

## Calculating the Focusing Effect of Laser Beam on the Penetrating & Cutting Speed

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### Abstract

In as much as employ activity of the laser in industrial applications specially in the drilling & cutting works, it is important to study all variables & factors that affect efficiency & speed of performance such as that processes. In this paper, the study of the focusing effect of laser beam on the penetrating & cutting speed was done, through deriving the mathematical equations, and re-wording it to demonstrating clearly the role of the focusing system on application speed, and calculate the variations of the efficiency of these processes.

The results demonstrated that the application speed (penetration, cutting) affected by the changing in the radius of laser beam, these variables were studied from one hand by comparing the cutting speed with and without the beam expander, where in CO<sub>2</sub> laser case it raised from (1.56 mm/sec) to (7.78 mm/sec) and from the other hand by using a number of concentrating lenses in the focusing system to show its effects on the application speed. Where the focal length of this lenses has a negative effect on the degradation of the cutting speed while, it has a double negative effect on the degradation of the penetration speed, where the degradation in penetration and cutting speed (0.574) and (0.384) respectively with change in collimated lens focal length about (100 - 200 mm).

**Keywords:** Laser Beam Focusing, Laser Cutting Speed, Laser Penetrating Speed.

### حساب تأثير تركيز شعاع الليزر على سرعة الاختراق والقطع

#### الخلاصة

نظراً لفعالية استخدام الليزر في التطبيقات الصناعية وخاصة التنقيب وأعمال القطع المختلفة، فقد أصبح من المهم دراسة وحساب جميع المتغيرات والعوامل التي تؤثر على كفاءة وسرعة أداء مثل هذه العمليات. تم في هذا البحث دراسة تأثير تركيز شعاع الليزر على كل من سرعة الاختراق والقطع، وذلك من خلال اشتقاق المعادلات الرياضية وإعادة صياغتها بشكل يوضح دور منظومة التركيز على سرعة التطبيق، وحساب التغيرات التي تطرأ على كفاءة هذه العمليات. فقد أوضحت النتائج إن سرعة التطبيق (الاختراق، القطع) تتأثر تأثيراً كبيراً بالتغيرات التي تحدث في قطر شعاع الليزر، وقد تم دراسة هذه التغيرات من خلال مقارنة سرعة القطع بوجود وعدم وجود موسع الحزمة حيث كانت الزيادة في سرعة القطع من (1.56 mm/sec) إلى (7.78 mm/sec) من جهة، واستخدام عدد من عدسات التركيز في منظومة التركيز لتوضيح تأثيرها على سرعة التطبيق حيث كان الانحلال في سرعة التطبيق سلبياً بالنسبة للبعد البؤري لعدسة التركيز، وأوضحت النتائج أن سرعة الاختراق تتأثر تأثيراً مضاعفاً بالنسبة لسرعة القطع بهذا الانحلال وكما

يلي (0.574) و (0.384) بالنسبة للزيادة للبعد البؤري لعدسة التركيز (100 - 200 mm) من جهة أخرى.

### 1.Introduction

Laser cutting shares many principles with conventional fusion cutting methods, but excels in applications requiring high productivity, a high edge quality, and a minimum of waste. If high productivity is the main criterion, then oxygen-assisted melt shearing is the cutting mechanism of choice[1].

If a high edge quality is more important, then the slower high pressure inert gas melt shearing mechanism is used. Laser cutting competes with a range of mechanical techniques. Technical comparisons can be made relatively easily, but economic comparisons are more difficult, particularly when the value of a novel cutting technique must be assessed. In general, laser cutting normally provides the best combination of quality and productivity with homogeneous materials less than about 3mm in thickness when the equipment is in use for about 16 hours per day[1].

The ability to concentrate laser light onto a very small region allows us to perform, with high speed and precision, mechanical work such as cutting, hole burning, soldering etc. on very different kinds of materials from metals to ceramics, plastics, wood etc. The possibility of controlling these operations with computers makes the new technique compatible with robotic automation[2].

Two kinds of lasers, that emitted radiation in the infrared spectral range,

are used in the industrial treatment of materials, gaseous CO<sub>2</sub> laser (10.6 μm) and solid state Nd-YAG laser (1.06 μm). Difference between them in the wavelength, charging efficiency and method of beam delivery to a work piece determines their exploitation in some specify production ranges. CO<sub>2</sub> lasers with higher efficiency 30% and higher depth of focus are able to cut low-carbon steel to 16 mm in thickness with continual power 2 kW. Quality of the cut is significantly dependent on the alignment of mirrors and lenses in beam delivery system. Nd-YAG lasers are charged by a krypton flash lamp and have lower efficiency than CO<sub>2</sub> laser, only 3%. Using a laser diode as a charging supply can increase it to 20 – 30 %. Nd-YAG laser beam can be focused to spot with diameter up to 0.03 mm, fine cutting and drilling of thin materials is possible. The main advantage of Nd-YAG laser is the possibility to deliver a beam by the flexible optical fiber into processing head, that can be fixed to machine tool. The optimal result of laser treatment is also dependent on the right setting of working parameters: i.e. power, beam diameter, travel speed, in case of pulsed laser also pulse length and frequency[3].

### 2.Theory

This section will observe the two main important parameters, which affect the performance of (penetration and cutting) works. These is the focusing of laser beam and the (penetration and cutting) speed. The

two parameters will be explained one by one as follow:

**a- The Laser Beam Focusing**

The high intensity of a laser pulse delivered in a very short interval will cause materials to vaporize, thus creating a hole. By focusing the laser beam through an optical system, the energy output can be delivered into a very small spot size [4].

A focusing lens, rather than a mirror, is normally used in laser cutting because of the relatively low power levels used. A lens can be incorporated into a cutting head, acting as the upper wall of the pressure chamber. The focal length of the lens determines the spot size and depth of field of the laser beam. For a TEM<sub>00</sub> CO<sub>2</sub> laser beam of diameter 15 mm, a 127mm (5 in) focal length lens produces a spot diameter of about 0.15 mm, with a depth of focus around 1 mm. This is a good combination for metals with a thickness in the range 0.2–8 mm[1].

For cutting or drilling, along focal length lens is used, in order to produce a narrow kerf and to reduce the tendency for the cut or drilled hole from becoming beveled [5].

A schematic diagram of the layout often used to direct the laser beam onto work piece is shown in figure (1). Basically the beam is passed through a beam expander and then focused to a small spot on the work piece using lens of focusing. The reason for incorporating a beam expander into the optical system is that enables a smaller final spot to be obtained [6].

Beam expander is an optical device increasing beam diameter and reducing divergence, result a smaller focused spot for more distance between lens and workpiece. The laser beam enters the short focal length lens  $f_1$ , and is focused to a real image at the focal

point of the other lens. This image serves as a point source for the other lens[6].

At the output of the second lens the beam has a larger radius, and a smaller divergence. The ratio of the beam diameter before & after the beam expander is given by [7]:

$$\frac{D_1}{D_2} = \frac{f_1}{f_2} = \frac{q_2}{q_1} \dots\dots\dots (1)$$

In other ward the beam diameter  $D_1$  expanded to  $D_2$  by  $f_2/f_1$ , and we can rewrite Equ.(1) as below:

$$D_2 = D_1 \frac{f_2}{f_1} \dots\dots\dots (2)$$

Where  $f_2/f_1$  is the Expansion Factor (F).

To achieve a maximum efficiency from the laser, the laser beam needs to be properly focused on the workpiece. Various focal length (95, 127, 190 & 254 mm) are used for different thicknesses of material. The thicker the material, the large the focal length. Improper focal length affects the application quality & edge parallelism [8].

Basically the beam is passed through a beam expander and then focused to a small spot on the workpiece using focusing lens. The focused spot size ( $r_s$ ) is given by[6]:

$$r_s = \frac{lf_3}{pw_L} \dots\dots\dots (3)$$

Where:

$r_s$  : Minimum spot size (mm).

$l$  : Wavelength (μm).

$f_3$ : The focal length of the collimated lens (mm)

$w_L$  : beam radius at the final focusing lens(mm)

**b- Speed of Penetration & Cutting**

One of the first industrial uses of the laser was reported in 1965 when a diamond die was drilling using pulse ruby laser. A hole 4.7mm in diameter & 2mm deep was made in about 15 minutes; using a mechanical process this had previously taken 24 hours[6].

From this forefront over and above to the many other advantages the speed it is the main advantage to use the laser in applications of the drilling and cutting, so, in this paragraph the equations of speed of Penetration & cutting will be derived & explained briefly.

If the laser beam irradiance is such that the temperature of the material reaches its boiling point, then significant amounts of the surface material may be removed. The rate of removal may be estimated by employing the energy balance equation[4]:

$$E = (CT + L_F + L_V) r p a^2 Z \dots \dots (4)$$

Where:

C: Specific heat capacity (J.kg<sup>-1</sup>.k<sup>-1</sup>).

T: Transformation temperature (k)

L<sub>F</sub>: Latent heat of fusion (J.kg<sup>-1</sup>).

L<sub>V</sub>: Latent heat of vaporization (J.kg<sup>-1</sup>).

ρ: Density (kg/m<sup>3</sup>).

a: Focusing beam radius (mm)

Z: Penetration depth (mm)

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

$$L_V \gg L_F$$

$$\Rightarrow E = (CT + L_V) r p a^2 Z \dots (5)$$

Then from well known formulas:

$$P = \frac{E}{t} \ \& \ H = \frac{P}{A} \ \&$$

$$V_P = \frac{Z}{t} \ \& \ A = p a^2$$

Where:

P: Power (W).

t: Time (sec)

V<sub>P</sub>: Penetration speed (mm/s)

H: Heat flow or Intensity (W/m<sup>2</sup>)

A: Spot area (mm<sup>2</sup>)

From division Equ.(5) on time(t) & area (A), we obtained:

$$H = (CT + L_V) r V_P \dots (6)$$

When the laser beam is focused on the material, the speed of penetration will be[6]:

$$V_P = \frac{H}{r (CT_V + L_V)} \dots (7)$$

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

$$t_C = n t_d \dots (8)$$

$$V_C = \frac{L}{t_C} \dots (9)$$

From (8 & 9)

$$t_d = \frac{L}{n V_C} \dots (10)$$

$$V_P = \frac{Z}{t_d} \dots (11)$$

From (10 & 11)

$$V_C = \frac{L V_P}{n Z} \dots (12)$$

Cutting length = n × Drilling diameter

$$L = n d \dots (13)$$

From (12 & 13)

$$V_C = \frac{d V_P}{Z} \dots (14)$$

From (7 & 14)

$$V_C = \frac{d H}{Z r (CT_V + L_V)} \dots (15)$$

Where:

L: Cutting length

d: Drilling or focused diameter (spot size)

t<sub>d</sub>: Drilling time

$t_c$ : Cutting time  
 $n$ : number of holes  
 $Z$ : Thickness of workpiece.

**3. Mathematical Deriving**

From Equ.(1) & (2):

$w_L = \frac{D_2}{2}$ , then we can rewrite Equ.(2) as shown:

$$r_s = \frac{2If_3}{pD_2} \dots(16)$$

Then  $a = \frac{r_s}{2}$ , where  $a$  is the radius

of the spot size (mm)  $\Rightarrow H = \frac{4P}{p r_s^2}$

so, equations (7 & 15) become:

$$V_P = \frac{4P}{p r_s^2 r (CT_v + L_v)} \dots(17)$$

$$V_C = \frac{4dP}{p r_s^2 Zr (CT_v + L_v)} \dots(18)$$

$$V_C = \frac{4P}{p r_s Zr (CT_v + L_v)} \dots(19)$$

**Note:**  $r_s = d$

Now, to evaluate the focusing effect of laser beam on cutting speed, the cutting speed was calculated at expansion factors ( $F=5, 1$ ), in another expression (With & without beam expander) by using CO<sub>2</sub> laser for metal & Nd:YAG laser for aluminum depending on the values in Table-1, and Equ.(17, 19).

Then to demonstrate the role of collimated lens on application speed, it's extracted at different collimated lenses.

**4.Results & Discussion**

**a. Cutting Speed & Expansion Factor**

Figures (3, 4) show the effect of expansion factor  $F$  on cutting speed for two materials (metal & aluminum) by using CO<sub>2</sub> & Nd:YAG laser, it can note that the cutting speed is affected by the expansion factor  $F$  (available beam expander), where the cutting speed with CO<sub>2</sub> record a high value (7.78 mm/sec) at (3 mm) thickness, where the spot size  $r_s = 5\text{mm}$  reduce to 1mm with  $F = 5$ , While at the same conditions (1.56 mm/sec), when the expansion factor equal to ( $F = 1$ ), (without beam expander). And the cutting speed is proportional reversely with the beam spot size & workpiece thickness see Equ.(19).

**b. Application Speed & Collimated Lens**

Figures (5, 6) explain the changes in application speed as a function of collimated lens focal length. Where from these figures we can see that the cutting speed shows inferior effects from the penetration speed by change in focal length as in Table-2, and Equ.(17, 19).

**5. Conclusions**

- The penetration speed is independent on the thickness of the work piece, while, the cutting speed is depend on it.
- The laser focusing system exhibit a better performance with a beam expander than without it.
- There is an important relation between the collimated lens focal length and both the cutting and penetration speeds, where this focal length has a negative effect on the degradation of the cutting

speed while, it has a double negative effect on the degradation of the penetration speed, but there is a limit for this focal ( i.e. the chosen focal length must be suitable with the distance between the collimating lens and the work piece) to have as could as possible a maximum intensity.

**6. References**

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**Table (1) The lasers & materials parameters <sup>[5]</sup>.**

Material	Laser Source		Specific heat capacity (J.kg <sup>-1</sup> .K <sup>-1</sup> )	Density (kg.m <sup>-3</sup> )	Boiling point (K)	Latent heat of vaporization (Jkg <sup>-1</sup> ) (10 <sup>6</sup> )	Focus Spot Size W <sub>0</sub> (mm).
	CO <sub>2</sub>	Nd-YAG					
Aluminum	--	1kW	903	2710	2720	10.9	5
Metal	1kW	--	435	7870	316	6.8	5

**Table (2) the degradation in Penetration & Cutting Speed as a function of Focal Length of Collimated Lens**

Laser Source	Martial	Change in Focal Length (mm)	Degradation in Penetration Speed (mm/s)	Degradation in Cutting Speed (mm/s)
CO <sub>2</sub>	Metal	Form 100 to 200	0.574	0.384
Nd-YAG	Aluminum	From 100 to 200	57.9	8.71

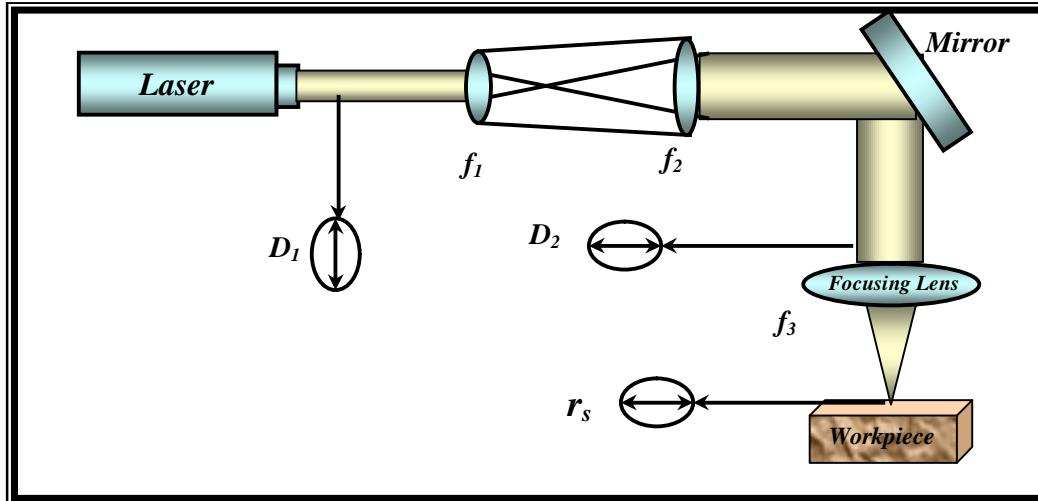


Figure (1) Schematic layout of a laser beam focusing system [6] system

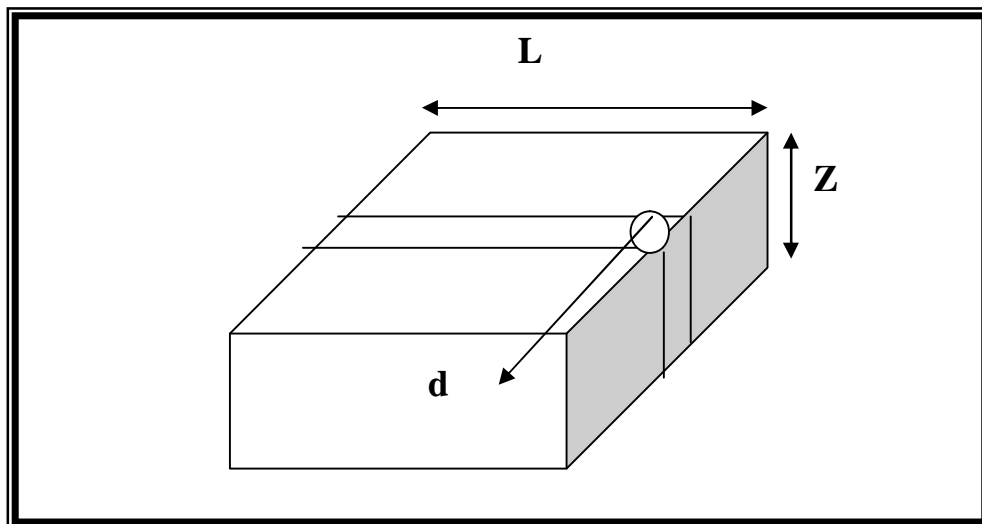


Figure (2) The Workpiece

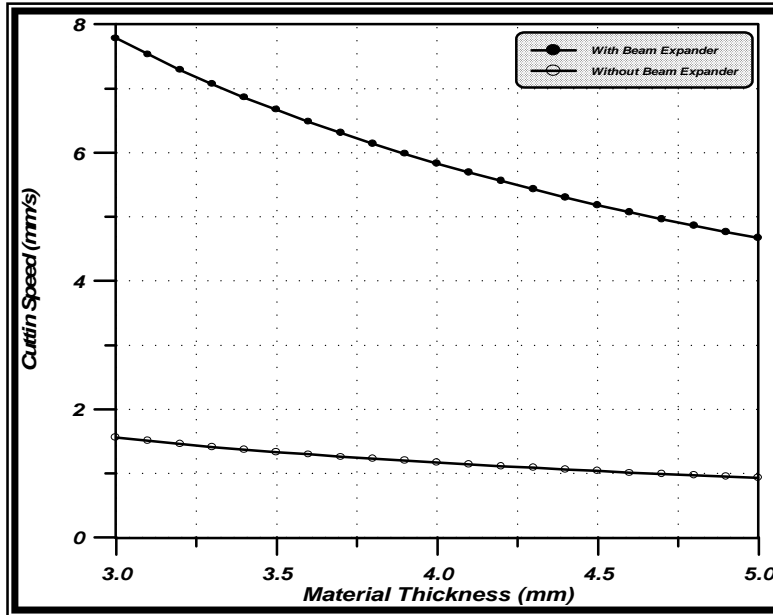


Figure (3) The effect of beam expander on cutting speed by using

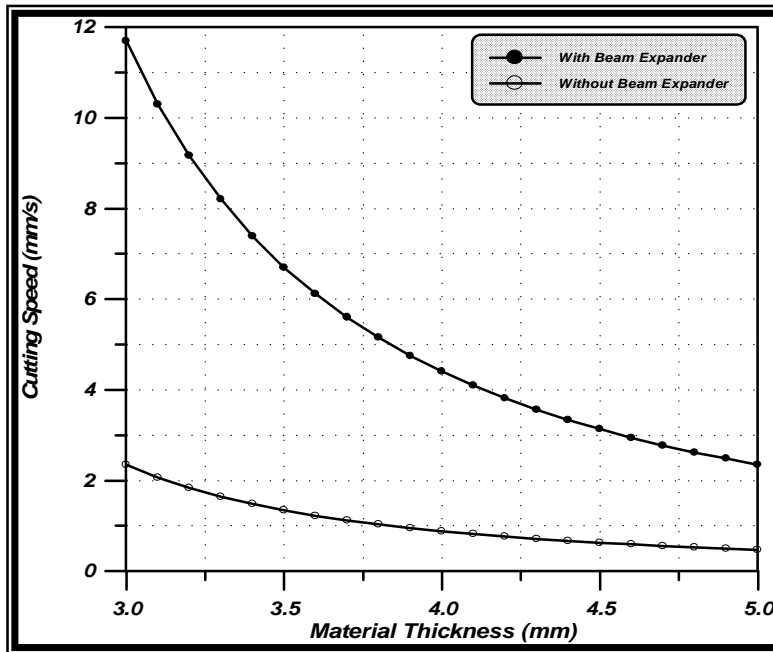


Figure (4) The effect of beam expander on cutting speed by using 1kW Nd-YAG laser in cutting a sheet of Aluminum



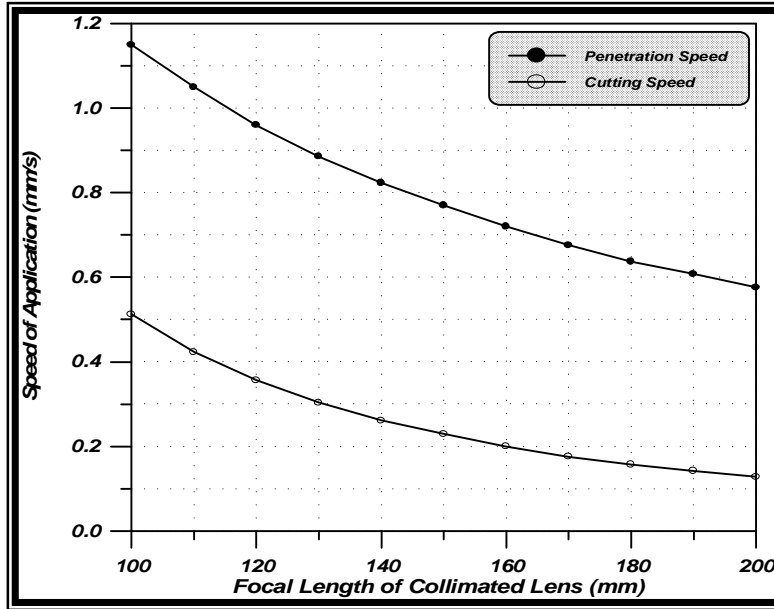


Figure (5) The effect of collimated lens on application speed with 1kW CO<sub>2</sub> laser & 3mm Metal

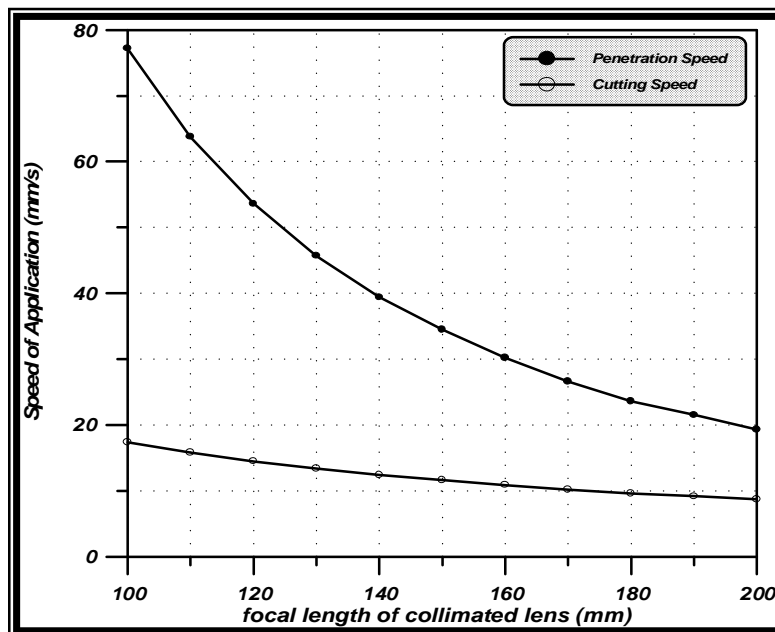


Figure (6) The effect of collimated lens on application speed with 1kW Nd-YAG laser & 3mm Aluminum