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Theoretical Study of comparative between the speed of penetration and cutting using a laser beam

Abstract*- This research is devoted to study the effect of a laser beam power TEA-CO_2 , Nd- YAG laser, and thermal properties of the materials when it is constant once and varying another once with the time on the penetration and cutting speeds. It is concluded that the processes of penetration and cutting by using laser Nd-YAG is the best comparative with using of laser TEA-CO_2, penetration speeds when ($P = P_0$, $C = C_0$, and $\rho = \rho_0$) by using laser Nd-YAG greater than penetration speeds by using of laser TEA-CO_2 by 15.5 approximately while penetration speeds when ($P = P(t)$, $C = C_0$, and $\rho = \rho_0$) by using laser Nd-YAG greater than penetration speeds by using of laser TEA-CO_2 by 8.519 approximately. In addition, the temperature of the evaporation of material plays an important role in the processes of penetration and cutting and whenever temperature of the evaporation of material less the cutting and penetration speeds are greater. (MATLAB 8) program was implemented for all simulation processes are related.*

Keywords*- Laser (TEA-CO_2 and Nd-YAG), Laser Cutting Speed, Laser Penetrating Speed.*

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1. Introduction

The laser beams are generally used for machining and other developed processes such as cutting, drilling, micromachining, marking, welding, sintering, and heat up treatment [11]. [12] calculated the time of laser drilling procedure for Haselloy-x using hybrid Ti: /KrF excimer chain laser at diverse values of each (number of shots, distance of sample from lens focal point, intensity as well as fluence) according to the establishment results of drill depth. [3] used low power laser diode and laser CO_2. They are showed that the parameters such as speed, current, voltage, number of pass, number of layer, and compressed air influence the depth of cut in the process of cutting. [7] achieved precise hole drilling via continuous wave (CW) CO_2 laser at 150 W maximum output power and wavelength 10.6 µm with the assistance of computerized numerical controlled (CNC) machine and assist gases. [10] applied a practical work on laser – steel cutting process for thin sheet to gain better information’s on cut quality. He showed the relationship between cutting speed and roughness of the surface at different pressures. [2] Investigated the effects of CO_2 laser irradiation on limestone included heavy and light oil of Iran Sarvak formation. They studied the amount of laser beam absorption by this oils for determining thermal fractured during the laser drilling laboratory process [4] investigated experimentally the effect of laser power on the quality of drilled micro holes using Cu50Zr50 amorphous alloys foils. They showed that the taper of drilled holes increased quickly to a stable value with the increase of laser power from 60 to 110 W, then decreased quickly when the laser power became larger than 170 W. [13] studied Cutting of stainless steel with fiber using CO_2 laser. They are showed and analyzed influence of wavelength on cut kerf formation and melt removal process in nitrogen cutting of stainless steel. [6] used Nd:YAG pulsed laser (with minimum pulse duration of 0.5 ms) in order to determine the effects of the peak power and the pulse duration on the holes of the alumina ceramic plates. The aim of this research is studying the effect of Nd-YAG and TEA-CO_2 laser beam power on cutting and penetration speeds when it is constant once and varying another once with the time.

2. Speed of Penetration & Cutting

If the laser beam irradiance is such that the temperature of the material reaches its boiling point, then important amounts of the surface material may be uninvolved. The rate of amputation may be estimated by employing the energy stability equation [5]

$$E= (CT+LF +LV) \rho\pi a2Z \qquad (1)$$

where:

C: Specific heat capacity (Jkg-1.K-1)

T: Transformation temperature (K)

LF: Latent heat of fusion (J.kg-1), LV: Latent heat of vaporization (J.kg-1)

ρ: Density (kg/m3).a: Focusing beam radius (mm)

Z: Penetration depth (mm)

Note: Latent heat of vaporization are much large than Latent heat of fusion

LV>> LF

$$E = (CT + LV)\, \rho\, \pi\, a\, 2\, Z \quad (2)$$

Then from well-known formulas:

$$P = \frac{E}{t} \text{ and } H = \frac{P}{A} \text{ and } V_d = \frac{Z}{t} \text{ and } A = \pi a^2$$

where:

P: Power (W)

t: Time (sec)

Vd: Penetration speed (mm/s)

H: Heat flow or Intensity (W/m2)

A: Spot area (mm2).

From division Eq. (2) on time (t) and area (A), we obtained

$$H = (CT + L_V)\rho V_P \quad (3)$$

when the laser beam is focused on the material, the speed of penetration will be [9]:

$$V_P = \frac{H}{\rho(CT+L_V)} \quad (4)$$

By assuming that the cutting is limited number of drilling, from the figure (2) below we get:

$$t_c = n\, t_d \quad (5)$$

$$V_c = \frac{L}{t_c} \quad (6)$$

From Eq. (5) and Eq. (6)

$$t_d = \frac{L}{nV_C} \quad (7)$$

$$V_d = \frac{Z}{t_d} \quad (8)$$

From Eq. (7) and Eq. (8)

$$V_C = \frac{LV_d}{nZ} \quad (9)$$

$$L = n\, d \quad (10)$$

From Eq. (9) and Eq. (10)

$$V_C = \frac{dV_d}{Z} \quad (11)$$

From Eq. (5) and Eq. (6)

$$V_C = \frac{dH}{Z\rho(CT_V+L_V)} \quad (12)$$

where:

L: Cutting Length

d: Drilling or focused diameter (spot size),

td: Drilling time

t_C: Cutting time.

n: number of holes

Z: Thickness of work piece.

$$r_s = \frac{f_3\lambda}{\pi w_l} \quad (13)$$

where:

(rs) Minimum spot size (mm)

(λ) Wavelength (μm), f3: The focal length of the collimated

Lens (mm)

(wL): beam radius at the final focusing lens (mm).

Then rs= a /

Where

a is the radius of the spot size (mm)

$$H = \frac{4P}{\pi {r_s}^2}$$

So, Eq. (4) and Eq. (12) become:

$$V_d = \frac{4P}{\pi {r_s}^2 \rho(CT_V+L_V)} \quad (14)$$

$$V_C = \frac{4dP}{\pi {r_s}^2 Z\rho(CT_V+L_V)} \quad (15)$$

$$V_C = \frac{4P}{\pi\rho r_s Z(CT_V+L_V)} \quad (16)$$

Note: rs = d

Intensity laser beam Nd-YAG equation [15]:

$$I = \frac{s.p.E_{normal}}{A.t} \quad (17)$$

where:

p: real number that implies (p=6.8241),

s =3.95 put to balance the magnitude of two sides of equation (17),

Enormal: normal energy.

From Eq. (17)

$$P = \frac{s.p.E_{normal}}{t} \quad (18)$$

Intensity laser beam TEA-CO2 equation [14]:

$$I_d = I_o \exp\left(-4\ln 2\left(\frac{t^2}{\tau^2}\right)\right) \quad (19)$$

where:

I0: intensity ambient laser beam TEA-CO2

From Eq. (19)

$$P = \left(I_0 \exp\left(-4\ln 2\left(\frac{t^2}{\tau^2}\right)\right)\right)A \quad (20)$$

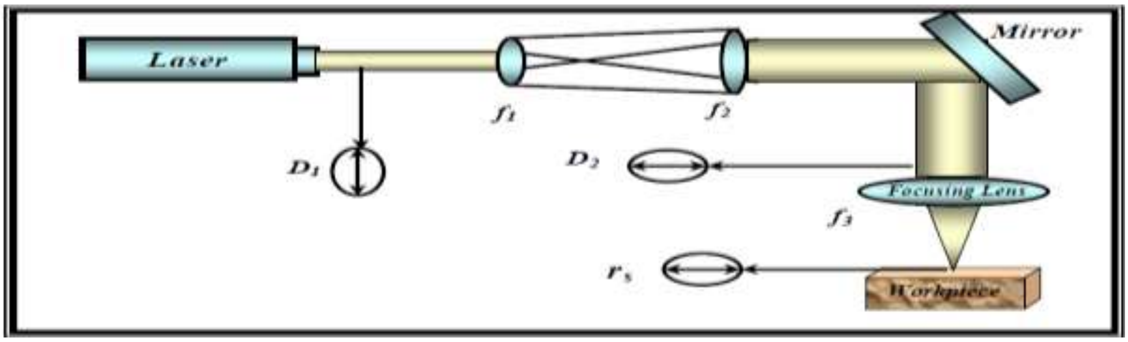

Figure1: Schematic layout of laser beam focusing system [5]

Table 1: Thermal properties of zinc [8]

T(K)	50	150	250	350	450	550	650	750	850	950
C(J/g.K)	0.0387	0.1093	0.1333	0.1376	0.1373	0.1384	0.1413	0.1437	0.1440	0.1445
P(Kg/m2)	2742.5	2720.8	2707.7	2696.6	2681.8	2658.7	2624	2576.5	2516.8	2448.1

Table 2: Thermal properties of aluminum [8]

T(K)	50	150	250	350	450	550	650	750	850	950
C(J/g.K)	0.1853	0.6131	0.8598	0.9828	1.0288	1.0344	1.0256	1.0181	1.0172	1.0175
P(Kg/m2)	2742.5	2720.8	2707.7	2696.6	2681.8	2658.7	2624.0	2576.5	2516.8	2448.1

Table 3: The materials parameters [14]

material	Specific heat capacity (J.kg-1.K-1)	Density (kg.m-3)	Latent heat of vaporization (Jkg-1) (106)	Temperature of vaporization (K)
Zn	0.39	7.13	1.748	1180
Al	0.9	2.7	10.800	2728

Table 4: The lasers parameters [1]

Laser Source	Wave length (µm)	Pulse Time µsec	Focus Spot Size (mm)
TEA-CO_2	10.6	40	5
Nd-YAG	1.06	800	5

3. Results and Discussion

To extract polynomial equations of intensity of laser beams, density and Specific heat capacity of the zinc and aluminum. the equations (17, 19) applying on values in the Tables [1,2,3, and 4] by using the (MATLAB 8) program, the relationships between the intensity of laser beam Nd-YAG and TEA-CO_2 as a function of time pulse and density and Specific heat capacity as a function of temperature were obtained and also shown in Figures (2, 3, 4, and 5).

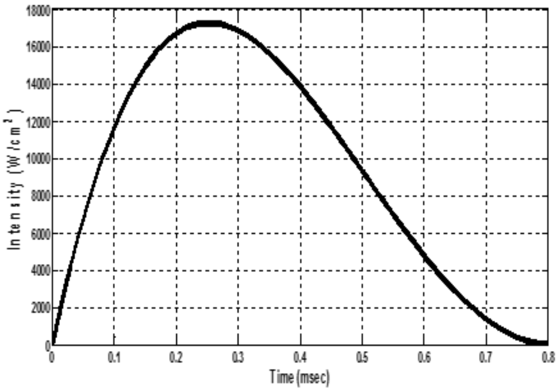

Figure 2: The power density of the laser pulse Nd-YAG as a function of time

$$I\ (t) = 26.694 + 1.5525*(10^5)*t - 4.1419*(10^5)*(t^2) + 2.6432*(10^5)*(t^3) + 71510*(t^4) - 72426*(t^5) \quad (21)$$

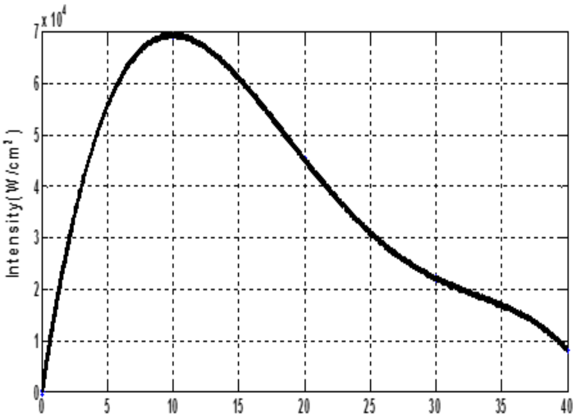

Figure3: The power density of the laser pulse TEA-CO_2as a function of time

$$I\ (t) = -0.34323*(t^4) + 35.585*(t^3) - 1271.6*(t^2) + 16087*t \quad (22)$$

Cases : to get the optimized results for the cutting and penetration speeds, the following combinations of conditions were tried as a three cases described as shown in table (5).

Table5: Cases details

case (A)	P=P0, C=C0, ρ = ρ0
case (B)	P=P(t), C=C0, ρ =ρ0
case (C)	P=P(t), C=C(T), ρ =ρ(T)

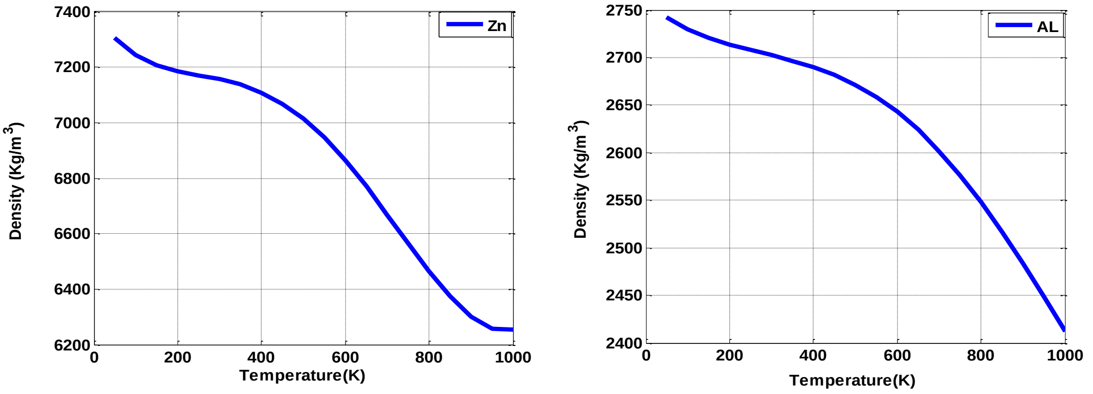

Figure 4: The density as a function of temperature

$P(T)$ (Zinc) $= 8.532*(10^{-9})*T^4 - 1.6748(10^{-5}) *T^3 + 0.0094445*T^2 - 2.378*T+7402.6$ (23)

$P(T)$ (Aluminum) $= 2.658*(10^{-13})*T^5 + 9.4931*(10^{-12})*T^4 - 1.217*(10^{-6})*T^3 +0.00096621*T^2 - 0.37126*T+2758.8$ (24)

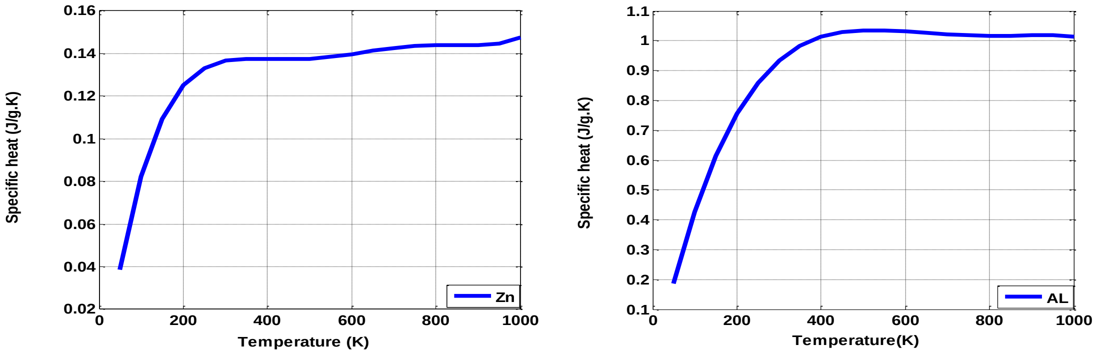

Figure5: The Specific heat capacity as a function of temperature

$C(T)$ (Zinc) $= 2.6546*(10^{-15})*T^5 - 8.3616*(10^{-12}) * T^4 + 1.0075*(10^{-8})*T^3 - 5.7659*(10^{-6}) * T^2 + 0.001572*T - 0.026698$ (25)

$C(T)$ (Aluminum) $= - 4.3354*(10-12)*T^4 + 1.3014*(10-8)*T^3 - 1.428*(10-5)*T^2 +0.0067324* T\ 0.1172$ (26)

Figures 6 and 7 as well as Table 6 explain the changes in the speed of penetration of the zinc and aluminum materials by using (Nd-YAG, TEA-CO_2) laser beams as a function of the focal distance of the lenses by applying equations (14), (21), (22), (23), (24), (25), (26) and the values in tables (3 and 4) in the (MATLAB 8) program. This figures show that the speed of penetration by using (Nd-YAG) laser for both materials is greater than the speed of penetration by using (TEA-CO_2) laser in the three cases as shown in table (7). Also, it can be seen that the differences in penetration speed by using both (Nd-YAG) laser and (TEA-CO_2) laser is grater for case (A) than cases (B) and (C), and, for cases (B) and (C) the differences in penetration speed by using both (Nd-YAG) laser and (TEA-CO_2) laser is too small as shown in Table (8).

Table 6: Speed of penetration of the material

material	Laser	(A)	(B)	(C)
Zinc	TEA-CO_2	2.6910	0.3095	0.3472
	Nd-YAG	41.7754	2.6369	2.9582
Aluminum	TEA-CO_2	1.1529	0.1326	0.1317
	Nd-YAG	17.8985	1.1298	1.1216

Table 7: Ratios of laser speed penetration by using (Nd-YAG) laser to the laser speed penetration by using (TEA-CO2) laser for three cases (A, B, and C) with Zinc and Aluminum materials.

Laser	Laser \ material	Zinc(TEA-CO$_2$)	Aluminum (TEA-CO$_2$)
Nd-YAG	cases	(A)	(A)
	(A)	15.5	15.5
Nd-YAG	cases	(B)	(B)
	(B)	8.519	8.52
Nd-YAG	cases	(C)	(C)
	(C)	8.52	8.516

Table 8: Ratios of laser speed penetration by using (Nd-YAG) laser once, and (TEA-CO$_2$) laser another once for three cases (A, B, and C) with Zinc and Aluminum materials.

Material		Zinc			Aluminum		
Laser	cases	(A)	(B)	(C))	(A)	(B)	(C)
Nd-YAG	(A)	1	15.8	14.1	1	15.84	15.9
	(B)	0.0631	1	0.891	0.0631	1	1.007
	(C)	0.0708	1.12	1	0.0626	0.992	1
TEA-CO2	(A)	1	8.69	7.75	1	8.69	8.75
	(B)	0.115	1	0.891	0.115	1	1.006
	(C)	0.129	1.12	1	0.114	0.993	1

$$\text{Note: ratio} = \frac{\text{speed value in row}}{\text{speed value in column}}$$

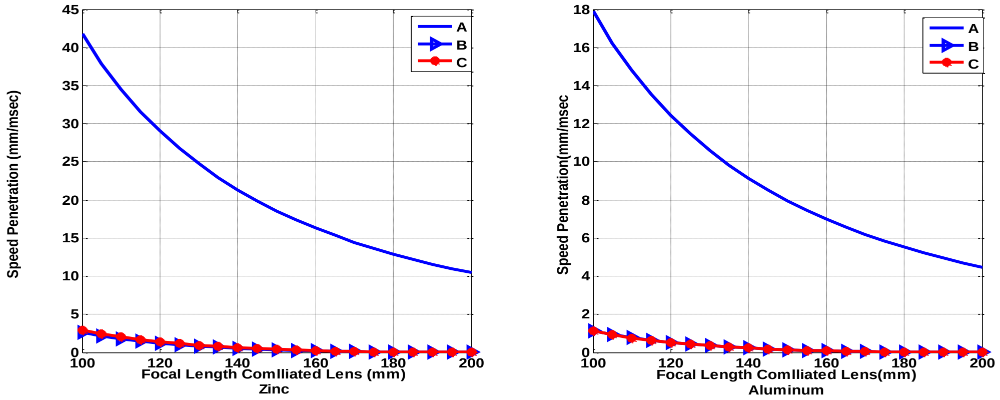

Figure 6: The speed of penetration as a function Focal length collimated lens of using laser (Nd-YAG) in three cases

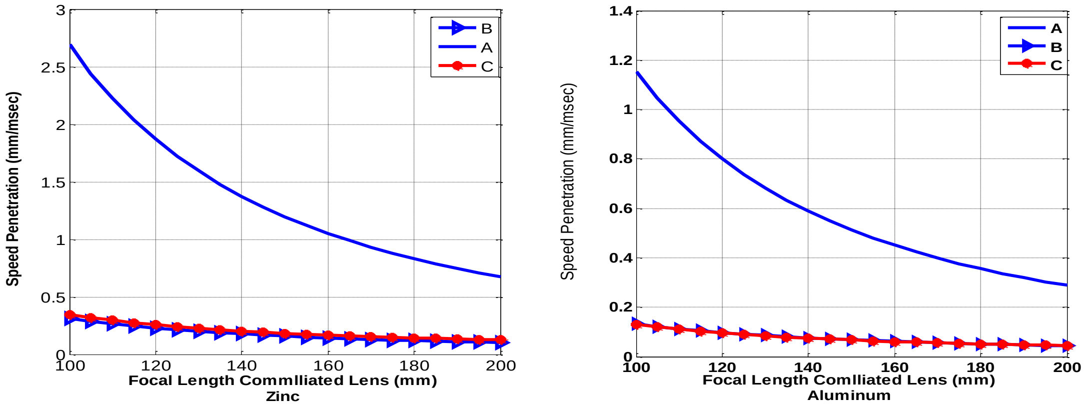

Figure 7: The speed of penetration as a function Focal length collimated lens of using laser (TEA-CO$_2$)

Figures 8 and 9 as well as Table 9 explain the changes in the speed of cutting of the zinc and aluminum materials by using (Nd-YAG, TEA-CO_2) laser beams as a function of the material thickness by applying equations (14), (21), (22), (23), (24), (25), (26) and the values in table (3) in the (MATLAB 8) program. This figures show that the speed of cutting by using (Nd-YAG) laser for both materials is greater than the speed of cutting using (TEA-CO2) laser in the three cases as shown in table (10). Also, it can be seen that the differences in cutting speed using both (Nd-YAG) laser and (TEA-CO_2) laser is grater for case (A) than cases (B) and (C), and, for cases (B) and (C) the differences in cutting speed by using both (Nd-YAG) laser and (TEA-CO_2) laser is too small as shown in Table 11.

Table 9: Speed of cutting of the material

material	Laser	(A)	(B)	(C)
Zinc	TEA-CO_2	0.1454	0.0167	0.0188
	Nd-YAG	0.5642	0.0356	0.0400
Aluminum	TEA-CO_2	0.0623	0.0072	0.0071
	Nd-YAG	0.2417	0.0153	0.0151

Table 10: Ratios of laser speed cutting by using (Nd-YAG) laser to the laser speed cutting by using (TEA-CO_2) laser for three cases (A, B, and C) with Zinc and Aluminum materials.

Laser	Laser \ material	Zinc(TEA-CO_2)	Aluminum (TEA-CO_2)
Nd-YAG	cases	(A)	(A)
	(A)	3.8	3.8
Nd-YAG	cases	(B)	(B)
	(B)	2.13	2.125
Nd-YAG	cases	(C)	(C)
	(C)	2.125	2.126

Table 11: Ratios of laser speed cutting by using (Nd-YAG) laser once, and (TEA-CO_2) laser another once for three cases (A, B, and C) with Zinc and Aluminum materials.

material		Zinc			Aluminum		
Laser	cases	(A)0	(B)	(C)	(A)	(B)	(C)
Nd -YAG	(A)	1	15.8	14.1	1	15.79	16
	(B)	0.06309	1	0.89	0.0633	1	1.01
	(C)	0.07081	1.12	1	0.0624	0.986	1
TEA-CO_2	(A)	1	8.7	7.7	1	8.65	8.77
	(B)	0.114	1	0.88	0.115	1	1.01
	(C)	0.129	1.125	1	0.113	0.986	1

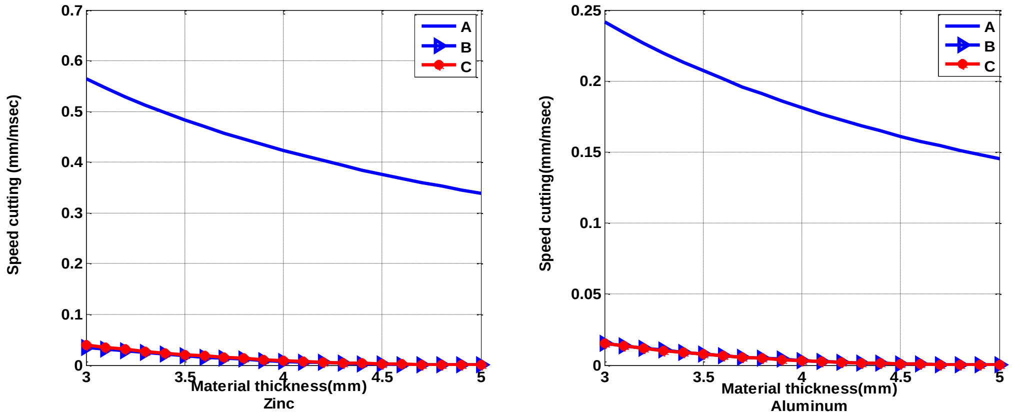

Figure 8: The speed of cutting as a function material thickness of using laser (TEA-CO2)

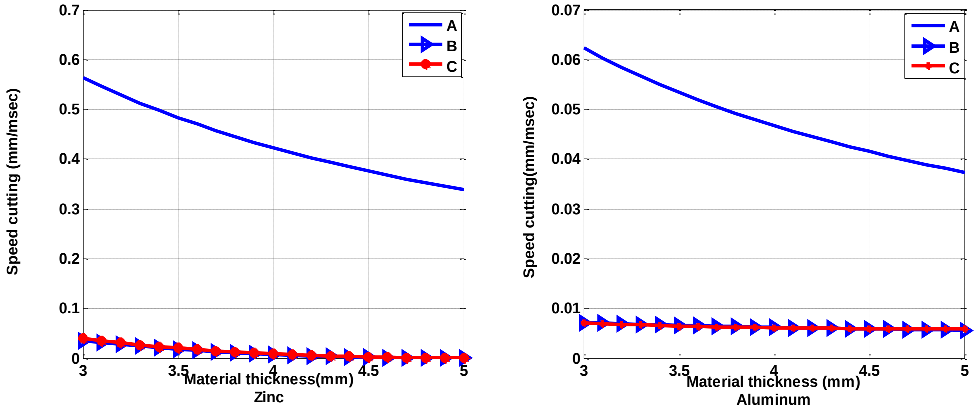

Figure 9: The speed of cutting as a function material thickness of using laser (Nd-YAG)

4. Conclusion

In this research, (MATLAB 8) program was used to extract polynomial equations of intensity of laser beams, density and Specific heat capacity of the zinc and aluminum materials. Two types of laser were used under three cases of power and thermal material properties constant and varying with time and temperature, respectively. It can be concluded that the laser (Nd-YAG) is the best in the penetration and cutting processes than using laser (TEA-CO_2) as well as the cutting and penetration speeds are very large when ($P = P_0$, $C = C_0$ and $\rho = \rho_0$), while the cutting and penetration speeds are very small when ($P = P(t)$, $C = C_0$ and $\rho = \rho_0$) and ($P=P(t), C=C(T), \rho=\rho(T)$. In addition, it is concluded that the temperature of the evaporation of material plays an important role in the penetration and cutting processes, where, the temperature of the evaporation of material is less when the cutting and penetration speeds are greater.

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