The study of CO_2 laser welding for stainless steel

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Abstract:

The laser welding process for (304) stainless steel by pulsed and continuous CO_2 laser ,had been studied , where all of (T,I(Z), β(t), υ, $\upsilon_{welding}$, Q_h, Q_m, Q_v and Q_{tot}) had been calculated as function of each (pulse speed at different repetition rates , pulse width) for pw-CO_2 laser and as a function of thickness at different values of incident laser power for cw-CO_2 laser. The pulsed CO_2 laser welding had been compared with continuous CO_2 laser welding and we found that the pw-CO_2 at high repetition rate is the best in welding process achieving because of highest values of welding efficiency .As well as , the using of high power laser fasten welding process. It can be concluded that the keyhole welding is more useful than spot welding because of it's highest value of each of welding speed ($\upsilon_{welding}$) and welding efficiency (ξ).

الخلاصة:

درست عملية اللحام الليزري للفولاذ المقاوم (304) بوساطة ليزر CO_2 النبضي والمستمر , حيث حسبت كل من (T, I(Z), β(t), υ, ξ, $\upsilon_{welding}$, Q_h , Q_m , Q_v, Q_{tot}) كدالة لكلاً من(سرعة النبضة عند معدلات تكرار مختلفة , أمد النبضة) لليزر النبضي وكدالة للسمك عند قدرات ليزرية ساقطة مختلفة لليزر المستمر . قورن اللحام الليزري بوساطة ليزر النبضي باللحام الليزري بليزر CO_2 المستمر , ووجدنا أن ليزر CO_2 النبضي عند معدلات تكرار عالية هو الأفضل في انجاز عملية اللحام بسبب القيم العالية لكفاءة اللحام .بالإضافة إلى أن استخدام ليزر بالقدرة العالية يسرَع عملية اللحام . يمكن الاستنتاج أن لحام ثقب المفتاح مفيد أكثر من لحام البقعة بسبب القيم العالية لكلاً من سرعة اللحام ($\upsilon_{welding}$) وكفاءة اللحام (ξ).

Keyword: CO_2 laser , industrial applications, welding

Introduction:

Laser welding has gained considerable acceptance in the automotive industry because it provides several advantages over other joining processes. Benefits include high productivity , good flexibility , and low maintenance and energy costs along with the ability to produce strong welds [1].

The laser welding process on ferritic stainless steel has been achieved and compared with electron beam welding on same alloy in 1989 [2] . J.O.Milewski,et al , are fabricated and assembled a fiber optic delivered Nd:YAG 1KW laser [3] , while J.A.Hamill and P.Wirth are investigated that powder metallurgy materials require special consideration and should not be laser welded using standard wrought steel parameters in 1994 [4]. In the same year , the preliminary data on weld speeds that can be achieved for both cw and pulsed multi-kilo watt CO_2 and Nd:YAG laser weld configurations subject to the constraint of material fit up requirements , has been provided [5].

In 1995 , D.Favez ,et al , present a study aimed to probe the potential of laser beam joining of dissimilar metals used in jewelry [6]. Pulsed Nd:YAG laser beam welding experiment were carried out on 304 stainless steel , using vertical and horizontal electric fields of different intensities to study its effectiveness on the welding process , regarding depth and weld quality [7]. A detailed investigation was performed to quantify the benefits of dual- beam laser processing and to understand the mechanism for improving weld quality [8]. A model for the transient behavior of the front keyhole wall is developed , and it is assumed that keyhole propagation is dominated by evaporation-recoil-driven melt expulsion from the beam interaction zone [9].

Thermal diffusivity and thermal conductivity of 304 stainless steel have been estimated using 2D and 3D moving heat source solutions to the conduction heat flow equation [10]. A 20 KW average power of the combined beam from cw COIL laser and pw Nd:YAG laser , was used to achieve the welding of 20 mm penetration on the stainless steel at a 1m/min welding speed [11] , while the high power cw CO_2 laser utilized in the welding process for thin sheets 304 stainless steel , was estimated using the experimental results and the dimensionless parameter model for laser welding , and also the energy balance equation model[12].

In 2003 , C.Eijk,et at , were concluded that the fusion welding of stainless steel show no compositional variation of the material through the weld , while the mechanical properties are significantly deteriorated after welding [13] . There was a conclusion that the composition of 304 stainless steel had been changed when it was welded by millisecond long Nd:YAG laser pulses [14] . Lastly , G.Kelkav , and N.Ball are compared and contrasted bon formation at the weld interface for laser and resistance welding and its effect on related factors such as part design and materials selection , in 2007 [15].

We are aimed from this research to study the changing each of pulse speed , pulse width , and thickness of stainless steel on laser welding mechanism by CO_2 laser .

Theory:

Laser welding is a powerful new joining technology [16] , and it is now a common production line manufacturing process in many areas of industry , notably the automotive , domestic goods , and electronics sectors [17] .

Laser welding represents a delicate balance between heating and cooling with in a spatially localized volume overlapping two or more solids such that a liquid pool is formed and remains stable until solidification . The objective of laser welding is to produce the liquid melt pool by absorption of incident radiation , allow it to grow to the desired size , and then to propagate this melt pool through the solid interface eliminating the original seam between the components to be joined [18].

There are two fundamental modes of laser welding : (1) conduction welding , and (2) keyhole or penetration welding . Under conduction limited conditions , the onset of surface melting can be estimated from the simple model . The temperature at the center of the beam focus [19] :

$$T(0,t) - T_0 = \frac{AI_0\omega}{K(2\pi)^{1/2}} \tan^{-1}\left[\frac{8kt}{\omega^2}\right]^{1/2} \ldots\ldots\ldots\ldots\ldots(1)$$

Where K is the thermal conductivity , k is thermal diffusivity , ω is the Gaussian beam radius , T_o is the ambient temperature , and (t) is the time of welding achieving , and (A) is the material absorptance.

An estimate of the depth of penetration (Z) , of the weld pool under spot welding conditions in which melting is included can be obtained , when consider (t_m) as the time at which $T_o(Z)=T_m$ [19]:

$$Z \cong \frac{0.16AI}{\rho L_m}(t - t_m) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where (ρ) is the density of the melt and (L_m)is the latent heat of fusion .

But the formation of a keyhole is of fundamental importance for penetration welding, which begins with vaporization at the surface of a weld pool. For a planar surface and an incident beam with a Gaussian intensity profile , then :

$$T_{\nu}-T_{O}=\frac{A_{\nu}I_{O}\omega}{K_{\nu}(2\pi)^{1/2}}\tan^{-1}\left[\frac{8k_{\nu}t}{\omega^{2}}\right]^{1/2}\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where the subscripts refer to values at or near the vaporization temperature . the linear vaporization rate (υ) is related to vapor pressure P(T) , as follows :

$$\nu=P(T)\left[\frac{\bar{m}}{2\pi K_{B}T}\right]^{1/2}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where m^{-} is the average mass of an evaporation , K_B is Boltzmans' constant , and T(K) is surface temperature . The vapor pressure is given by the Clausius – Clapeyron equation :

$$P(T)=P(T_{B})\exp\left[\frac{\bar{m}L\nu}{\rho K_{B}}\left(\frac{1}{T_{B}}-\frac{1}{T}\right)\right]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where (T_B) is the boiling temperature , and (L_υ) is the latent heat of vaporization . The linear vaporization rate is [19] :

$$\nu=\frac{\beta(T)}{\rho}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

For optimal vaporization , The mass evaporation rate (β) must be equal to that limited by conservation of energy . Then :

$$\frac{\beta(T)}{\rho}=\frac{AI}{L_{m}+L_{\nu}+C(T-T_{0})}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Where (C) is the heat capacity , T_o is ambient temperature , L_m and L_υ are the latent heats of melting and vaporization , respectively , and $I(Z) = P_o/\pi\,\omega^2$, [18,19] .

$$I(z) = I_o\, e^{-AZ} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Under conditions of high traverse rate , typical of laser beam welding , then the temperature distribution in a plate around a moving , though thickness line heat source , which is a realistic approximation of the keyhole produced during single pass laser beam welding can be written explicitly as :

$$T-T_{O}=\frac{Q}{\nu_{welding}d(4\pi K\rho Ct)^{1/2}}\exp-\left(\frac{r^{2}}{4kt}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

Where (T) is temperature , (T_O) is initial temperature , Q is absorbed laser beam power , ($\upsilon_{welding}$) is welding speed , (d) is plate thickness and (R) is the lateral distance from the weld centerline .
By differentiating equation (9) with respect to time , and noting that at the peak of the temperature cycle dT/dt = 0 , an equation describing the variation of peak temperature (T_P) with lateral distance from the weld centerline is obtained as follows :

$$T_P - T_O = \left(\frac{2}{\pi e}\right)^{1/2} \frac{Q}{2\nu_{welding} d\rho C r} \text{..................}(10)$$

Re arrangement of equation (9) gives :

$$Q = 2\nu_{welding} d\rho C r \left(\frac{\pi e}{2}\right)^{1/2} (T_m - T_O) \text{..........................}(11)$$

The laser beam power used to heat the material (Q_h) is characterized as that used to increase the temperature at the fusion line to the melting temperature , and is given by :

$$Q_h = \frac{\nu_{welding} d^2 \rho C}{4} \left(\frac{\pi e}{2}\right)^{1/2} \left(T_m - T_O\right) \text{...................}(12)$$

The power used to form the molten weld pool (Q_m) is obtained from a heat balance based on the geometry of the weld bead and the latent heat of melting (L_m) as :

$$Q_m = \frac{\nu_{welding} d^2}{4} L_m \text{...........................}(13)$$

The power used to vaporize the keyhole cavity (Q_υ) can be estimated by assuming the keyhole to be a cylinder of diameter of the focused laser beam , and length equal to the plate thickness . A heat balance gives :

$$Q_\nu = 2\nu_{welding} d\omega L_\nu \text{.........................}(14)$$

Where

$$\nu_{welding} = \frac{x}{t} \text{..................}(15)$$

Where (x) is the weld width , (L_υ)is the latent heat of vaporization and (t) is the time of laser welding process which is equal to

$$t = t_h + t_m + t_v + t_c \quad \text{…………………} (16)$$

Where $t_h = (\pi / k) \, [\, (K(T_m - T_o))/2I_o]^2$ ………….. (17)

$$t_m = [\pi^3 \omega^4 K^2 T_m^{\,2}]/[4\alpha^2 P_o^{\,2} k] \text{ …………..} (18)$$

$$t_v = [\pi^3 \omega^4 K_v^{\,2} T_v^{\,2}]/[4\alpha^2 P_o^{\,2} k_v] \text{ …………..} (19)$$

$$t_c = (\alpha^{-1})^2/k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(20)$$

By assuming that power is used only for heating , melting , and vaporization , the total beam power (Q) can be expressed as [17,20] :

$$Q_{tot} = Q_h + Q_m + Q_v \ldots\ldots\ldots\ldots\ldots\ldots(21)$$

While the melting efficiency of the work piece surface is defined as [21]:

$$\xi = \frac{v_{welding} d \omega L_m \rho}{P} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(22)$$

Experimental setup :

The experimental setup , schematically shown in fig.1 , was used to measure welding speed , weld width , laser power absorbed at many values of 304 stainless steel sheet thickness . |It consists of an indigenously developed transverse flow cw CO_2 laser integrated with a laser beam delivery system and a computer controlled x-y coordinate table . The focal length of the lens is (100mm) and the spot size of the focused laser beam at the metal sheet surface is about (300 µm) . Fig.2 –(a,b,c) shows the transverse cross-section of the weldment of 304 stainless steel sheet of (1.2mm , 0.5 mm , , and 0.1 mm thickness , respectively [12].

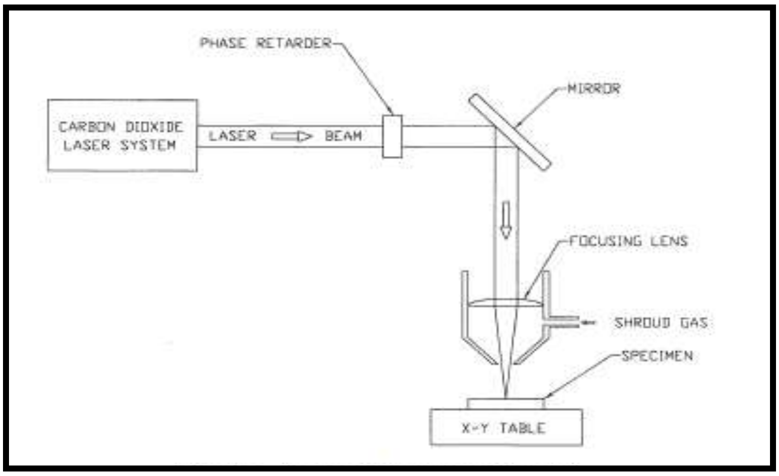
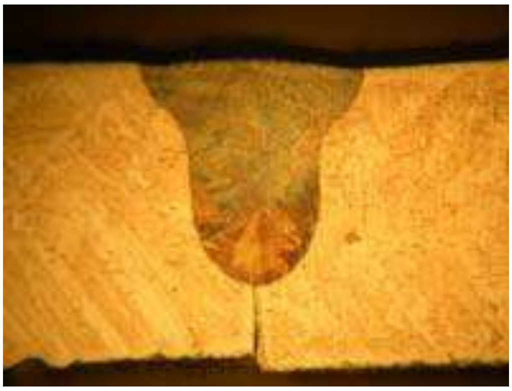


Fig.(1)
The laser welding system [12]

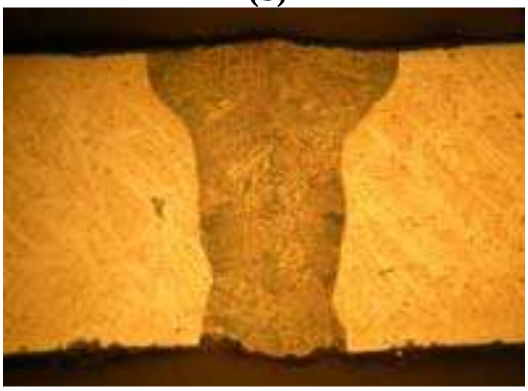
The other procedure is to determine weld penetration depth into (1.22 mm) thick 304 stainless steel at various pulse widths . Where the beam delivery from the spot welding . Setup consisted of a 101.6 mm focusing lens that produces a (0.13 mm) diameter spot with a (3.1 mm) depth of focus . At a power level of (400 watts) , the pulses of (5,10, 20,40, and 80)ms , were fired into the stainless steel . Fig.3-(a,b,c) shows the shape of spot welds at (400 watt) of CO_2 laser welding for stainless steel [22].

A keyhole welding was implemented on (1.22 mm) thickness of 304 stainless steel using (500 watt) power of CO_2 laser . The laser spot size on the sheet is (0.5 mm) . The aim of this procedure is to measure the weld width , and the penetration at different laser pulse speed values [19,23]. Figs.4-(a,b,c,d,e,f) show the shape of welds on (0.5 mm) stainless steel at a (3.8,5.1,6.3,7.8,8.9, and 11.4) m/sec laser pulse speed , respectively .



(a)

(b)



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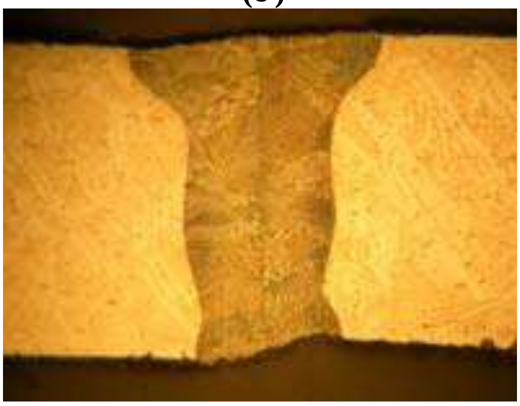
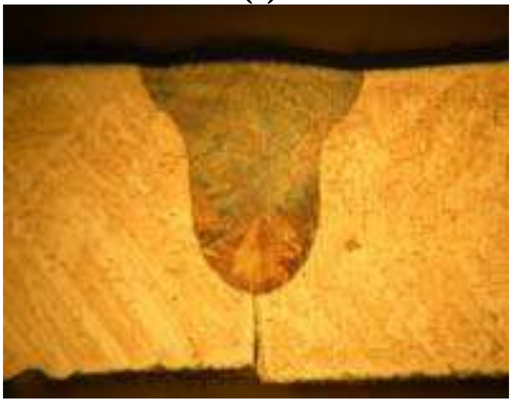


(d)

(e)

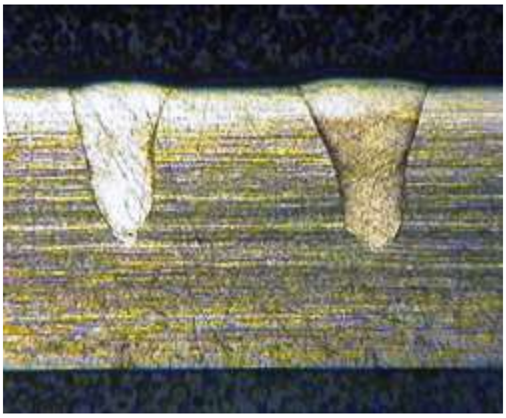


(f)

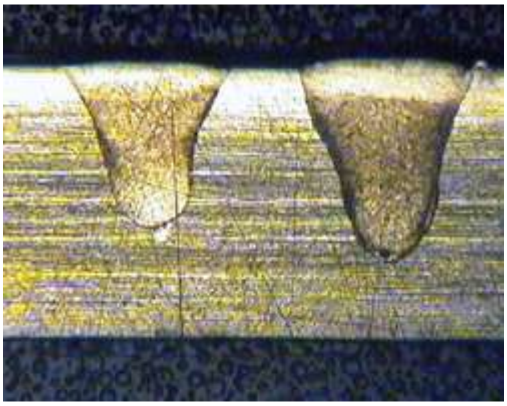
Fig.2

The shapes of weld pool in stainless steel of (1.22mm) thickness which is welded by (500 Watt) pw-CO_2 laser of (0.5mm) spot on metal surface [keyhole welding] [19]at different pulse speed as :

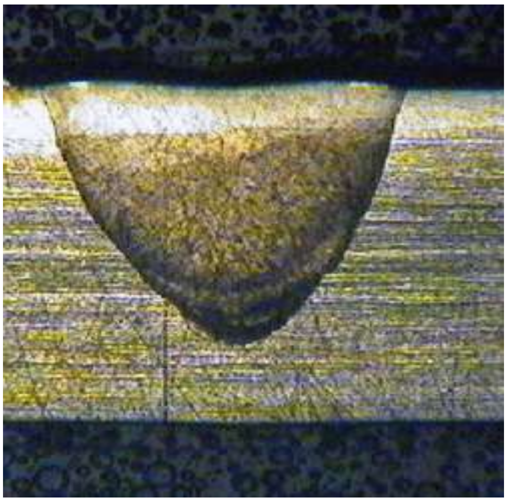
(a) 6.3 m\min pulse speed (b) 5.1 m\min pulse speed
(c) 3.8 m\min pulse speed (d)11.4 m\min pulse speed
(e) 8.9 m\min pulse speed (f) 7.8 m\min pulse speed



(a)

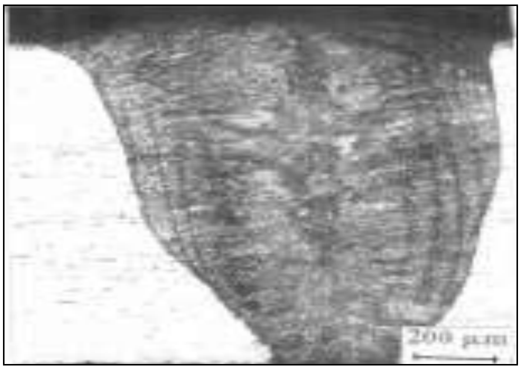


(b)

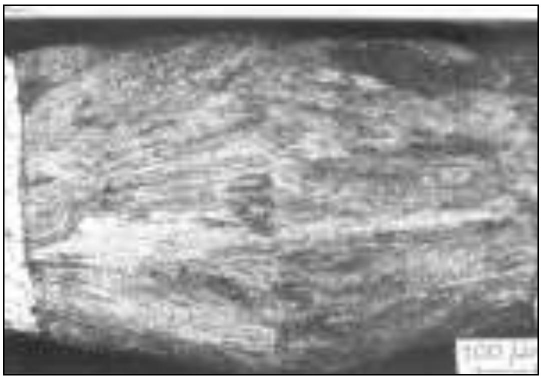


(c)

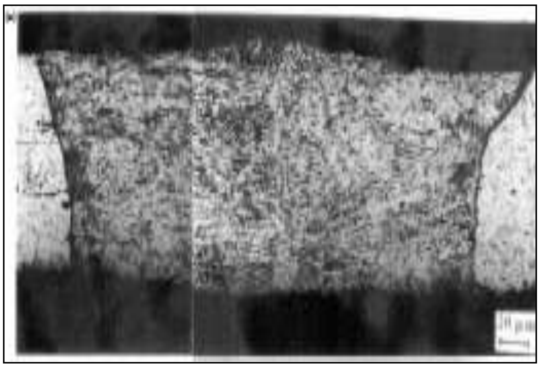
Fig.(3)
The shape of spot welds for stainless steel of (1.22mm) thickness at (400watt) of pw- CO_2 laser of 0.13mm) spot diameter on metal surface [spot welding] [22] which has duration of :
(a) 5msec and 10 msec (b) 20 msec and 40 msec (c) 80 msec



(a)



(b)



(c)

Fig.4:
The shape of weldment of 304 stainless steel which is welding by cw-CO_2 laser and 30µm spot laser on metal surface [spot welding] [12] where :
(a) 1.2 mm thickness and 2250 Watt laser
(b) 0.5mm thickness and 1700 Watt laser (c) 0.1 thickness and 1200 Watt laser mm

We must notice that the type 304 stainless steel is often used in food processing , chemical storage , and hospital equipment because it withstands corrosion .It is also a valuable material for containers used to store liquefied gases and for equipment used at cryogenic temperatures . In most of these applications , laser welding can be used to process the type 304 stainless steel [24,25].

The properties of 304 stainless steel is summarized in table (1-a,b) .

Table 1 :
The properties of 304 stainless steel [14,24-29]
- a –
Composition of 304 stainless steel

Alloying element	Mn	Cr	Ni	Si	C	P	S	Fe
Wt %	1	18.1	8.6	0.69	0.046	0.012	0.003	balance

- b –
Other properties data which will be used for calculations

property	*value*	*property*	*Value*
Density of liquid metal (kg/m^3)	$7.2x10^3$	Effective thermal conductivity of liquid (J/ms.K)	209.3
Absorption coefficient	0.27	Density of solid(kg/m^3)	$7.93x10^3$
Solidus temperature (K)	1697	Latent heat of evaporization(J/kg)	$6.1x10^6$
Liquidus temperature (K)	1727	Latent heat of melting(J/kg)	$2.73x10^5$
Specific heat of solid (J/kg.K)	711.8	Melting temperature(K)	1685
Specific heat of liquid (J/kg.K)	837.4	Vaporization temperature (K)	2910
Thermal conductivity of solid (J/ms.K)	19.26	Critical temperature (K)	4074

Calculations and results :

Each of laser intensity absorbed by metal I(z) , metal surface temperature (T), mass evaporation rate (β) , the linear vaporization rate (υ) , total laser power required to achieve welding (Q_{tot}) and welding efficiency (ξ) , have been calculated using Eqs.(8,10,7,6 and 21-22), respectively and drawn as functions of pulse speed , pulse width , and sheet thickness in Figs.(5-10)-a,b,c, respectively, where (T_o) has been taken in (300 K) .

While welding speed ($\upsilon_{welding}$) , laser power which is required to heating (Q_h), melting (Q_m) , and evaporation (Q_v) and penetration (Z) , were calculated using Eqs.(15, 12,13 and 14) , respectively, at different values of pulse speed at (10,25,100) kHz repetition rates , pulse width , and thickness , as listed in tables (2-a,b,c,and (3,4),respectively .

The time of laser welding achieving (t) has been calculated using Eqs.(16-20) and we found that (t = 3.10732 sec) for (1.22mm) stainless steel thickness welded by (500 Watt) pw-CO_2 laser at different pulse speed and repetition rates , (t= 327.9335 sec) for (1.22mm) stainless steel thickness welded by (400 Watt) pw-CO_2 laser at different pulse width and (t= 0.2545 sec) for (different values of thickness) stainless steel welded by (different values of power) cw-CO_2 laser .

It is important to notice that the dependent data in these calculations , are listed in appendix (1-3) . Where appendix(1) shows the dependent (penetration (z) , weld width)data at (t = 3.10732 sec) welding time and different values of pulse speed at (10,25,100)kHz repetition rate [19]. While appendix(2) shows the dependent (penetration (z) , weld width)data at (t =327.9335 sec) welding time and different values of pulse width [12] . Lastly , appendix(3) shows laser power incident , laser power absorbed , and weld width at (t= 0.2545 sec) welding time and different values of sheet thickness [22].

Table (2)

The absorbed intensity (I(Z)), surface temperature (T) ,welding speed ($\upsilon_{welding}$) , linear evaporation rate (**υ**), mass vaporization rate (**β**),the total heat required to heating ,melting and evaporation (Qtot = Q_h,Q_m,and Q_v)and welding efficiency (ξ) at (t = 3.10732 sec) welding time and different values of pulse speed (m/min) ,and repetition rate is :(a)- 10 kHz (b)- 25 kHz (c) – 100 kHz

-a –

Pulse speed m\min	I(Z) $x10^{8}$ Watt/m^2	T $X10^{15}$ K	$\upsilon_{welding}$ $x10^{-3}$ m/sec	υ $X10^{-14}$ Kg/m^2.sec	β $x10^{-11}$ Kg^2/m^5.sec	Q_h $X10^{-13}$ Watt	Q_m $X10^{2}$ Watt	Q_v Watt	Q_{tot} Watt	ξ %
12.5	11.436	-	-	-	-	-	-	-	-	-
11.25	10.608	551.0833	0.0514	0.175342	1.390483	2997607.5	0.41405	3.0333	44.438	13.9
10.00	10.162	551.0835	0.0643	0.175338	1.390414	3749925.4	0.517968	3.794	55.590	18.5
8.75	9.031	551.0838	0.0772	0.175336	1.390383	4502243.3	0.621884	4.555	66.743	20.38
7.5	8.468	551.0843	0.0965	0.175338	1.390367	5627804.1	0.777355	5.6949	83.430	25.48
6.25	7.287	551.0846	0.1158	0.175337	1.390358	6753364.9	0.9328269	6.8339	100.11	30.58
5.0	6.406	551.085	0.1512	0.175332	1.390339	8817865.1	1.2179916	8.92306	130.72	39.93
3.75	6.007	551.0853	0.1930	0.17533	1.390299	11255608	1.554711	11.3898	166.86	50.97
2.5	5.754	551.0857	0.2156	0.175307	1.39026	12573622	1.736765	12.7236	186.4	56.94
1.25	5.059	551.0864	0.3057	0.175297	1.390235	17828183	2.4625663	18.0408	264.29	80.74

-b-

Pulse speed m\min	I(Z) $x10^{18}$ Watt/m^2	T $X10^{15}$ K	$\upsilon_{welding}$ $x10^{-3}$ m/sec	υ $X10^{-14}$ Kg/m^2.sec	β $x10^{-11}$ Kg^2/m^5.sec	Q_h $X10^{-13}$ Watt	Q_m $X10^{2}$ Watt	Q_v Watt	Q_{tot} Watt	ξ %
12.5	10.722	-	-	-	-	-	-	-	-	-
11.25	9.840	551.0838	0.0933	0.175372	1.390529	5441182.6	0.90729	5.5060	96.235	24.64
10.00	9.326	551.0839	0.0965	0.175368	1.390534	5627804.1	0.77735	5.6949	83.43	25.48
8.75	8.112	551.0844	0.1158	0.175363	1.390532	6753364.9	0.93282	6.833	100.116	30.584
7.5	7.771	551.0849	0.1222	0.175361	1.390534	7126607.9	0.98438	7.211	105.649	32.27
6.25	6.906	551.0852	0.1383	0.175357	1.390534	8065547.2	1.11407	8.161	119.569	36.52
5.0	6.072	551.0855	0.1737	0.175355	1.390504	10130047	1.3992	10.25	150.174	46.87
3.75	5.754	551.0861	0.2124	0.175348	1.390479	12387001	1.71098	12.53	183.633	56.09
2.5	5.391	551.0865	0.2317	0.175348	1.390453	13512561	1.8664	13.673	200.319	61.19
1.25	4.170	551.0869	0.3218	0.175344	1.390448	18767123	2.5922	18.991	278.217	84.99

-c –

Pulse speed m\min	I(Z) $x10^{18}$ Watt/m^2	T $X10^{15}$ K	$\upsilon_{welding}$ $x10^{-3}$ m/sec	υ $X10^{-14}$ Kg/m^2.sec	β $x10^{-11}$ Kg^2/m^5.sec	Q_h $X10^{-13}$ Watt	Q_m $X10^{2}$ Watt	Q_v Watt	Q_{tot} Watt	ξ %
12.5	9.840	-	-	-	-	-	-	-	-	-
11.25	9.326	551.0842	0.1126	0.175391	1.39066	6568493	0.9072	6.646	97.375	29.74
10.00	8.839	551.0845	0.1126	0.175386	1.390648	6568493	0.9072	6.646	97.375	29.74
8.75	7.525	551.0851	0.1287	0.175382	1.390644	750684.9	1.0369	7.596	111.286	33.99
7.5	7.132	551.0856	0.1448	0.17538	1.390644	8445205.3	1.1665	8.545	125.197	38.24
6.25	6.406	551.086	0.1609	0.175379	1.390631	9384144.7	1.2962	9.496	139.117	42.49
5.0	5.754	551.0863	0.1930	0.175381	1.390642	11260857	1.5554	11.39	166.938	50.99
3.75	5.449	551.0866	0.2252	0.175382	1.390639	13133486	1.81409	13.29	194.699	59.47
2.5	4.643	551.087	0.2574	0.175379	1.390656	15011365	2.0734	15.19	222.538	67.98
1.25	3.746	551.0875	0.4183	0.175377	1.390602	24394927	3.3696	24.68	361.647	110.74

Table(3)

The calculated values of each of $(I(Z)),\upsilon,\upsilon_{welding},Q_h,Q_m,Q_v,\xi$) at (t= 327.9335 sec) welding time and different values of laser pulse width .

Pulse width (msec)	I(Z) $x10^{11}$ (Watt/m^2)	T $X10^{13}$ K	$\upsilon_{welding}$ $X10^{-6}$ m/sec	υ $X10^{-10}$ Kg/m^2.sec	β $x10^{-7}$ Kg^2/m^5.sec	Q_h $X10^{-6}$ Watt	Q_m $X10^{-3}$ Watt	Q_v Watt	Q_{tot} Watt	ξ %
80	5.635	541007.4	7.022	37.828	7.082819	0.0153	2.063	302.32	302.3241	33.8
40	5.946	541007.4	5.905	37.837	7.082819	0.012	1.621	237.54	237.5488	25.8
20	6.619	540996	6.352	37.859	7.082818	0.0111	1.498	219.54	219.5491	24.7
10	6.984	540995.2	4.877	37.872	7.082804	0.0078	1.056	154.76	154.762	17.3
5	6.84	540994.6	4.484	37.887	7.082804	0.0065	0.884	129.56	129.5624	14.4

Table(4)

The calculated values of each of $(I(Z),Z,\upsilon,Q_h,Q_m,Q_v,\xi)$ at (t= 0.2545 sec) welding time and different values of sheet thickness

Sheet thickness (mm)	I(Z) $x10^{11}$ (Watt/m^2)	Z mm	T $X10^{21}$ K	$\upsilon_{welding}$ $X10^{-3}$ m/sec	υ $X10^{-3}$ Kg/m^2.sec	β $x10^{-11}$ Kg^2/m^5.sec	Q_h $X10^9$ Watt	Q_m $X10^8$ Watt	Q_v $X10^3$ Watt	Q_{tot} $X10^8$ Watt	ξ %
1.55	7.959	0.409	149.12	0.51072	0.8100	6.4239	2.062	11.056	42.122	31.68	22.3
1.2	7.96	1.682	192.61	0.3928	0.6271	4.9735	1.586	8.5036	25.081	24.36	13.6
1.0	6.369	1.669	231.13	0.3928	0.4181	3.3156	1.586	8.5036	20.901	24.36	14.1
0.5	6.015	1.749	462.27	0.3339	0.2787	2.2104	1.348	7.2285	8.8834	20.71	6.37
0.1	4.246	1.794	426	0.1571	0.1974	1.5657	0.6344	3.4010	0.8359	9.745	0.85

Discussion:

When the pulse speed of (400)Watt (pw-CO_2) laser is increased , each of penetration depth (Z) and weld width (X) are decreased as shown in Appendix(1) .This refers to the incident laser intensity has been enormously absorbed by metal (high I(Z))as shown in Fig.(5-a) and increasing in each of mass evaporation rate (β) and linear vaporization rate (υ) as in Fig.(7-a) and Fig.(8-a),respectively. As we Know , the vaporization process is energy absorbed process ,then the metal surface temperature (T) has been decreased ,as in Fig.(6-a) .This is decreases the magnitude each of penetration depth (Z) and weld width (X) , that leads to low abundant heat quantity to completely laser welding process achieving (low Q_{tot}) as in Fig.(9-a) and makes each of ($\upsilon_{welding}$, ξ) low as in Fig.(10-a) .

The increasing of pw-CO2 laser repetition rate at same pulse speed , each of penetration depth (Z) and weldment width (X) are increased as shown in Appendix(1-a,b,c) . That means increasing the number of reached laser pulses to metal surface at same time , that causes metal surface heating (high (T)) as in Fig.(6-a) and increasing each of mass evaporation rate (β) and linear vaporization rate (υ) as in Fig.(7-a)and Fig.(8-a), respectively , while laser intensity absorbed by metal were decreased (low (I(Z))) as in Fig.(5-a). The high heat quantity on metal surface lead to high abundant heat quantity (high Q_{tot}) as in Fig.(9-a) ,which accelerates the laser welding process achieving (high $\upsilon_{welding}$) as explained in table (2-a,b,c) and improving the welding efficiency (ξ)as in Fig.(10-a)because of increasing each of weldment properties (Z and X) as in Appendix (1-a,b,c) .

The welding of stainless steel of (1.22 mm) thickness has been achieved by (400 Watt)(pw-CO_2) laser at (t= 327.9335 sec) , the increasing of laser pulse width leads to increasing each of (Z and X) as in Appendix(2) . This can be explained by that the increasing of laser pulse width means increasing in (FWHM) causes decreasing laser intensity decreasing (low I(Z)) as in Fig.(5-b) . the high laser pulse width gives more heat quantity to metal which increases (T) as in Fig.(6-b) and each of (β) and (υ) as shown in Fig.(7-b) and Fig.(8-b) , respectively. This makes the heat quantity to achieve welding and each of ($\upsilon_{welding}$ and ξ), too high as explained in Fig.(9-b) ,table (3) and Fig.(10-b), respectively .

For study the effects of metal thickness variation in welding process , the laser power must be varied also ,as shown in Appendix(3) . Table (4) explained that the highest value of metal thickness leads to decreasing in (Z) and increasing in (X) as shown in table(4) and Appendix(3) ,respectively. This can be interpreted by increasing incident laser power on the metal surface which was used by workers on laser welding for metals of large thickness and the absorbed laser intensity by metals (I(Z)) will be high as Fig.(5-C) .I(Z) causes an increasing in each of weldment width (X) as Appendix(3) , mass evaporation rate (β) as Fig.(7-C) , linear vaporization rate (υ)as Fig.(8-C) and ($\upsilon_{welding}$ and ξ)as table(4) and Fig.(10-C).The decreasing of penetration depth (Z)with increasing of metal thickness , in spite of high laser power used to welding, can be attributed to that the laser power were be used in mass evaporation of metal surface and increasing of weldment width (X) instead of penetration depth (Z) , decreasing in temperature of metal surface (T) as Fig.(6-C) .In the same time it makes heat quantity of laser welding (Q_{tot}) high as Fig.(9-C).

The best laser welding has been explained when (500Watt) pw-CO_2 laser at (1.25 msec)pulse width and (100kHz) repetition rate is used , where highest welding efficiency (ξ) of (110.7%) has been obtained by using it. While lowest (ξ) of (0.85%) has been obtained using (1200 Watt)(cw-CO_2) for stainless steel of (0.1mm) thickness .The pulsed laser with high repetition rates had been preferred in laser welding process because of it's high efficiency ,while the continues laser don't prefer until in highest laser power.

The highest ($\upsilon_{welding}$) is of (0.5107X10^{-3}m/sec) which be obtained using (2250 Watt)(cw-CO_2) at (t= 0.2545 sec) for stainless steel of (1.55mm) thickness as shown in table (4) , while low value of ($\upsilon_{welding}$) is of (0.00109 X10^{-3}m/sec) had been obtained using (400Watt)(pw-CO_2)laser of (5msec) pulse width at (t=327.93 sec) which is used to weld stainless steel of (1.22mm) thickness. The highest laser power is the best in the speed of welding (high $\upsilon_{welding}$).

A (1.2mm) which is the highest penetration depth (Z) , had been obtained in stainless steel of (1.22mm) thickness ,welded by (500Watt) (pw-CO_2) laser at (1.25m/min)pulse speed with (100kHz) repetition rate ,as shown in Appendix(1-a,b,c),while the lowest (Z) of (1.63X10^{-5} mm) had been obtained using (1200Watt)(cw-CO_2) laser for welding of stainless steel of (0.1mm)thickness. The highest penetration depth had been obtained using pulsed laser vise inverse of continuous which causes (Z) decreasing.

Appendix(3) shows the highest value of weldment width (X)of (1.3mm)in a stainless steel of (1.55mm) thickness using (2250Watt) (cw-CO_2) laser , while the lowest (X) of (0.84mm) in a stainless steel of (1.22mm) thickness , had been obtained using (400 Watt)(pw-CO_2) laser . The continuous laser enhances weldment width (X) and accelerates welding process , while the pulsed laser increases penetration depth and welding efficiency .

All the results listed in table (2-a,b,c) where the pulse speed was varied, was of (Keyhole welding) type , while the results in table (3) where the pulse width was varied , was of (Spot welding) type and all the results in table (4) where thickness was varied , was of (spot welding) type , except at (1.55mm)thickness which was of (Keyhole welding) type.

Conclusions:

For improving the efficiency of laser welding process , it is prefer to use pulsed laser with highest repetition rates until the pulse speed was law , where (110.7%) welding efficiency had been obtained using (500Watt)(pw-CO_2) laser with (100kHz) repetition rate , in spite of the pulse speed was too law of (1.25 m/min) , while the continuous laser had the lowest welding efficiency , where the lowest (ξ)of (0.85%) had been achieved using (1200 Watt)(cw-CO_2) for stainless steel . The pulsed laser causes an increasing in penetration depth (Z) inside the metal, where the highest (Z) of (1.2mm) had been achieved by (500Watt)(pw-CO_2)laser at (1.25 m/min) pulse speed and (100kHz) repetition rate , while the continuous laser causes decreasing in (Z) as ($1.63X10^{-5}$mm)obtained by cw-CO_2 laser of (1200 Watt) . The continuous laser enhances weldment width (X) upon penetration depth and increases ($\upsilon_{welding}$) as we notice that the highest (X)of (1.3mm) in (1.55mm) metal thickness had been obtained using (2250 Watt) (cw-CO_2)laser, the highest ($\upsilon_{welding}$) of ($0.5107X10^{-3}$m/sec) in (1.55mm) metal thickness at (2250 Watt)(cw-CO_2)laser . While the lowest (X) of (0.16mm) in (1.22mm)metal thickness had been obtained at (400Watt)(pw-CO_2)laser of (12.5 m/min pulse speed) at (10kHz) and lowest ($\upsilon_{welding}$) of ($0.00109X10^{-3}$m/sec) achieved for (1.22mm) metal thickness using (400Watt) (pw-CO_2)laser at (5msec) pulse width . The highest laser power accelerates welding achieving ($\upsilon_{welding}$) and enhances laser welding efficiency ,where high($\upsilon_{welding}$)of ($0.5107X10^{-3}$m/sec) had been obtained using (2250 Watt)CO_2 laser and (ξ) of (22.85%) , while ($\upsilon_{welding}$) of ($0.157X10^{-3}$m/sec) had been obtained using (1200Watt)laser and (ξ) of(0.85%) achieved in the same laser. The main conclusion is the pulsed laser with highest repetition rates is the best in laser welding than continuous and it was preferred to use highest laser power in laser welding .The welding efficiency (ξ) was rightly proportion with penetration depth (Z) , while welding speed ($\upsilon_{welding}$)was rightly proportion with weldment width (X) . The Keyhole welding is the best than spot welding where (110.7%)of (ξ) had been obtained in keyhole welding at (1.25 m/min pulse speed) ,while (0.85%) of (ξ) had been obtained in spot welding at (1200Watt)for (0.1mm)metal thickness .

Appendix(1) [19]

The dependent data in the calculations when pulse speed was variable at : 10KHz , 25 KHz , and 100 KHz .

Pulse speed m/min	At 10KHz		At 25 KHz		At 100 KHz	
	Penetration (mm)	Width (mm)	Penetration (mm)	Width (mm)	Penetration (mm)	Width (mm)
12.5	0.16	-	0.22	-	0.3	-
11.25	0.23	0.16	0.3	0.29	0.35	0.35
10.0	0.27	0.20	0.35	0.3	0.4	0.35
8.75	0.38	0.24	0.48	0.36	0.55	0.4
7.5	0.44	0.3	0.52	0.38	0.6	0.45
6.25	0.58	0.36	0.63	0.43	0.7	0.5
5.0	0.7	0.47	0.75	0.54	0.8	0.6
3.75	0.76	0.6	0.8	0.66	0.85	0.7
2.5	0.8	0.67	0.86	0.72	1.0	0.8
1.25	0.92	0.95	1.1	1.0	1.2	1.3

Appendix(2) [22]
The dependent data at variable pulse width were :

Pulse width (msec)	Penetration (mm)	Weld width (mm)
80	0.76	0.84
40	0.71	0.66
20	0.61	0.61
10	0.56	0.43
5	0.51	0.36

Appendix (3) [12]
The dependent data at variable sheet thickness were :

Thickness (mm)	Weld width (mm)	Laser power P_o (watt)	Power absorbed (watt)
1.55	1.3	2250	1450
1.2	1.0	2250	370
1.0	1.0	1800	300
0.5	0.85	1700	260
0.1	0.4	1200	175

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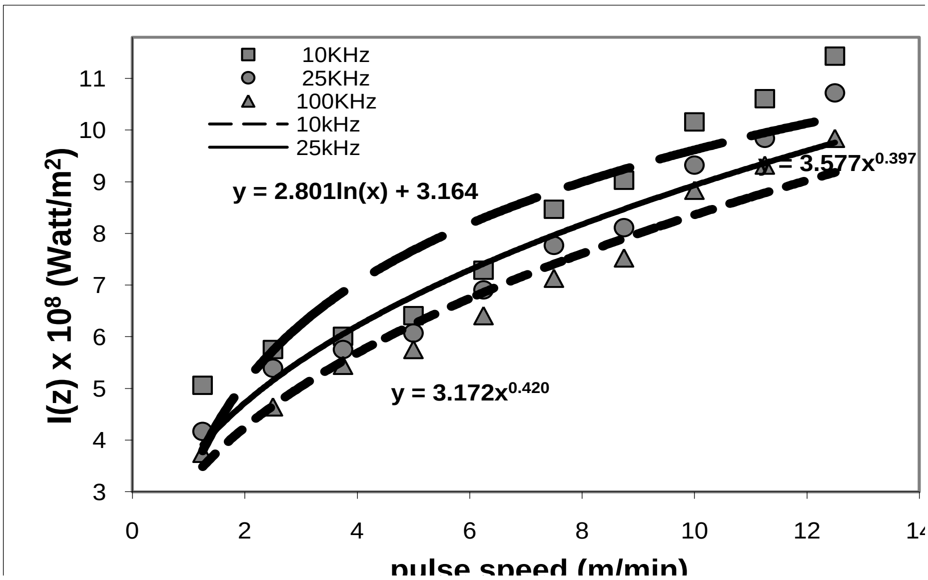

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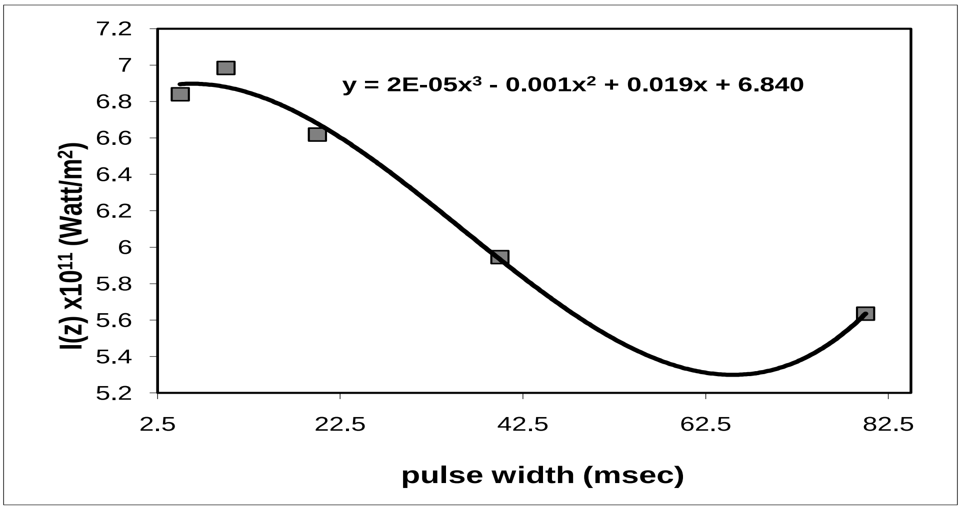

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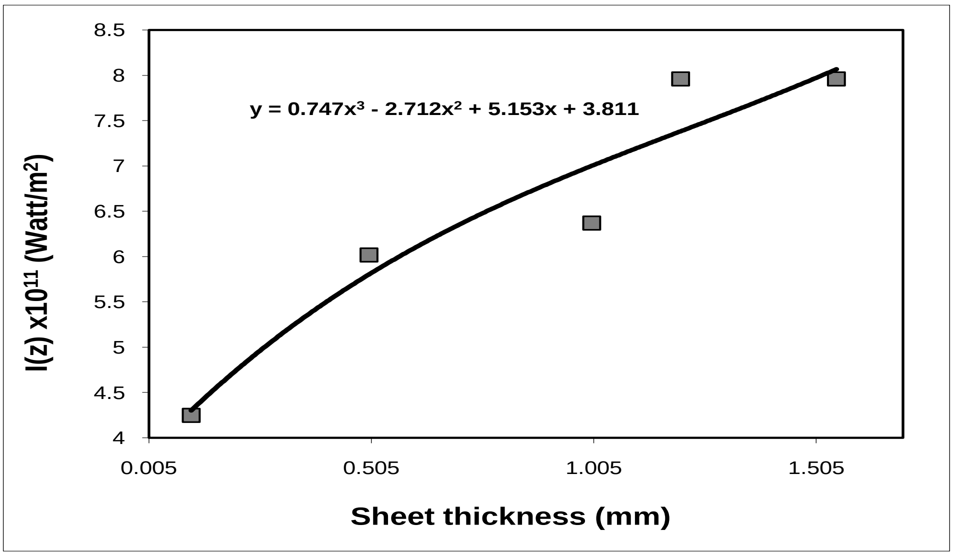
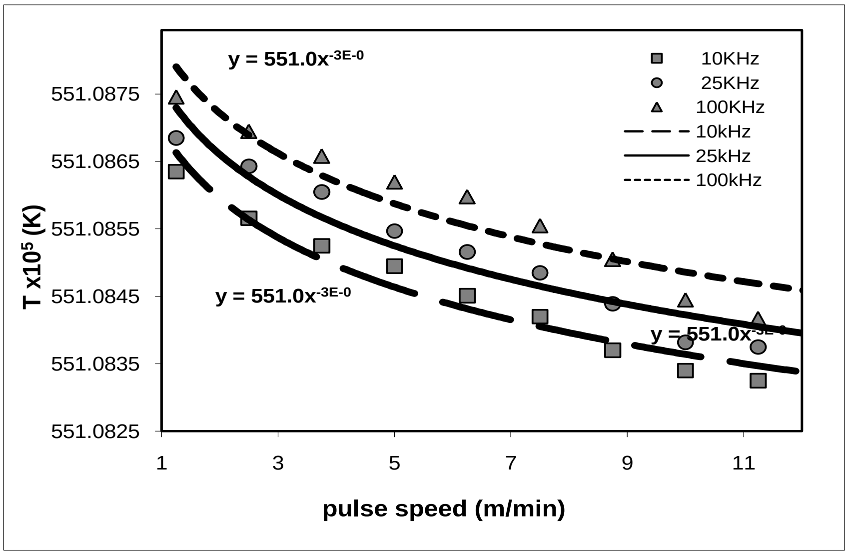


(C)

Fig.(5) Laser intensity absorbed I(Z) as a function of :
(a) pulse speed at (10, 25 and 100) kHz for pw-CO_2 laser [keyhole welding]
(b) pulse width for pw-CO_2 laser [spot welding]
(C) metal thickness for cw-CO_2 laser [spot welding] except at 1.55mm thickness (keyhole welding)



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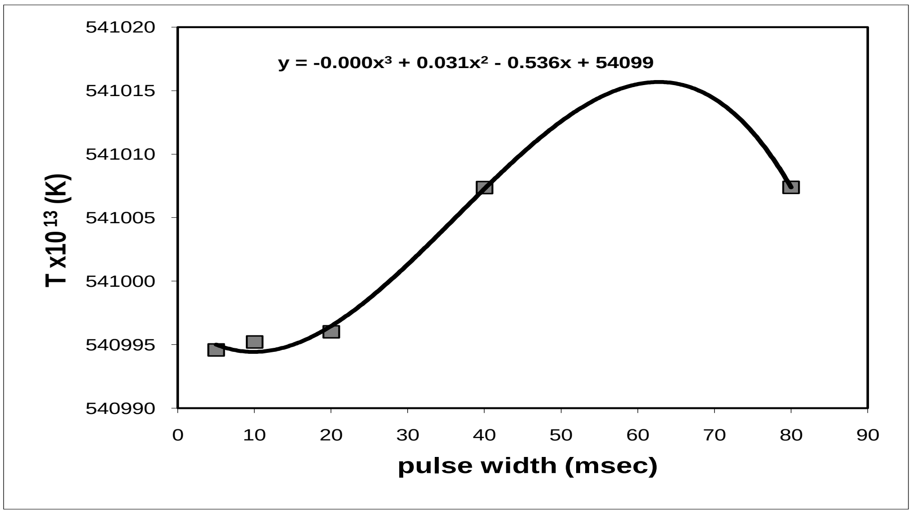

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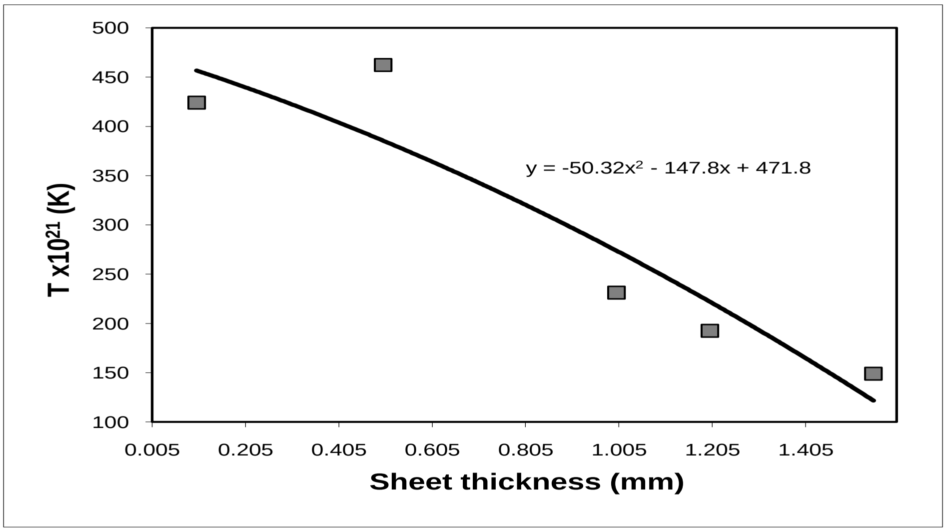


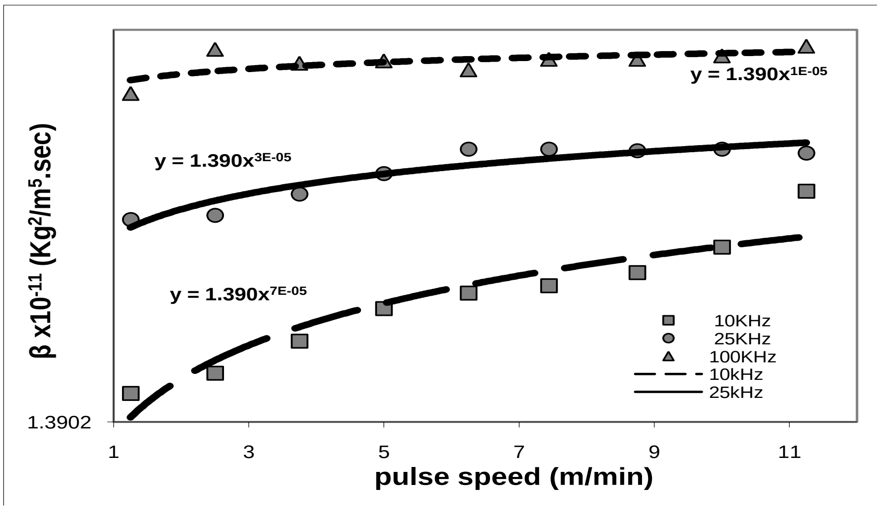
(C)

Fig. 6: Metal surface temperature (T) as a function of :

(a) pulse speed at (10, 25 and 100) kHz for pw-CO_2 laser [keyhole welding]

(b) pulse width for pw-CO_2 laser [spot welding]

(C) metal thickness for cw-CO_2 laser [spot welding] except at 1.55mm thickness (keyhole welding)



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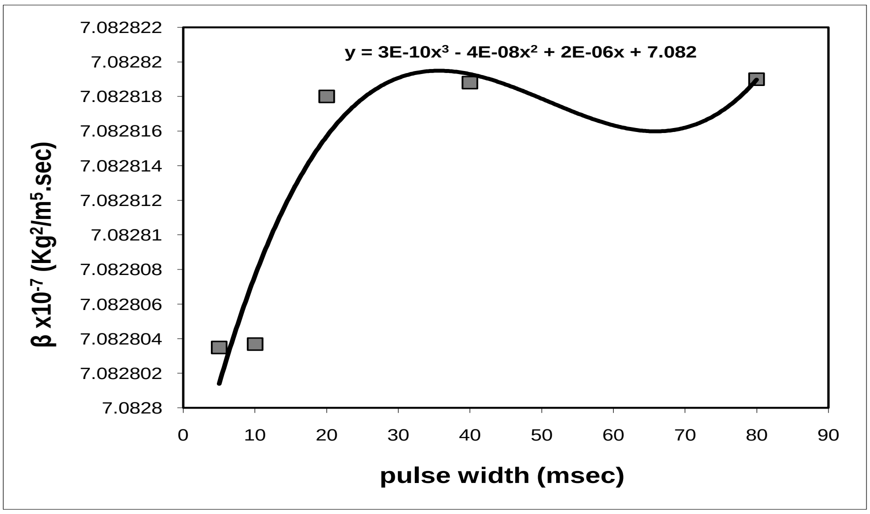

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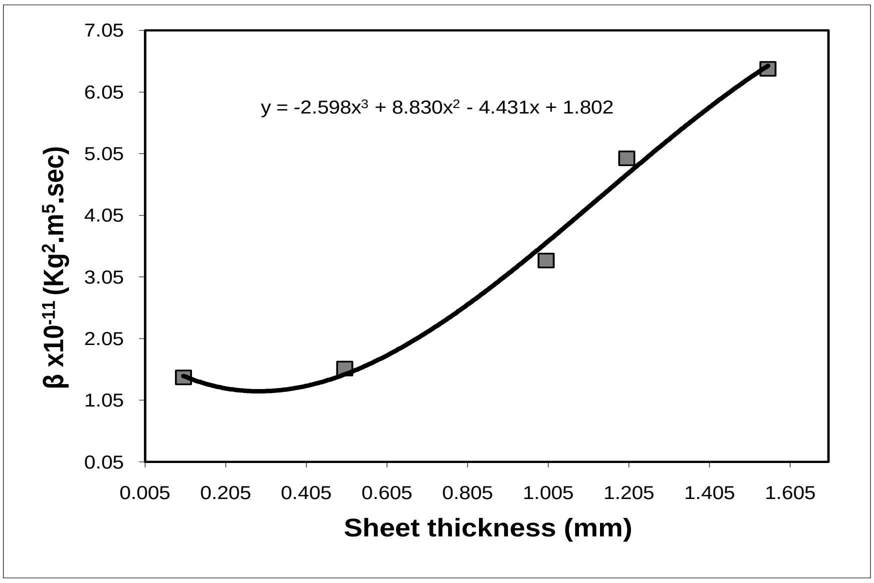


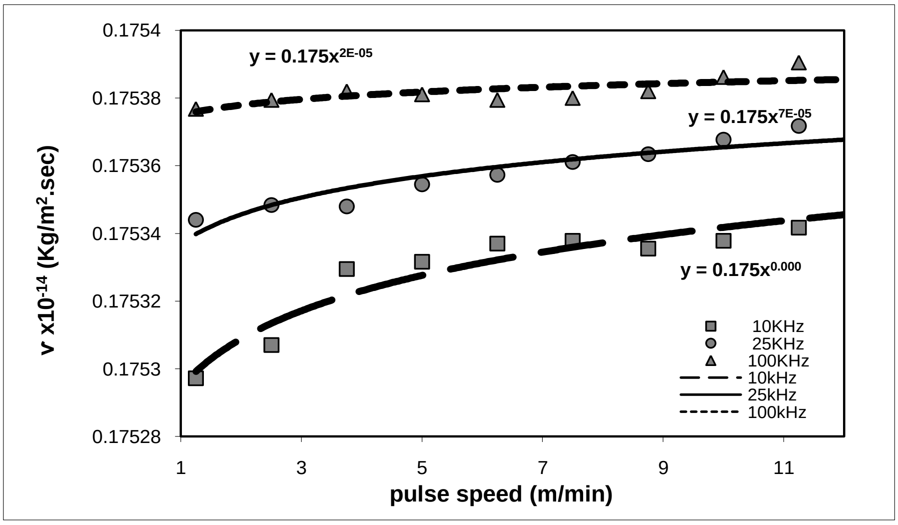
(C)

Fig. 7 : Mass evaporation rate (β) as a function of :

(a) pulse speed at (10, 25 and 100) kHz for pw-CO_2 laser [keyhole welding]

(b) pulse width for pw-CO_2 laser [spot welding]

(C) metal thickness for cw-CO_2 laser [spot welding] except at 1.55mm thickness (keyhole welding)



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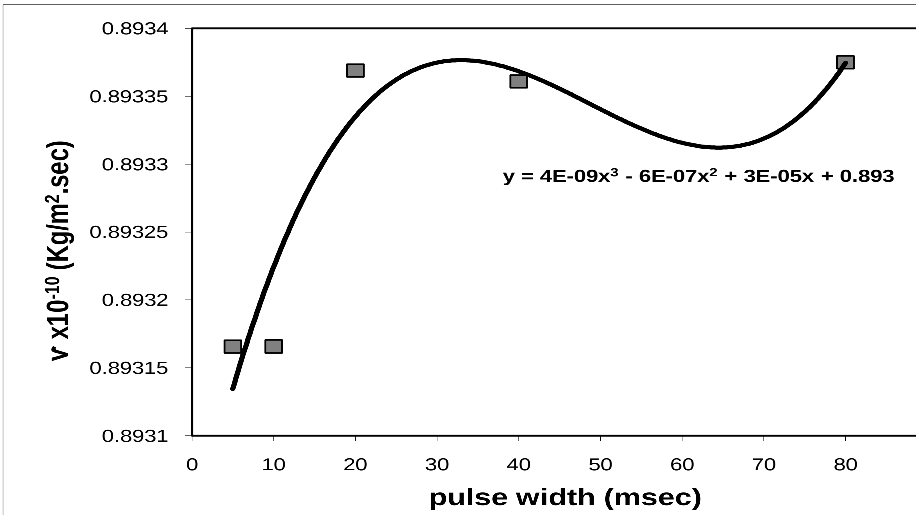

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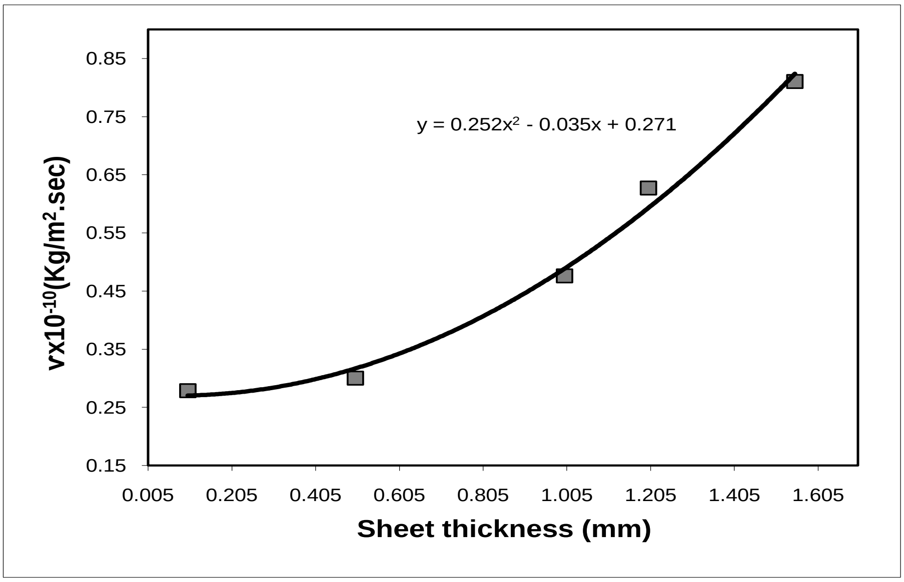


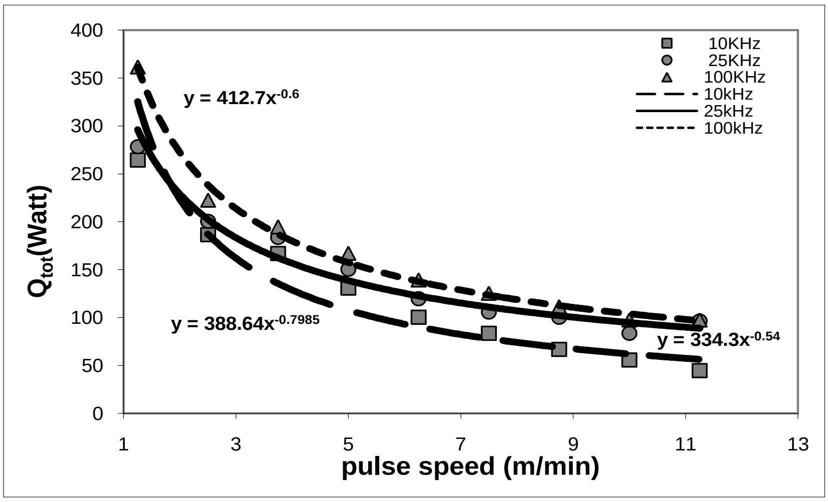
(c)

Fig.8 : The linear vaporization rate (ν) as a function of :

(a) pulse speed at (10, 25 and 100) kHz for pw-CO_2 laser [keyhole welding]

(b) pulse width for pw-CO_2 laser [spot welding]

(C) metal thickness for cw-CO_2 laser [spot welding] except at 1.55mm thickness (keyhole welding)



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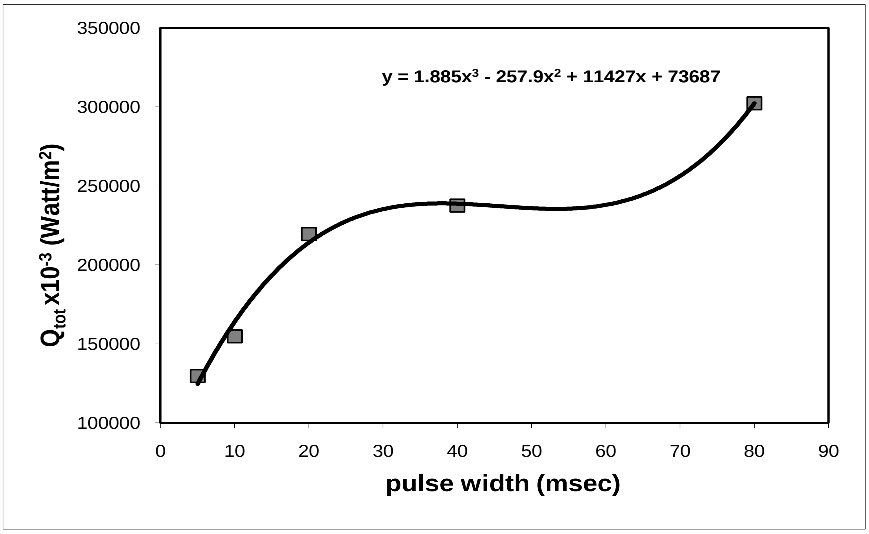

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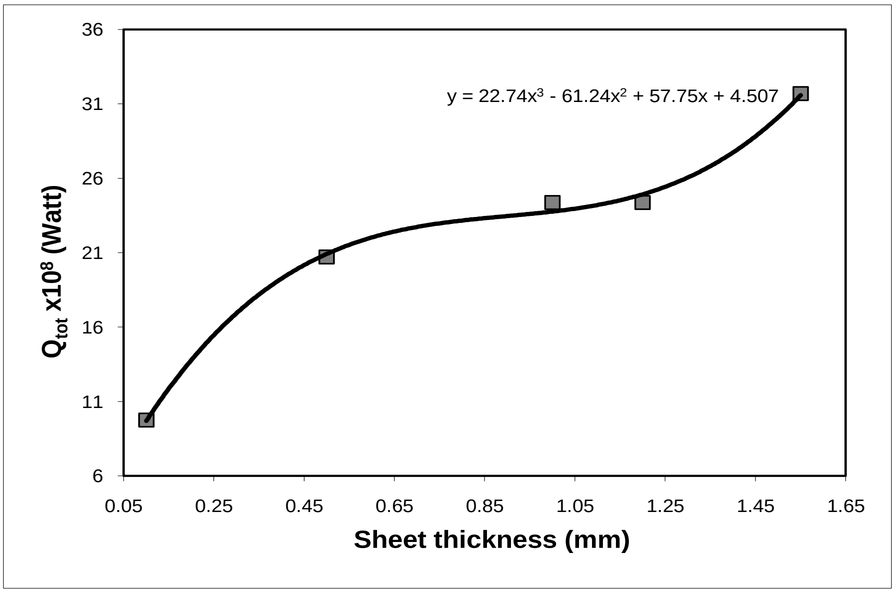
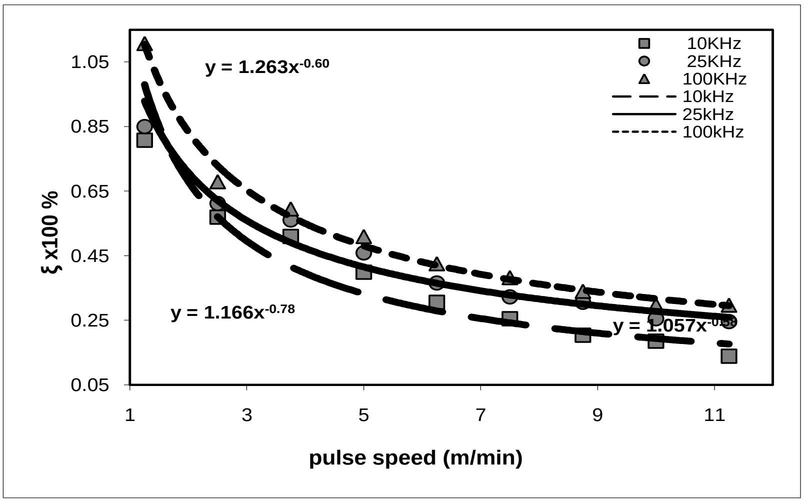


(C)

Fig.9 : The total quantity of heat for laser welding (Qtot) as a function of:
(a) pulse speed at (10, 25 and 100) kHz for pw-CO_2 laser [keyhole welding]
(b) pulse width for pw-CO_2 laser [spot welding]
(C) metal thickness for cw-CO_2 laser [spot welding] except at 1.55mm thickness (keyhole welding)



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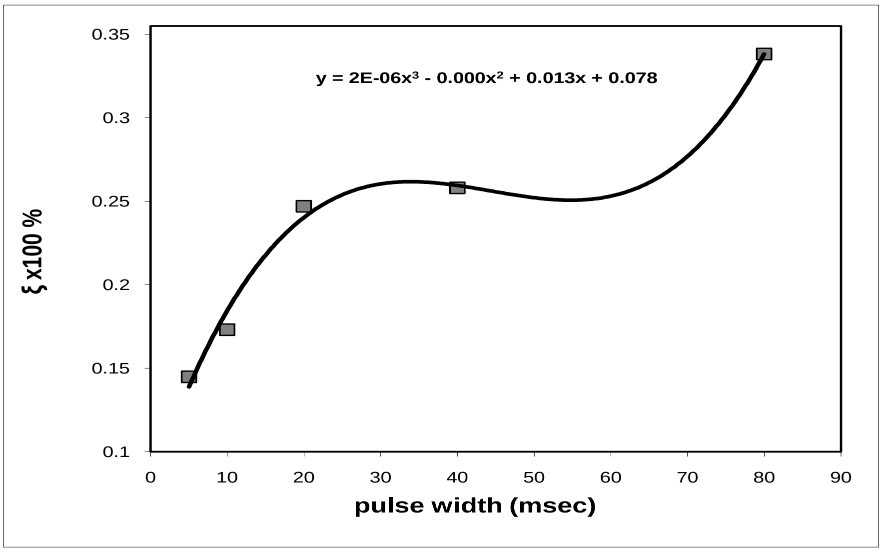

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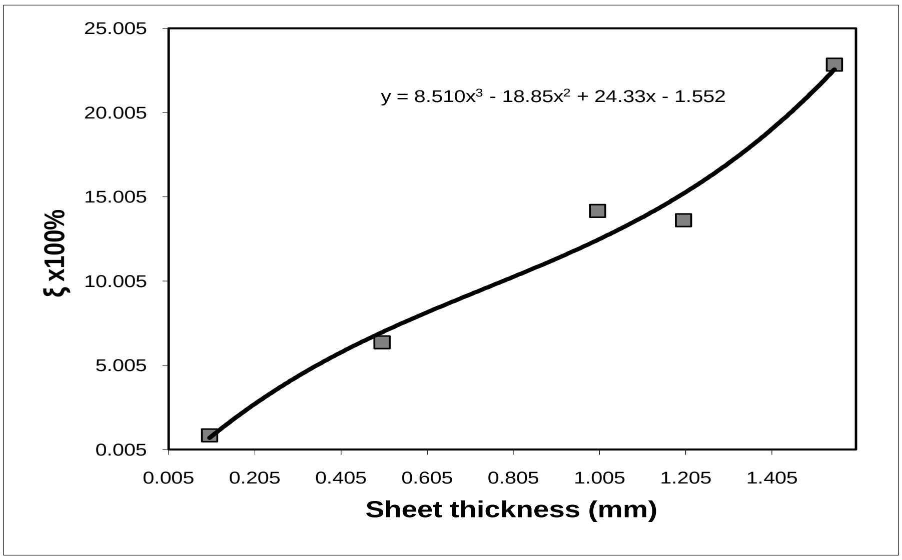

(C)

Fig.10 : The welding efficiency (ξ) as a function of :
(a) pulse speed at (10, 25 and 100) kHz for pw-CO_2 laser [keyhole welding]
(b) pulse width for pw-CO_2 laser [spot welding]
(C) metal thickness for cw-CO_2 laser [spot welding] except at 1.55mm thickness (keyhole welding)