a new two-dimensional evaporation drilling model was proposed which predict the temperature field in the beam interaction Zone based on the assumption that no melt motion occurs. Semak et al., were proved that this assumption be valid if the absorbed beam intensity is sufficiently high that the material evaporates faster than it moves, and the interaction time is short enough that noticeable melt displacement cannot occur [7] . Furthermore, with lower intensities or longer interaction times , melt ejection from the interaction zone will be generated due to evaporation recoil pressure [8] .Han , introduced an experimental study to measure the temperature variations during laser micro drilling processes and the data were correlated to numerical results based on the fundamental thermal analysis[9] . In 2000 Low et al. was reported that the physical characteristics of spatter formation during laser percussion drilling on NIMONIC 263 alloy , have been affected by the assist gas such O_2,Ar,N_2,and compressed air[10] . But Shen et al., were developed another model for the melting depth profile and time evolution of the temperature under the assumption that the process of laser heating and melting is a linear process , that is , the physical parameters of the material are independent of the temperature [11]. The drilling of a thick metal samples by UV output from a diode-pumped Q-switched Nd:YAG laser with frequency doubling and tripling , gives a significant advantage due to higher average drilling speed and accuracy , and minimal recast layer [12].

The effect of laser peak power and pulse width on the repeatability of hole geometry was studied for pulsed Nd:YAG laser drilling on 2mm thick mild steel sheets [13]. The improvement of the laser drilling efficiency was based on the recoil pressure generated by rapid evaporation of the molten material by the second laser pulse [14]. The characteristics of spatter formation under the effects of different laser parameters were investigated for laser drilling on NIMONIC 263 alloy sheets [15]. Ghoreishi et al., were studied the effects of controllable laser variables on hole taper and circularity in laser percussion drilling on stainless steel work piece [16]. The simulation of melting profiles using both Stefan conditions and the physical quantity enthalpy models was proven to be more efficient thermal considerations for laser processes in solving the problems with multiple phases [17] .In 2004 , one-dimensional heat conduction problem was solved approximately for a semi-infinite model in the solid and liquid regions , which gave the variation of the melt depth with time and temperature distributions in four materials as; Aluminum , Titanium , Copper , and Silver [18] . The effect of systematic parameters on the resultant profiles of the holes for laser drilling of micrometer size holes on thin metal sheets has been investigated [19]. The good edge quality features and higher processing speed have been obtained with diode – pumped solid –state (DPSS) laser micro drilling on the silicon and stainless steel [20]. The increasing of the hole throughput rate to several seconds or less per hole , is very useful to the airborne laser program . This attempt was achieved on Nickel-based alloys such Hastelloy-X by UV laser , where the effect of number of shots, distance to focus , intensity , and influence on the hole throughput rate have been studied [21] . This research aims to study the thermal parameters which affects the laser drilling mechanism such as Temperature gradient , heat penetration length , drilling velocity .

2. Mechanism of the laser drilling

Laser drilling is of considerable interest , since narrow , intense laser beams can be used to drill relatively deep, fine diameter holes, with little thermal or mechanical damage to the surrounding material [22,23]. Laser has an interest in drilling the cooling holes in turbine blades , to allow higher engine operating temperatures , drilling fine holes in aerofoil surfaces to reduce turbulence and associated drag [24] , and drilling petroleum reservoir rocks , since the infrared lasers show the capability to spall , melt and vaporize natural earth materials [25] . Laser drilling is a very complex process , since both melting and vaporization are encountered , and the phenomena such as fluid flow , gas dynamic , and plasma effects are involved . During laser drilling , material is removed via vaporization and physical ejection of molten material [18]. 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 [26]. Figure (1) show the features of laser drilled holes [27]. Barreling is the effect of energy trapped inside the work piece to form a cavity , the formation of the barrel can guide the ejected material as it passes through the hole , forcing the molten material around the hole to com away from the sides . Resoldified material indicates the amount of material that had vaporized or melted during drilling , but had not escaped from the hole and so had resolidified on the internal surface . Taper is the measure of overall taper of the hole sides , but does not include inlet and exit cones. The surface debris is an assessment of the amount of resolidified materials appearing on the surface of the hole . The inlet and exit cones are the measure between the entrance and minimum hole diameter and the measure between the minimum and exit hole diameters, respectively [18].



laser drilled hole profile[27]. Fig.(1)

Laser drilling can be performed through continuous drilling with the use of a continuous – wave beam , or percussion drilling with the use of a pulsed beam . In continuous drilling , material removal occurs through bottom of the hole with the aid of a gas jet , where figure(2) .

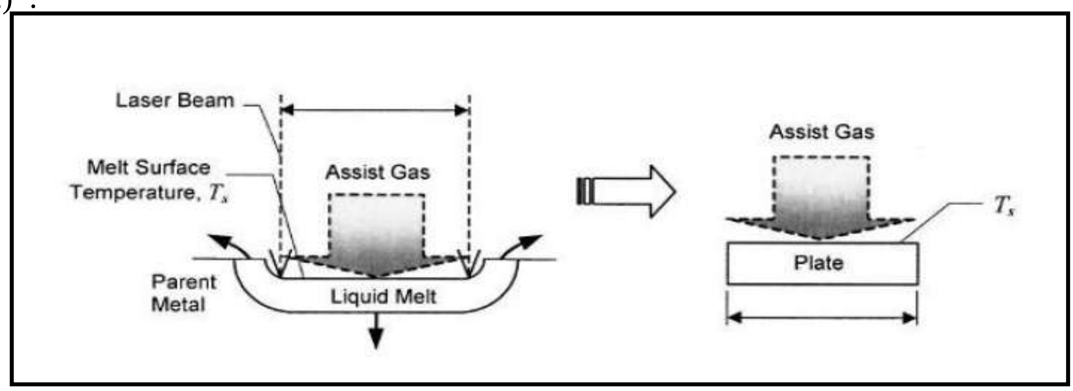
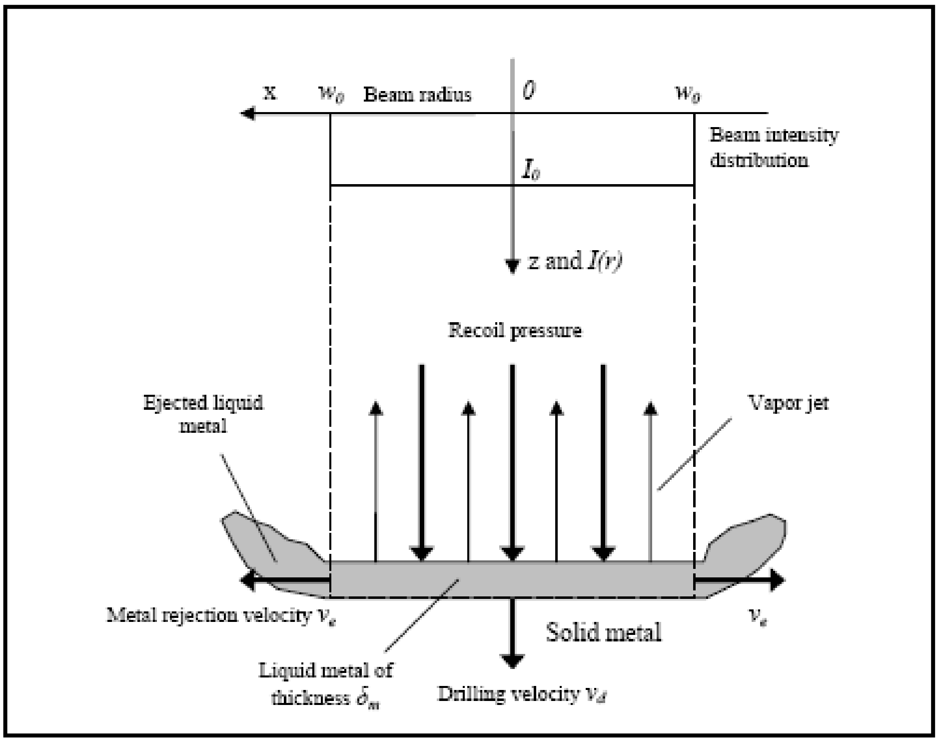


Fig.(2) Approximation of the forced convection cooling of the melt surface by the assist gas at the hole bottom [27] .

In percussion drilling , a pulsed beam removes material through melting and localized detonation or explosion . In this case , about 90% of the material is removed through detonation effects . Additionally , a reactive gas jet can be used to remove material through oxidation , chemical reactions . Drilling efficiency is strongly dependent on the phenomenon of laser – supported detonation waves . Plasma formation at the work piece surface due to laser/material interaction severely decreases laser drilling effectiveness because it absorbs a significant portion of the incoming beam energy and shields the work piece surface . A laser – supported detonation wave occurs when the absorbing plasma layer is coupled to a shock wave occurring when material at the erosion front detonates .Drilling can be divided into two stages : heating and material removal . In the heating stage , temperature of the work piece surface , T_s , is increased up to the phase transition temperature , T_m , by a laser beam . The heating stage is usually very short because the laser beam intensity is very high , the work piece surface is not thermally eroded , and a hole is not made because phase transition does not occur . But the material removal stage has two processes : 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 , while 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 , where the evaporation rate and the related recoil pressure on the melt surface vary along the surface . Since the recoil pressure plays an important role in laser drilling as shown in figure (3) .



Figure(3) Illustration of melt ejection from the laser –material interaction zone [18] .

The energy required to remove material via melt ejection is about one quarter of that required to vaporize the same volume[18] .The drilling process is influenced by melt expulsion , absorption , and refraction of laser radiation in the expanding vapor plasma .

3. Theory

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 [28] and that the laser beam intensity is uniform (I_o) defined as [18] :

$$I_o = \frac{P}{\pi\omega^2}$$

………………………………(1)

where (P) is the laser power , (ω) is the radius of a laser beam . The temperature distribution inside the work piece is equal to [28]:

$$T - T_o = \frac{2I_o}{K}\left(\frac{kt}{\pi}\right)^{1/2} e^{\frac{-Z^2}{4kt}} - \frac{I_o Z}{K}\left[1 - erf\,\frac{Z}{2(kt)^{1/2}}\right].$$

……………………….(2)

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 [28]:

$$k = \frac{K}{\rho C}$$

………………………………..(3)

where (ρ) , (C) are the density and the heat capacity of the metal , respectively. The temperature distribution is valid under the condition that $(kt)^{1/2} < \omega$ 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 [18] :

$$T_m - T_o = \frac{2I_o}{K}\left[\frac{kt}{\pi}\right]^{1/2}$$

(4)...

where (T_m) is the melting point , and (T_o) is the ambient temperature. The duration of the heating stage (t_h) can be calculated as [18] :

$$t_h = \frac{\pi}{k}\left[\frac{K(T_m - T_o)}{2I_o}\right]^2$$

…………………………(5)

The energy balance at the drilling front can be expressed as [18] :

$$\alpha I_o = \rho L_m \frac{\partial S}{\partial t} - K\left[\frac{dT}{dZ}\right]_{Z=0}$$

……………………………..(6)

where α is the absorptivity of the material , (ρ) is the density , L_m is the latent heat of fusion , and $\partial S/\partial t$ is the drilling velocity . Equation (5) can be rewritten as [18] :

$$-\frac{1}{k}\left(\frac{\partial S}{\partial t}\right)\frac{dT}{dZ}=\frac{d^2T}{dZ^2}$$

……………………………..(7)

then at Z=0 , $T = T_m$
(8) ...... }………………………….
at $Z\rightarrow\infty$, $T = T_o$

By applying the boundary conditions given by equation (8) , then equation (7) can be solved for the temperature distribution inside the solid as [18]:

$$\frac{T-T_o}{T_m-T_o}=\exp\left[-\frac{1}{k}\left[\frac{dS}{dt}\right]Z_D\right.$$

………………………..(9).

Where

$$Z_D = 2(kt_p)^{1/2}$$

………………………………. (10)

The temperature gradient at the drilling front can be determined using equation(9), to be [18]:

$$\left[\frac{dT}{dZ}\right]_{Z=0}=-\frac{1}{k}\left(\frac{dS}{dt}\right)(T_m-T_o)$$

……………………………(11)

The drilling velocity dS/dt can be expressed as [18]:

$$\frac{dS}{dt}=\frac{\alpha I_o}{\rho[L_m+C(T_m-T_o)]}$$

…………………………… (12)

The hole depth (S) can be determined by integrating equation.(12), where

S=0 , at $t \le t_h$

but when $t > t_h$

$$S=\frac{\alpha I_o(t-t_h)}{\rho(L_m+C(T_m-T_o))}$$

…………………………..(13)

$$S = \frac{4\alpha P(t - t_h)}{\pi\omega^2 \rho(L_m + C(T_m - T_o))}$$

…………………………….(14)

Equations (13) and (14) show that the hole depth is proportional to the laser beam power and the beam interaction time [18]. 4 number has been appeared in equation (13) dependent on the hole shape ,The energy flux absorbed by the surface(φ_{Ea}) can be obtained using the following [29] :

$$\phi_{Ea} = I_O \alpha t$$

…………………………..(15)

4. Description of the used laser system

The drilling laser system is shown in figure (4), which is contained from the laser system , positive lens, and metal plate of Hastelloy-X . The laser system used to create UV filaments is a hybrid Ti:Sapphire/KrF excimer chain . The front end is a Ti:Sapphire amplifier chain tuned to 745.8 nm capable of up to 15 mJ in 200 fs at 10Hz. After frequency tripling, the 248.6 nm seed beam (of less than 0.2 mJ) is sent into two cascaded KrF excimer amplifiers. The final output is up to 100 mJ in about 1ps [21].

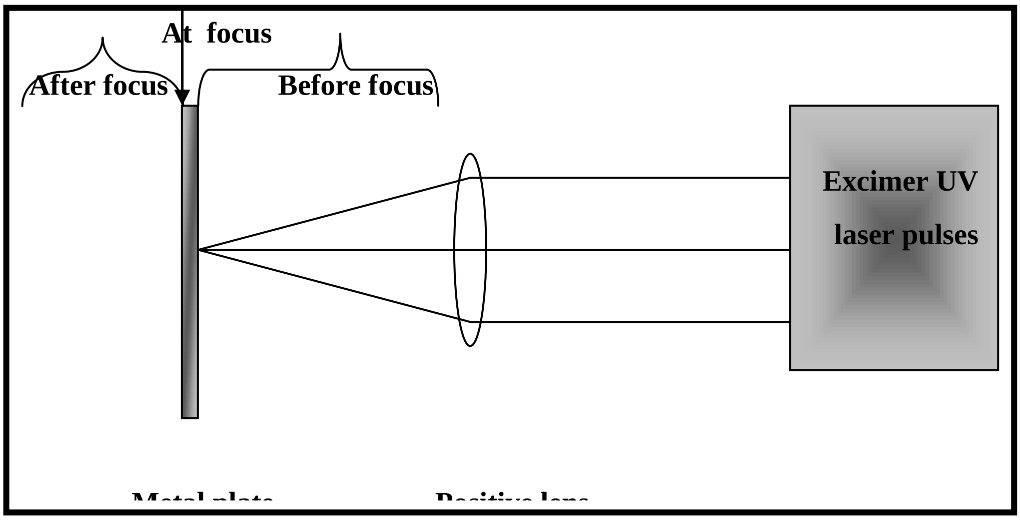


Fig.(4)Setup for the hole drilling in atmosphere [21].

The 10 cm focal length lens which focused a 3X4 cm UV beam at an energy of 25 mJ onto a Hastelloy-X sample. The set of experiments was conducted under atmospheric conditions to explore the effect of oxidation and laser plasma interaction [21].Hastelloy-X is an austenitic nickel base alloy containing approximately 22 percent chromium for outstanding resistance to oxidation at high temperatures [30-32]. The alloy has good high temperature and stress rupture properties above (788 C◦) and can be used for applications up to (1204 C◦) [30-31]. The chemical composition of Hastelloy-X is shown in table (1), and the physical, mechanical and thermal properties of Hastelloy-X at room temperature were illustrated in table (2).

Table(1) Chemical composition of Hastelloy-X [30,32].

Element	***Percent***
Carbon	0.05-0.15
Manganese	1.00 max
Phosphores	0.040 max
Sulfur	0.030 max
Silicon	1.00 max
Chromium	20.50-23.00
Molybdenum	8.00-10.00
Cobalt	0.50-2.50
Tungsten	0.20-1.00
Iron	17.00-20.00
Aluminum	0.50 max
Titanium	0.15 max
Boron	0.01 max
Copper	0.50 max
Nickel	Balance

Table(2) Some of a Hastelloy-X properties

Property	**Typical value**	**Ref.**
density	8.22 gm/cm^3	[32]
Specific gravity	8.22	[30]
Viscosity, absorptivity	7.5 $X10^{-3}$ N/m^2 , 0.3799	[32]
Poisson's ratio	0.382	[31]
Tensile strength	570 Mpa	[32]
Elongation at break	54%	[32]
Modulus of elasticity	205 Gpa	[32]
Magnetic permeability	< 1.002	[30]
Magnetic susceptibility	0.000342	[32]
Electrical resistivity	1.18 μΩ.cm	[31]
Heat capacity	486 J/Kg.K	[31]
Melting point	1628.5 K	[32]
Heat of fusion	208.218 J/gm	[32]
Thermal conductivity	9.1 W/m.K	[31]
Thermal diffusivity	2.277 X 10^{-6} m^2/sec	[32]

5. The calculations and results

The incident laser beam (I_o) on a Hastelloy-X has been calculated using equation (1) . We find that (I_o) of (353 X107 J/sec.cm^2) where (ω = 1.5 cm) and (P) of (25 X 10^9 watt).A (0.0589 psec) duration of heating stage (t_h) has been calculated according to equation (5). The thermal diffusion distance (Z_D) for Hastelloy-X were calculated by using equation (9), and it has been found of (3.017X10^{-9} m).The drilling speed (dS/dt) of (1.652 X10^3 m/sec) was calculated by using equation (12) , and it is utilized to calculate the temperature gradient inside the metal dT/dZ of (-1163.017 X 10^9 k/m) , and the temperature distribution inside the solid (d^2T/dZ^2) of (+843.787 X10^6 k/m^2) using equations (6 and 7), respectively. A(478.15961 k) metal surface temperature within heating stage was obtained by equation (9).

from the drilling depth data as a function of no. of shots ,were distance utilize to focus, fluence, and intensity when the sample in front of the focus or behind it, which are illustrated in ref .[21], were used to calculate the drilling stage time (t) by equation (13). Figures (5-a,b,c) show the (t) as a function of no. of shots, distance to focus and fluence at (I_o) of (353 X 10^{11} watt/m^2), (T_o) of (298.5 k) and (t_h) of (5.89 X 10^{-14} sec).The effect of the intensity on the drilling stage time (t) firstly, when the sample in front of the focus , and secondly , when the sample behind the focus have been studied at (T_o) and (t_h) are constant , as shown in figures (5-d,e).The time of heating stage (t_h) at different values of intensity has been calculated by equation (5) where (K) of (9.1 watt/m.k) , (T_m) of (1628.5 k) and (k) of (2.277 X 10^{-6} m^2/sec) as calculated by equation (3) .Figures (6-a,b) show the (t_h) as a function of intensity when the sample in front of the sample and behind it .We are calculated the drilling velocity (dS/dt) by equation (12) at many different values of intensity , (α) the sample absorptivity of (0.3799) , the sample density (ρ) of (8.22 X 10^3 Kg/m^3), latent heat of fusion (L_m) of (486 J/kg.k) , melting temperature (T_m) of (1628.5 k) and ambient temperature (T_o) of (298.5 k) . The effect of the intensity variation on the drilling velocity is shown in figures (7-a,b).

The temperature gradient (dT/dZ) has been calculated according to equation (6) at different values of (I_o) when the sample in front of the focus and the sample behind it. Figures (8-a,b) show (dT/dZ) as a function of (I_o) at drilling velocity of (1.652 X10^3 m/sec), and all values of (α , ρ , L_m , and K) have been illustrated in table (1).

The temperature of the metal surface during the drilling stage (T) has been calculated using equation (9) where (Z_D) is the heat diffusion distance of (3.017 X 10^{-9} m) according equation (10) , drilling velocity (dS/dt) of (1.652 X 10^3 m/sec) ,(T_o) of (298.5 k) and (T_m , k) are shown in table (1) . Figures (9-a,b) show (T) as a function of intensity when the sample in front of the focus and behind it .Fig.(10-a,b) show the energy flux absorbed by the metal surface (φ_{Ea}) as a function of intensity for two different positions of the sample to lens focus: in front of it and behind it .We are calculated the effect of ambient temperature (T_o) variation on the heating stage time (t) , drilling velocity (dS/dt) , the temperature of the metal surface within drilling stage (T), the temperature gradient (dT/dZ) and the energy flux absorbed by the metal surface (φ_{Ea}) using equations (5,4,12,10,6 and 15) , respectively. The effect of (T_o) variation on each of (t_h , t , dS/dt , T , dT/dZ and φ_{Ea}) are shown in table (3) .

Table (3) The effect of an ambient temperature on laser drilling mechanism parameters for Hastelloy-X .

T_o (k)	t_h (psec)	dS/dt X10^2 (m/sec)	dT/dZ X10^{11} (k/m)	T (k)	t (psec)	S (pm)	Φ_{Ea} (J/m^2)
298.5	0.0404	25.231	-9.9912	345.49	0.0189	-	0.254
323.5	0.0389	25.714	-9.9005	366.75	0.0213	-	0.286
373.5	0.0360	26.738	-9.7078	409.82	0.0266	-	0.357
423.5	0.0332	27.848	-9.4990	453.60	0.0326	-	0.438
473.5	0.0305	29.053	-9.2724	498.09	0.0393	18.811	0.528
523.5	0.0279	30.367	-9.0253	543.27	0.0468	41.420	0.628
573.5	0.0254	31.805	-8.7549	589.10	0.0550	67.048	0.738
623.5	0.0231	33.387	-8.4573	635.55	0.0641	96.060	0.859
673.5	0.0208	35.134	-8.1287	682.58	0.0739	128.84	0.991
723.5	0.0187	37.075	-7.7636	730.15	0.0846	165.89	1.134
773.5	0.0167	39.242	-7.3561	778.22	0.0961	207.71	1.289

6.Discussion

The time of drilling stage (t) depends on the velocity of achieving heating , absorption ,melting, vaporization and cooling processes which are affect by exposed material quantity to incident laser photons . The increasing of incident laser photons energy on the metal by increasing of number of photons, intensity, or fluence as shown in figures (5-a,c,d,e),the large absorption of photons by material molecules, large energy diffusion on a large area of metal will be occur, and that need more time to complete drilling process .The position of the sample as to lens focus controlled on the drilling stage time , where we notice that when the sample at focus ,(t) has a higher value, but when the sample distance to focus increases ,the drilling time will be decreased as shown in figures (5-b). This behavior can be interpreted by that the sample will be exposed at whole to laser photons when it is at focus , and that require each of heating , melting , vaporization and cooling processes for whole sample to achieve drilling process. But when the sample distance to focus increased , the exposed material area to laser photons is decreased and the drilling process need less time to complete . Figures (6-a,b) shows that the increasing of incident laser photons intensity on the metal surface lead to achieve the heating stage of metal in a short time because of increasing the average of energy transfer by thermal conduction at high photons intensities , and the high value of the energy flux absorbed by the surface (Φ_{Ea}) as shown in figures (10-a,b) .

The falling laser photons intensity on the metal surface (I_o) has been expended to achieve whole drilling process (containing metal heating , melting, vaporization and surface cooling) , then that the increasing of incident laser intensity on the metal surface to cause accomplishment the drilling process in a highly velocity as shown in figures (7-a,b) , because of large decreasing in the metal surface temperature (cooling process) as shown in figures (9-a,b).

In spite of the incident laser photons intensity increasing but the results of temperature gradient (dT/dZ) which are shown in figures (8-a,b), illustrate large decreasing in temperature with increasing of distance from the metal surface. That may be attributed to expended laser energy to complete the drilling process without any increasing in temperature to occur. There is no benefit from the sample position changing with regard to lens focus (in front of it or behind it) on the laser drilling mechanism parameters such as (t_h , dS/dt , dT/dZ , T), unless (t and Φ_{Ea}), so long as intensity in the same value. We notice that the (t) and (Φ_{Ea}) of highest value when the sample was in front of the focus than behind it. That may be attributed to highest incident energy flux on the metal when the sample in front of focus which increases the exposed material area to laser photons and it requires long period to complete drilling process for whole material.

Table (3) illustrates the effect of ambient temperature changing (T_o) on the laser mechanism parameters , so we mention that : (t_h) decreasing with (T_o) increasing because of (T_o) approaching from melting temperature (T_m) which decreases heating stage time, (t) increasing with (T_o) increasing due to the high value of ambient temperature increases the metal surface temperature and increases the temperature gradient (dT/dZ) with farness from the metal surface , the increasing of energy flux absorbed by the surface (Φ_{Ea}) which means increasing of exposed material area to laser and it may be needed more time to achieve laser drilling stages . We are also notice drilling velocity (dS/dt) increasing with (T_o) increasing that can be attributed to increasing of energy which abundant from (T_o) and leads to increasing of the material vaporization velocity. The directly proportion between (T) and (T_o) has been caused by the temperature is utilized to heating and thermal conduction without any surface cooling occurs because of that drilling process is not complete to the range ($\leq$ 423.5 k) of ambient temperature (S=0) to limit (T_o = 473.5 k) which (t) becomes larger than (t_h) and drilling process completes by achieving material vaporization stage and (T) decreasing by cooling .

7. Conclusion

The ambient temperature (T_o) is the more efficient parameters than incident laser photons intensity on the metal in specification the achievement velocity of laser drilling process. The sample position with regard to lens focus is not affect on most laser drilling parameters except (t) which is larger at the front position than for behind position with respect to focus. In order to get clean, sharp, deep hole, we must keep laser arrays direction in small spot without any diffusion to a larger area from material so it affects in achievement time of laser drilling process and the quality of drilled hole .

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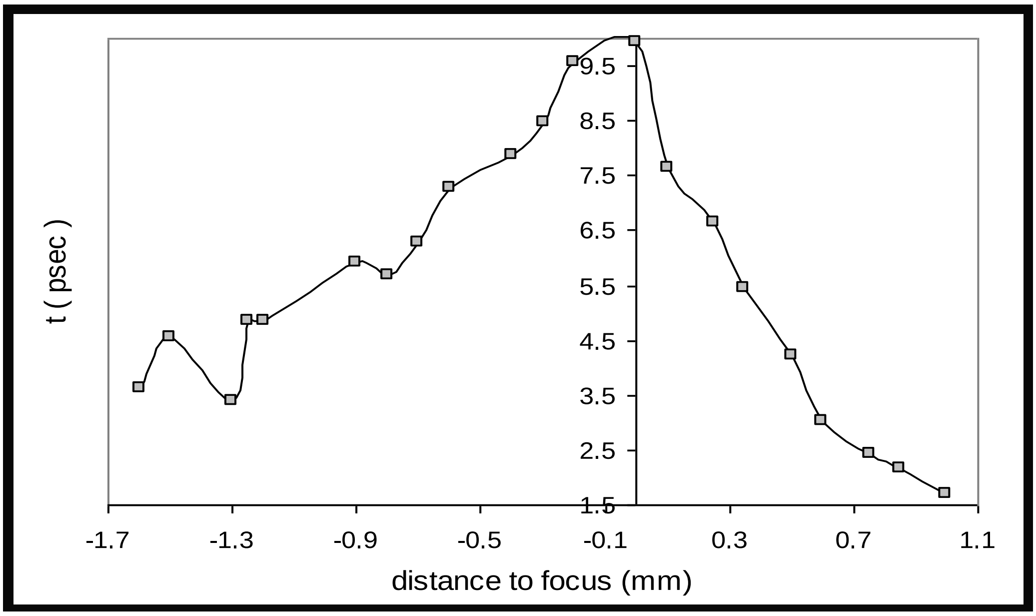
(a)



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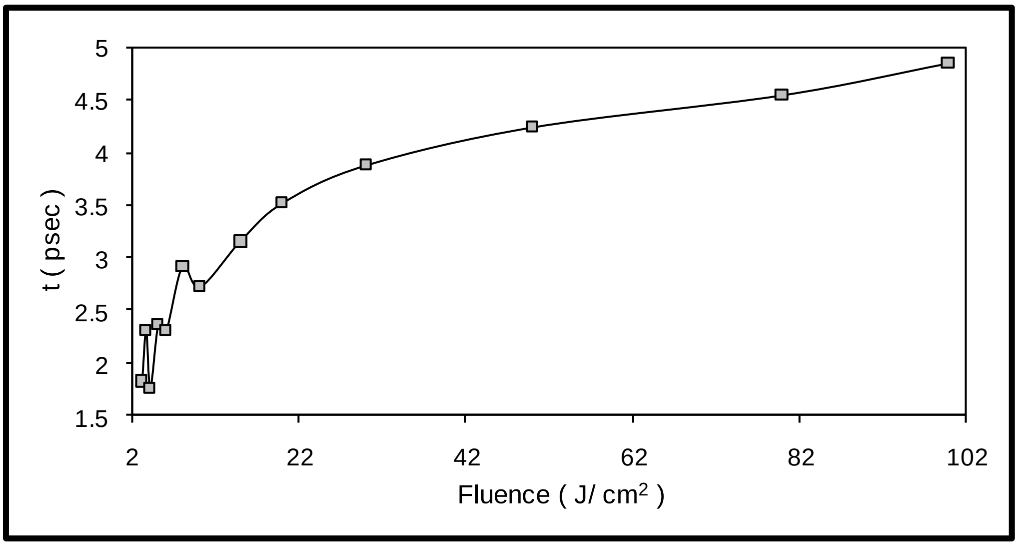

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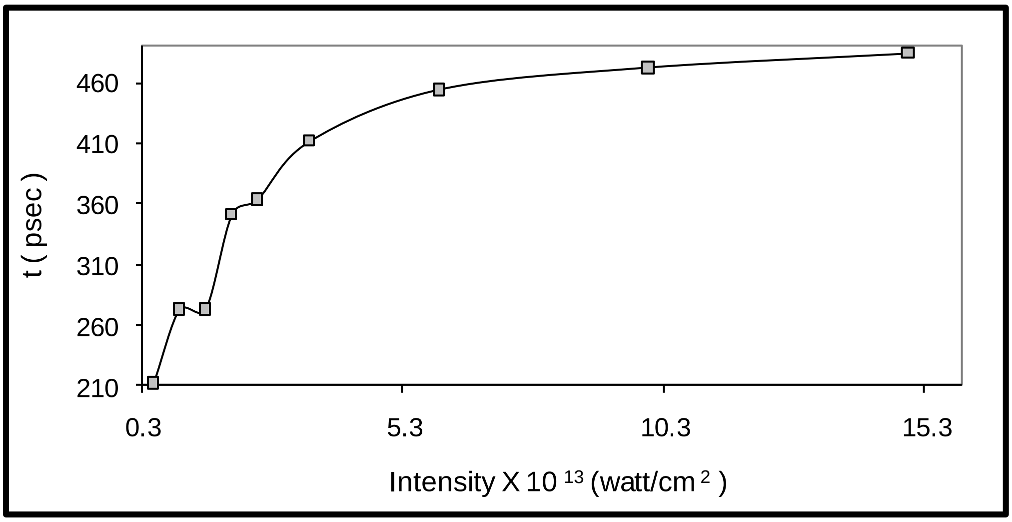

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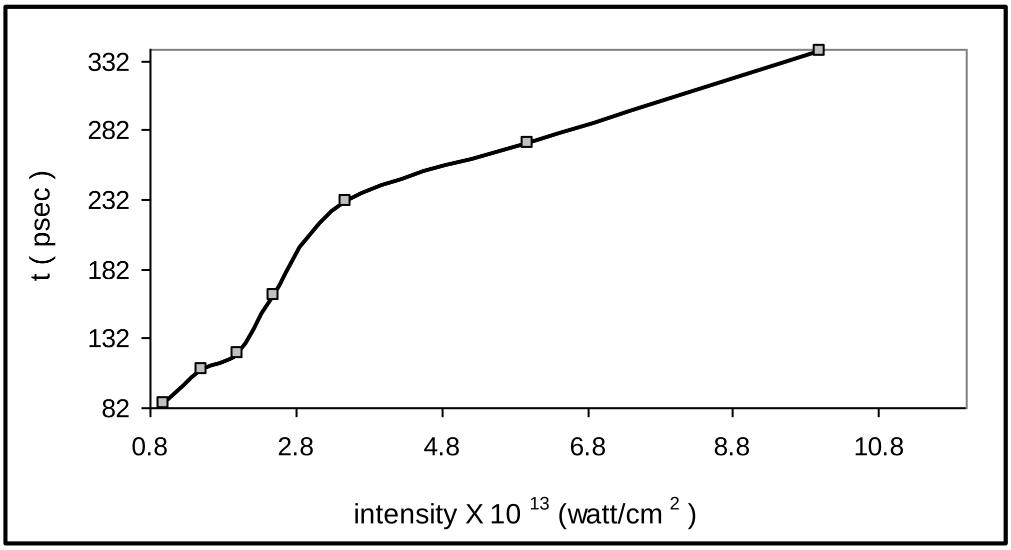
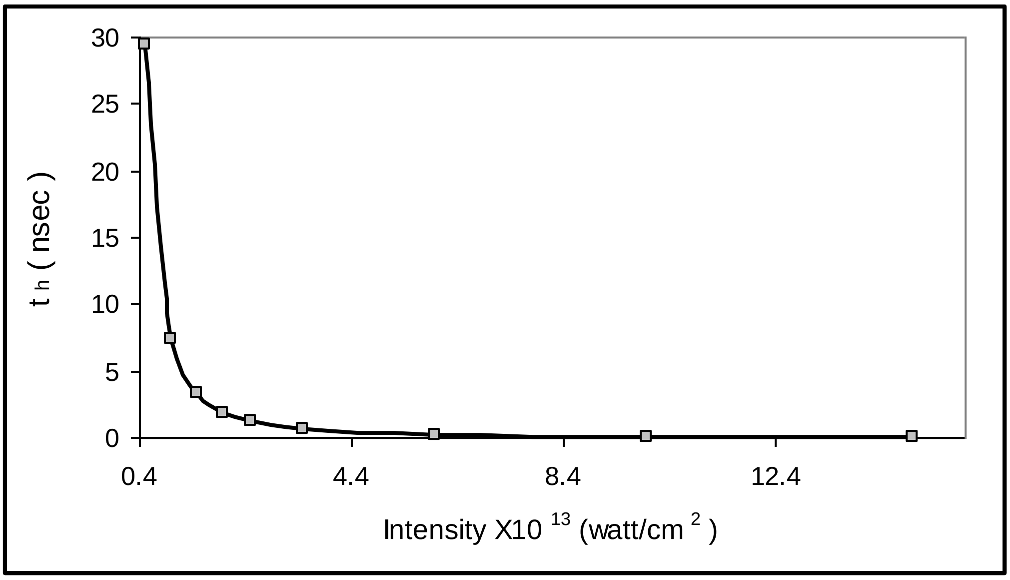


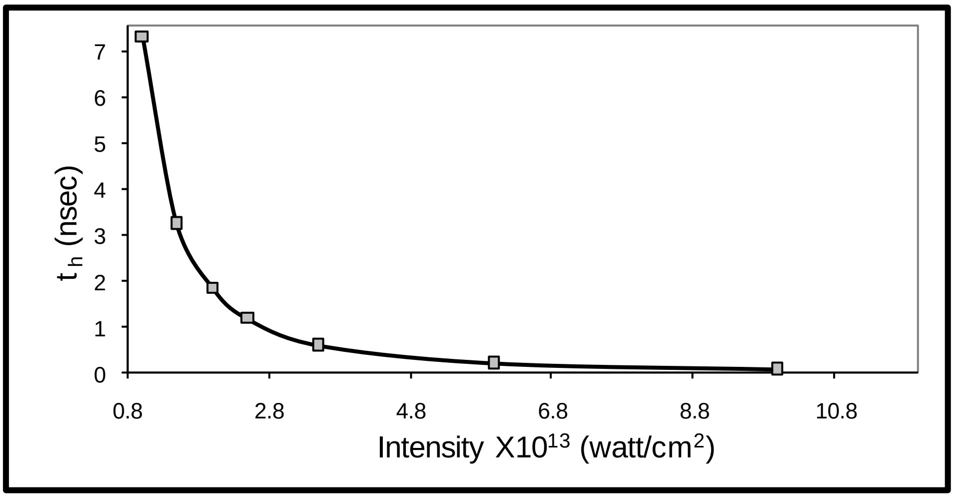
(e)

Fig.(5) the time of drilling stage (t) for a Hastelloy-X at different values of :

(a) – number of shots.
(b) – distance to focus.
(C) – fluence .
(d) – laser intensity when the sample in front of the focus .
(e) – laser intensity when the sample behind the focus.

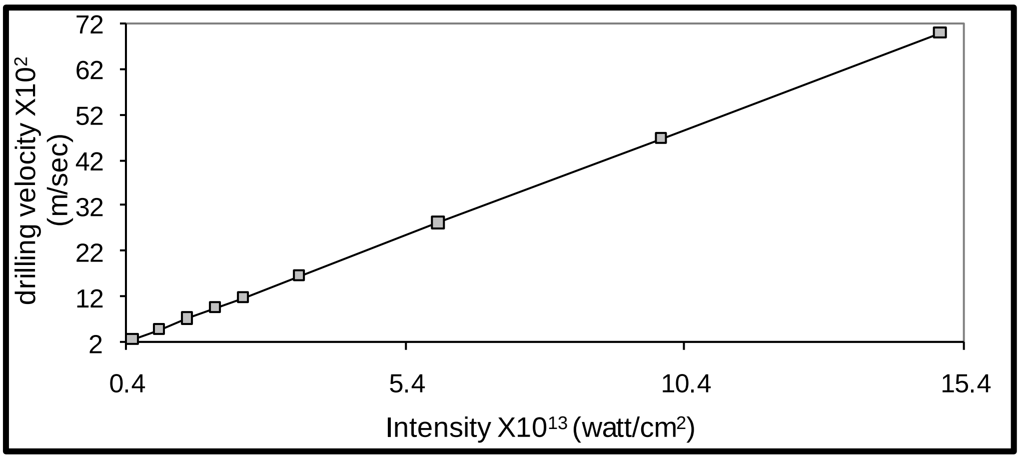


(a)



(b)

Fig.(6) The time of heating stage for a Hastelloy-X as a function of laser intensity when the sample
(a) – the sample in front of the focus.
(b) – the sample behind the focus .



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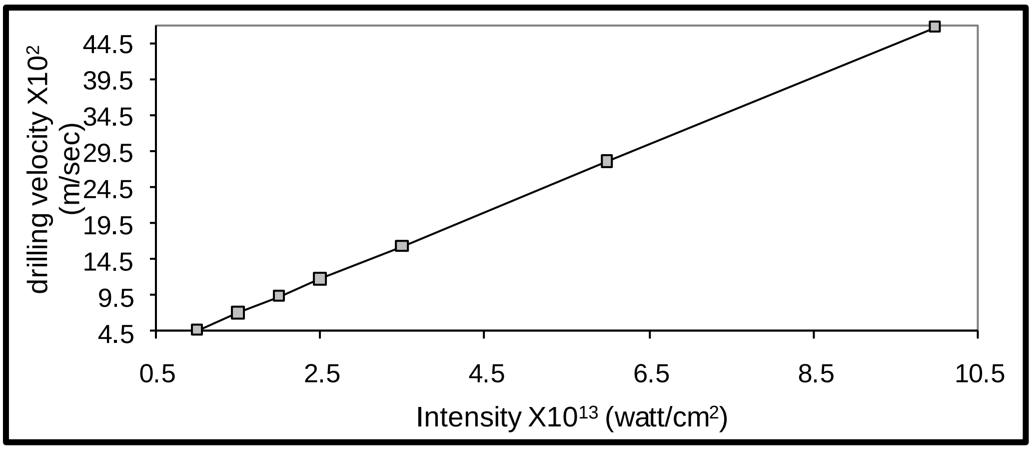
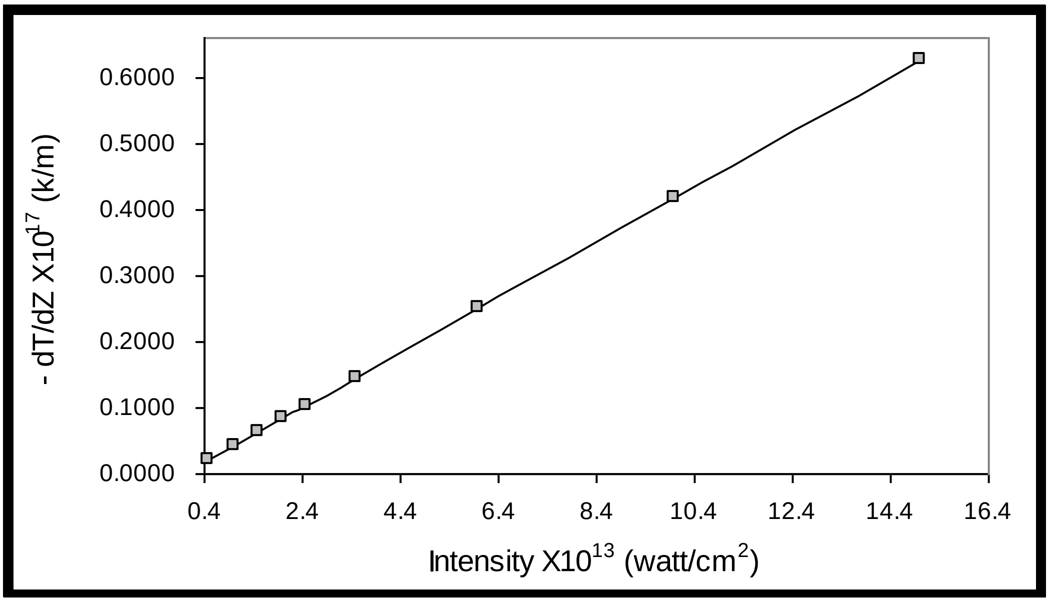


(b)

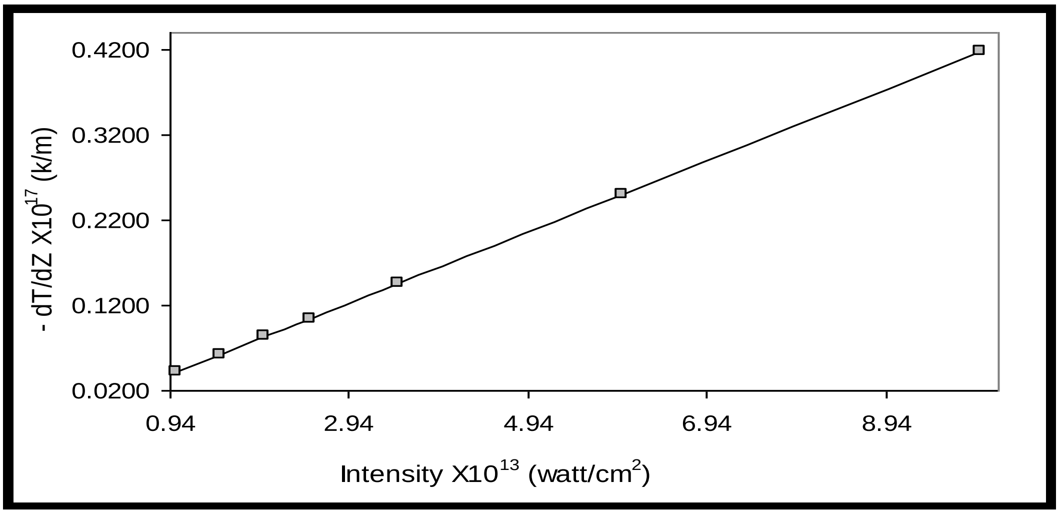
Fig.(7) The drilling velocity as a function of laser intensity when the sample :

(a) – in front of the focus .

(b) – behind the focus .

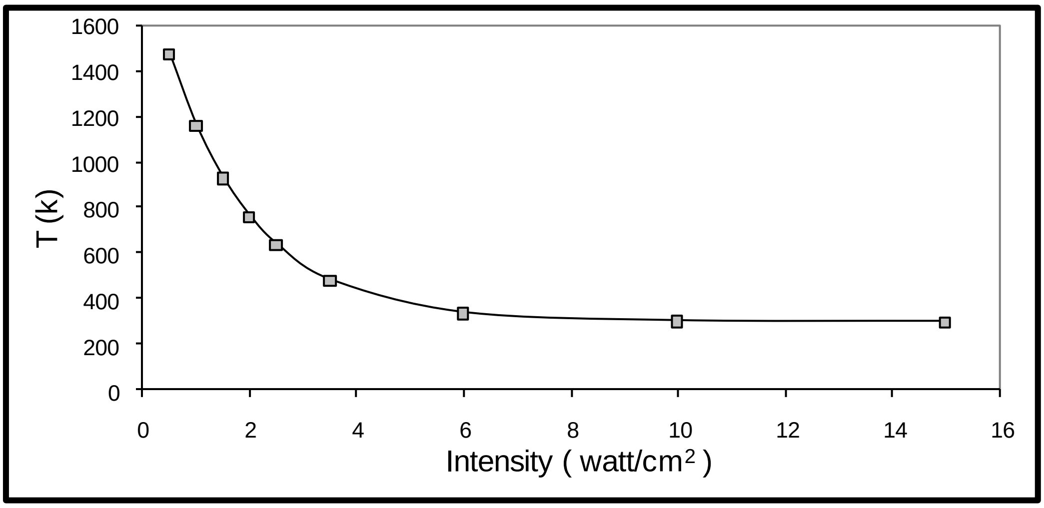


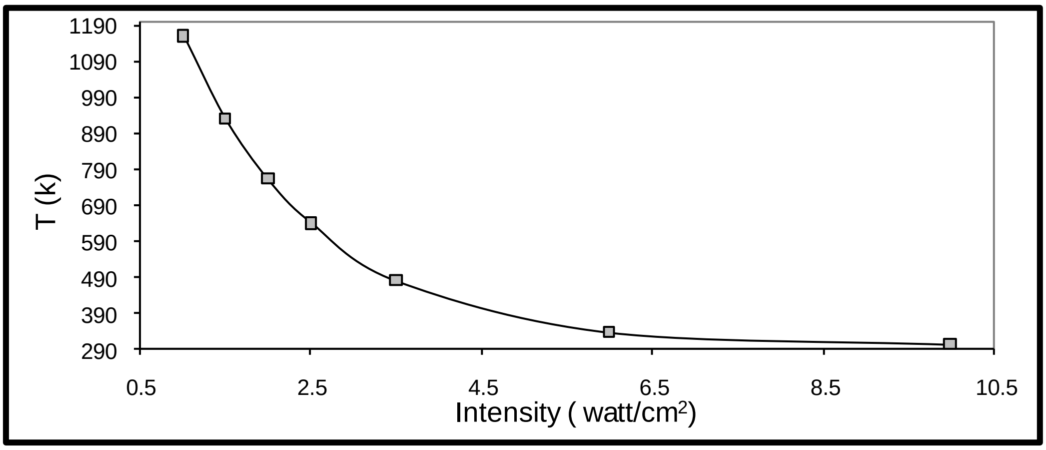
(a)



(b)

Fig.(8) Temperature gradient of a Hastelloy-X at different values of laser intensity when the sample
(a) – in front of the focus
(b) – behind the focus .

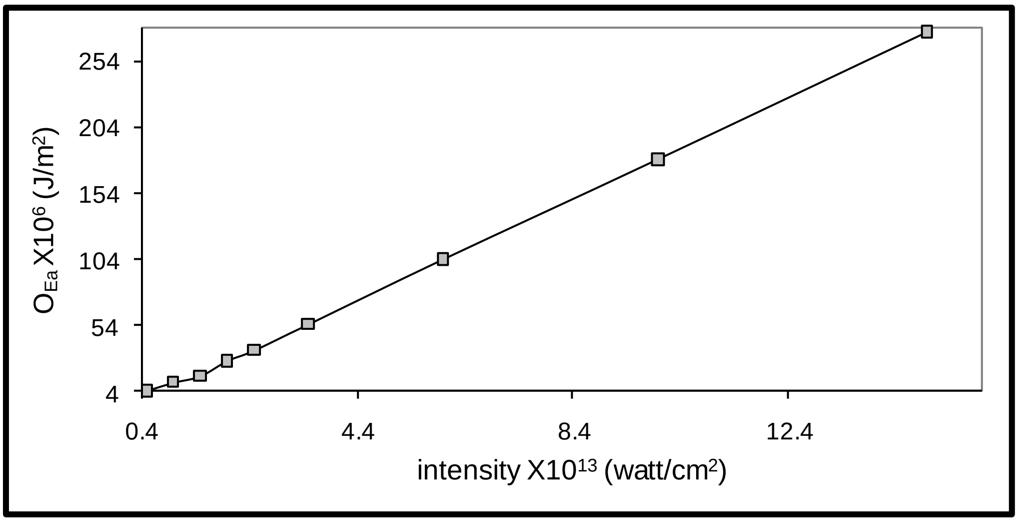




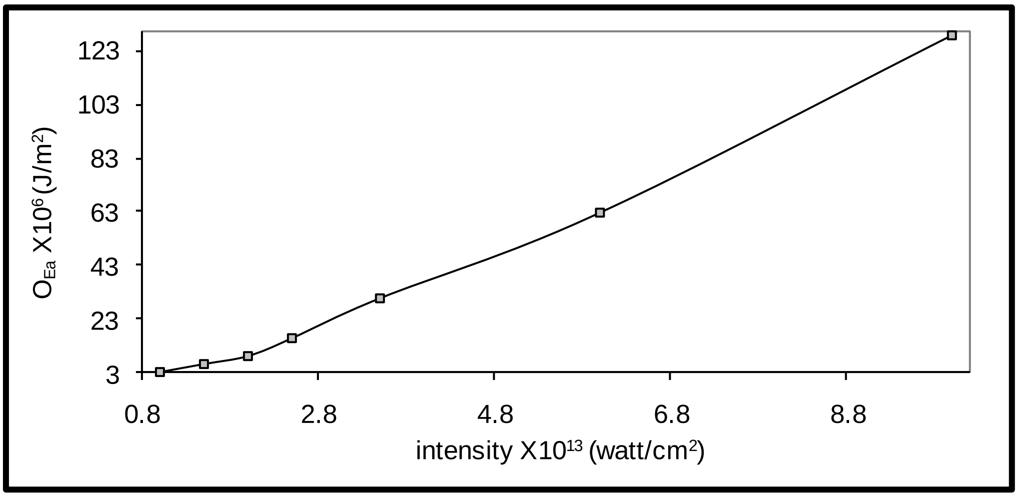
(b)

Fig.(9) The temperature of a Hastelloy-X surface as a function of intensity when the sample :
(a) – in front of the focus .

(b) – behind the focus .



(a)



(b)

Fig.(10) The energy flux absorbed by the metal surface as a function of intensity when the sample :
(a) – in front of the focus .
(b) – behind the focus .