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in metal –cutting with "CO₂ laser –gas jet"
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Abstract

The aim of the present research is to study the role of nozzle and the effect of the stand –off distance which are the most important parameters for cutting mild steel by "CO₂ laser – gas jet .

Relationship between the laser power and stand-off distance of nozzle at different cutting speed and thicknesses were achieved. It was found that the power increases with cutting speed for particular stand-off distance. In addition , the laser power proportional with stand-off distance for low cutting speed but out the proportionality at high cutting speed .

However, the results of this study are necessary in order to move another step towards understanding and to clarify their benefits for cutting process by laser.

Key words: Nozzle, standoff distance , cutting , CO₂ laser

دور النوزل والمسافة الفاصلة في قطع المعادن بواسطة ليزر
ثاني اوكسيد الكاربون ودفق غازي

جاسم حسن رشيد

الخلاصة

الهدف من البحث الحالي هو دراسة دور النوزل وتأثير المسافة الفاصلة عن سطح العينة وهما عاملين مهمين جدا في عملية القطع بمنظومة ليزر ثاني اوكسيد الكاربون مع وجود دفق غازي .

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لقد تم ايجاد علاقة بين قدرة الليزر والمسافة الفاصلة للنوزل عند سرع قطع مختلفة لعينات من الفولاذ ذات اسماك مختلفة حيث وجد بان القدرة تزداد مع سرعة القطع لمسافة فاصلة محددة بالاضافة فان هذه القدرة تتناسب طرديا مع الفاصلة عند السرع الواطئة وتكون خارج التناسب الطردي عند السرع العالية.

ان نتائج هذه الدراسة ضرورية للتقدم خطوة اخرى نحو فهم وايضاح فوائد عملية القطع بواسطة منظومة الليزر.

الكلمات المفتاحية: نوزل , المسافة الفاصلة , القطع , ليزر ثاني اوكسيد الكاربون

Introduction

Since the appearance of CO₂ lasers, Laser cutting of metals has been widely adopted in the industry .Due to this development many laboratories and laser companies are investigating the process to improve cutting velocities and qualities . The first major step in the industrial applications of the laser cutting in sheet metals was the introduction of gas assisted cutting (1) . By using a coaxial oxygen gas jet through nozzle , cutting velocities and cutting qualities were improved.

However , nozzles are producing a gas jet coaxial to the laser beam which is suited for laser cutting .Both laser beam and gas jet are always directed at the same point on the surface of the material and the gas jet is efficiently guided into the cut.

The stand off distance is the distance between nozzle and the workpiece .This distance influences the flow patterns in the gas which have a direct bearing on the cutting performance and cut quality (2).Relationship between the power and the stand off distance for particular nozzle are produced.

The influence of the stand off distance on laser cutting process is studied throughout the present research.

The CO₂ laser

CO₂ laser emit the infrared laser radiation with a wavelength of 10-6µm and posses overall efficiencies of approximately 10-20% .The laser – active medium in a CO₂ laser is a mixture of CO₂ , N₂ and He gases, where CO₂ is the laser active molecule. The stimulation of the

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laser active medium is accomplished by electrical discharge in the gas. During the stimulation process, the nitrogen molecules transfer energy from electron impact to the CO_2 molecules . The transition from energetically excited CO_2 molecules (upper viberational level to a lower energy level) is a companied by photon release leading to emission of laser beam . The CO_2 molecules return to the ground state by colliding with the helium atoms, which comprise the major share of the gas mixture, and the CO_2 molecules in the ground stat are then available for another cycle . The stimulation of the electrical gas discharge in the gas mixture is accomplished by either direct current or radio frequency stimulation. Indirect current stimulated lasers, gas discharge between electrodes allows the electrical energy to be directly coupled into the laser gas while the radio frequency stimulated lasers are characterized by capacitive in coupling of the electrical energy needed for gas discharge (3, 4 , 5) .

There are different designs of the CO_2 laser that use different modes of the gas flow and cooling enabling effective beam delivery over a wide range of output power.

Parameters of cutting process

a-Parameters Dependent on the laser Heat Source:

i- Power and Power density : It was reported by Arata(6) that for processing materials , the power of the laser must be high enough to raise the material temperature very fast which leads to a reduction in the reflected light and an increase in absorption phenomena by causing appropriate physical and chemical change .The power density must also be enough to overcome the loss of energy due to reflection , scattering and transportation of the heat from the surface through the bulk of the material .

The following are the major point which affects the laser power and power density during the material cutting process: Spot size , the amount of reflected radiation or the amount of absorbed radiation and laser power available on the workpiece .

ii-Mode Structure : The best modes for industrial use are: single mode (TEM)which is called zero order mode and has a Gaussian distribution . TEM_{oo} provides a beam that can be focused to a minimum spot size giving highest passible power density. The second order

mode $(TEM)_{01}$ which has two regions of maximum intensity and divided into two equal beams .The third is called a doughnut

$(TEM)^{*}_{01}$. This mode is appropriate to the application of heat treatment .

iii-Divergence It is dependent on the mode structure ,and it is higher for the multi mode than for the single mode.

The divergence for perfect Gaussian beam is smallest for certain wavelength and beam diameter . The definition of the beam divergence is shown in figure(1) and can be estimated as follows :

At its waist (Z= 0) , the beam spot radius is:

$$W_o = \sqrt{\frac{2 z_o}{K_n}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where $K_n = \dfrac{2\pi}{n}$, (called ware number)

$$W_o = \sqrt{\frac{\lambda z_o}{\pi}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$Z_o = \frac{\pi w_o^2}{\lambda} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

If $\varphi = \dfrac{W_o}{z_o}$, (called the Divergence angle) (4)

Thus $\varphi = \dfrac{\lambda}{\pi w_o}$ $\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$ (5)

Where W_o is the smallest possible value of the spot size.

Z_o is the distance from the laser window .

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Divergence has a great influence on the laser power density which in turn affects the cutting process

iv-laser beam energy is not distributed in an ideally uniform manner but distributed at the focused spot in a Gaussian shape .Kogelink (7) used this as the basis of theoretical study to predict the propagation characteristics of the laser beam through deferent media .

v- Polarization : The Polarization is a result of restricting the vibrations of the electromagnetic field to a single phase . This prevents optical losses due to interference between the lasing medium and optical elements. It was concluded by M. Bass(8) that polarization is very important for cutting due to the absorption under incident angles close to tangential , Particularly with metals of high reflectivity .

b-Parameters Dependent on the optical system:

Focal spot Diameter and Focal Depth (9) :

The focal spot diameter and the depth of focus are related to the focal length for a certain beam diameter and wavelength . Both decrease with a decreasing focal length . The minimal focused diameter is expressed by:

$$d_f = 1.22 \frac{\lambda f}{\pi d} \quad \text{.. (6)}$$

Where d_f is the focused beam diameter.

    d   is the unfocused beam diameter.

    P   is the focal length .

    λ   is the radiation wavelength.

and the depth of focus is :

$$b = \frac{2\lambda}{\pi} \left(\frac{f}{d/2} \right)^2 \quad \text{... (6)}$$

where:

b is the depth of focus .

The effective spot diameter , defined by the resultant heat affected zone within the material .

The smallest spot size attainable is usually desirable for cutting process.

c-Parameters Dependent on the target:

i-Reflectivity : Gagliano (10) stated that , generally speaking the reflectance of most metals increases with wavelength, hence more power is required from a long wavelength laser than a short wavelength to initiate absorption. Also the temperature of the surface is another factor which greatly affects the reflectivity to metals. As the temperature increases reflectivity often decreases –Arata (6) pointed out that in general , highly polished metallic surface have a very high reflectance at a wavelength of 10-6μm . The reflectivity of metals , however , varies with their surface conditions.

ii-Thermal properties:

Thermal conductivity is found generally to be directly proportional to absolute temperature (11) but the radiation is small over the range of temperatures occurring during laser processing and the variation in thermal conductivity is almost ignored throughout the literatures.

iii-Absorption : The infrared absorption of metals is largely dependent on conductive absorption by free electrons. Arata and Miyamoto (12) produced techniques to improve the absorption of polished surface by adopting the following (6 , 13).

Roughening the surface , coating the surface with either non-metallic thin layer or fine metallic powder and creating a cavity or keyhole by focusing the laser beam

d- Parameters Dependence an the Gas and Nozzle:

i-Gas jet pressure and Gas flow: According to Thomason and Olsen (14) , the pressure

at the cut kerf can be divided into two elements :

(1)-Static pressure which indicates the density of the molecules . For a given values of static pressure and temperature its value can be derived from stagnation temperature (16)

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$$\frac{P_a}{P} \left(\frac{T_o}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left[1+ \left(\frac{\gamma-1}{2}\right) M^2\right]^{\frac{\gamma}{\gamma-1}}$$

(2)-Dynamic pressure which indicates the density as well as the velocity of the molecules .

Gas flow is controlled by both gas pressure and the nozzle outlet diameter(15, 16). Forbes and Tirumula (17, 18) have shown that the flow will affect the cutting performance at a given laser output .It was also assumed by Birkket (19)that the actual flow properties play an important role in gas jet assisted laser cutting . Duley and Gonsalves (20) showed that increasing the gas flow rate increases the cutting speed.

Nielson (1) also reported that the cutting speed is increased significantly when the oxygen pressure is increased. Chen Kai and Modi Vijay (21) concluded that the fluctuation of pressure gradient and shear force of the machining front has determinately effects on the removal capability of the gas jet which often results in power cut quality (22) .The structure of wave shocks present in supersonic flow from laser cutting nozzle results in the reduction of the stagnation pressure across the shock (2) . The interaction of the shocks with workpiece result in a cutting pressure that shows large variations as a function of nozzle stand-off distance . For higher nozzle pressure , the cutting performance is impaired by the formation of a strong normal shock . The flow downstream is subsonic having suffered a large drop in stagnation pressure and results in a low laser cutting pressure . Becides causing a significant reduction in the cutting pressure . The Mack shock also encourages the formation of a stable stagnation bubbles on the surface of the workpiece . The stagnation bubble could result in ineffective debris removal and plasma formation due to absorption of laser radiation by trapped debris (23).

ii-Type of Gas :

The type of gas used in the cutting process plays a significant role due to the quantity of heat released during reaction between active gases and some metals such as steels .It was

recommended by Lunau and Paine (24) to mix oxygen with inert gas to avoid over reactions during cutting some metals such as Niobium . Nielson (1) used a mixture of oxygen , nitrogen , helium or carbon dioxide during cutting steel.

iii-Stand off Distance:

Stand off distance is the height of the nozzle relative to the workpiece surface . The distance has an influence on the cutting process and it is considered a critical parameter if the gap is large then the gas velocity of the jet impinging on the workpiece is too low and therefore the quality of the cut is reduced. J. Huber (25) found that the variation in the nozzle gap had a significant effect on cut quality .

The same author reported that when increasing the nozzle gap above 12.5mm permitted great divergent of the gas jet and resulted in excessive heating of the top surface , extreme irregularity of the kerf and reduced penetration .

The nozzle gas studies indicates that the smallest gap will result in the best quality cut. Catherine (2) report at large variations in pressure can occur if the stand – off distance smaller than the nozzle diameter is recommended because large stand off distances result in turbulence and large pressure changes in the gap between nozzle and workpiece . However with a short stand off distance , the kerf cuts play as a nozzle and the nozzle geometry is not so critical (26) .Kai Chen (21) concluded that the fluctuation of pressure gradient and shear force at the machining front has detrimental effects on the removal capability of the gas jet which often results in poorer cut quality (22).

iv- Nozzle and its effects:

Gases and vapours are expanded in nozzle by providing a pressure ratio across them . According to the equation below (27) :

$$\frac{dA}{A} = \frac{dp}{\rho c^2}\left(1 - \frac{c^2}{a^2}\right) = \frac{dp}{\rho c^2}(1 - M^2)\ldots\ldots\ldots\ldots(1)$$

Where A is the area of the eross section .

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ρ is the density

P is the pressure

The shape of the passage depends on the local Mach number .Since the purpose of a nozzle is to accelerate the flow by providing a pressure drop (dp) is always negative . following three possible conditions are considered for equation (1) :

*For M< 1 , this shows that the area of the nozzle decreases giving a convergent passage . Aconvergent flow section in which flow reachs the subsonic velocity .

*For M=1 which implies that there is no change of passage area at the point where M > 1 .This section is referred to as the throat of the passage.

The flow reaches the velocity of sound which called sonic velocity .

*For M=1 this shows that the area of the nozzle increases continuously giving a divergent passage .In this section the sonic flow is accelerated to become supersonic .

Nozzle design and hole geometry play a major role in laser material cutting (1 , 8 , 15 , 16) . The purpose of the nozzle in laser material cutting is to direct and accelerate the gas . The configuration of the nozzle depends mainly on the mach number desired.

Mach number is the ratio of the velocity of the fluid to the local velocity of sound (27) .

$$ M = \frac{c}{a} \quad , \text{ where } \quad a = \sqrt{\gamma R T} \quad ; \quad \gamma = \frac{c_p}{c_v} $$

Where ;

C_p is specific heat at constant pressure.

C_v is is specific heat at constant volume

R is gas constant.

Birkket stated (19) that the parallel exit nozzle did not give as good as a cut quality as any of the supersonic nozzles . A wide area of heat affected zone is noticed .

Most industrial applications use a parallel nozzle , but there would be some advantages in using supersonic (convergent / divergent).

Thechniques of Combining the beam and gas jet

There are two configurations to combine the laser beam and gas jet as below:

a-Off- axis technique : with this techniques the gas flow and beam axes are inclined to one another . This technique has some advantages and disadvantages which can be summarized as follows:

 i-Advantages are; a simple optical system, a simple nozzle system and finally both the nozzle and optical system are independent designs.

 ii- Disadvantages includes the limitation on angle between gas jet and laser beam , limitation on the distance between nozzle and material surface , in addition to being complicated to implement on curve cutting

b- Coaxial technique : The first characteristics of this approach is that the laser beam is directed along the same path as the gas jet , secondly there is no limit in nozzle distance , thirdly it is possible to control gas flow condition and the where approach may be readily implemented in industrial production . However , this technique has disadvantages is that it is more complicated , since the optical and nozzle designs are dependent an each other .

The coaxial technique may be favored by industry because it is easier to engineer for multi – directional cutting .

The common features of a coaxial nozzle are .

a- It must be big enough to pass the beam without it touching the nozzle (the smaller the nozzle ,the more difficult to alignment with beam).

b- The flow the nozzle must couple effectively with the kerf to remove the molten dross and enhance the cutting action.

Experimental Equipments and procedures

a-CO₂ laser system: The 500w CO_2 laser system (525 Everlase model) is typical of equipment used for mild steel processing

b-Beam path :A number of mirrors are used to change the beam polarization .

The beam transmitted from the mirror is plane polarized for cutting convenience , circular polarization is necessary .

The 45º mirror , which deflects the output beam from the laser through 90º is good coated . The coating is made so that   almost all- the energy in the beam is reflected from it.

The 45º flat mirror is used to direct the laser beam, and the lens is used to focus the energy . This lens is a zinc serenade (Zn Sn) with focal length of 63.5mm.

c-cutting head : The reflected beam from the 45º mirror is passed through a lens nozzle assembly called the cutting head .

The lens is mounted in a holder so that the lens axes central. The nozzle , through which the focused beam and the gas stream leave the head , is located accurately in the base of the head and can be adjusted by screws. The nozzle used have diameters of 0.1mm .

d-The nozzle and nozzle gas control : The nozzle shown in figure (2) was designed and manufactured for the current project . The diameter of the nozzle should be in general large enough to let the laser beam through .

The assisting gas in this experimental investigation is oxygen . The gas from a bottle is fed into a nozzle assembly, through the gas inlet .

e-Checking Alignment , procedure: Standard beam visualization plate was used .This consists of a plate coated with material which fluoresces in ultra violet light , but stops fluorescing when heated . Such a plate was irradiated using minimum laser power for a short period and where the laser beam impinged , a dark spot developed as the temperature rise of the base stopped its florescent action .A distorted spot shape was seen when the laser beam was not centralized with the gas jet.

f-Mild steel sheets of 1.68 mm and 2.0 mm thickness are used with different velocities at 20 p.s.i pressure of oxygen jet . The maximum velocity of the laser beam is 33.334 mm/sec

.cutting speed is expressed as a percentage through out these calculations, viz 5%, 25% , … , u%. The following table shows the true speed related to maximum speed.

U%	U(mm/s)
05	1.667
25	8.335
50	16.667
75	25.005
100	33.334

Results and Discussion

Figure(3) represents the relationships between the power and the stand off distance at different cutting speeds for 1.68 mm mild steel thickness . Stand off distance is the gap distance between the outlet nozzle and the surface of the material .

When the stand off distance is zero, the focal point is actually 1.25 mm below the surface . As the nozzle tip is lifted by 0.625 mm, the focal point is still 0.625 mm below the sample surface .Therefore the focal point to be on the top surface of the sample , the nozzle tip should be lifted to a height of 1.25 mm above the surface .

However , for particular speed (say 5% of maximum speed of 33.334 mm/s) the power does not change with these nozzle height settings as shown in figure (3) . When the focal is 0.625 mm underneath the top surface , the power required to cut 1.68 mm thick material is equal to that required when the focal point is at the surface and above the surface by 0.625 mm (i.e the gap distance is in the range 0.625 – 1875 mm). Higher than 1.825 mm, the power required is greater. Above 3.75 mm no cut was achieved . This is due to the fact that as the focal plane is raised , the laser spot diameter becomes larger giving smaller power density which is the power divided by the area covered the laser beam spot , in addition to the pressure variation. As the pressure variation decreases , less exothermic energy is expected and /or the gas

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momentum is less effective , i .e, if jet momentum is not high enough , the molten layer builds up and may become thick enough to reduce heat conduction in the cutting direction . The cutting process may finally stop unless cutting speed decreases or the laser power increases .

However , two facters play a major role which may balance each other leaving the laser power effect unchanged when the stand off distance is in the range of 0.625 – 1.875 mm:

a-Higher power density expected when stand off is smaller than when it is higher . This factor should reduce the laser power required .

b- when the gap distance is too low , the gas pressure plays a cooling role . Due to this factor the laser power needs to be increased .

The above two factors contradict each other and both influences may cancelled out . The question might be asked why the gas jet used since it is possible to reduce laser power at very low stand off distance . The answer is that the gas jet is still important and vital to the process because it is used to clear the molten material out of the kerf to keep the process going and to improve cut quality which is due to that the cut edge is cooled by the gas flow as it does
 not reach the ignitions point , thus rest restricting the width of the HAZ.

Fig (4) shows the influence of stand off distance for 2 mm thick sample A similar trend is produced to that shown in fig (3) .

An attempt to cut mild steels(without nozzle) for both 1.68 mm and 2.0 mm was done but the complete cutting process was not achieved . This failer simply means that the nozzle is necessary and its role is very important for cutting process.

Conclusion

The results showed that the cutting of mild steel of 1.68mm can be achieved at different velocities .It was found that the power employed is proportional with stand-off distance particularly with the high velocity .

The power required to cut the sample is greater with the higher velocity at the same stand –off distance due to limit of interaction time between laser beam and workpiece.

Similarity was shown for cutting thicker sample (2 mm) .

However , the cutting process for the same metal was not achieved in spite of similar conditions were employed but without nozzle which ensure the importance of nozzle for cutting process.
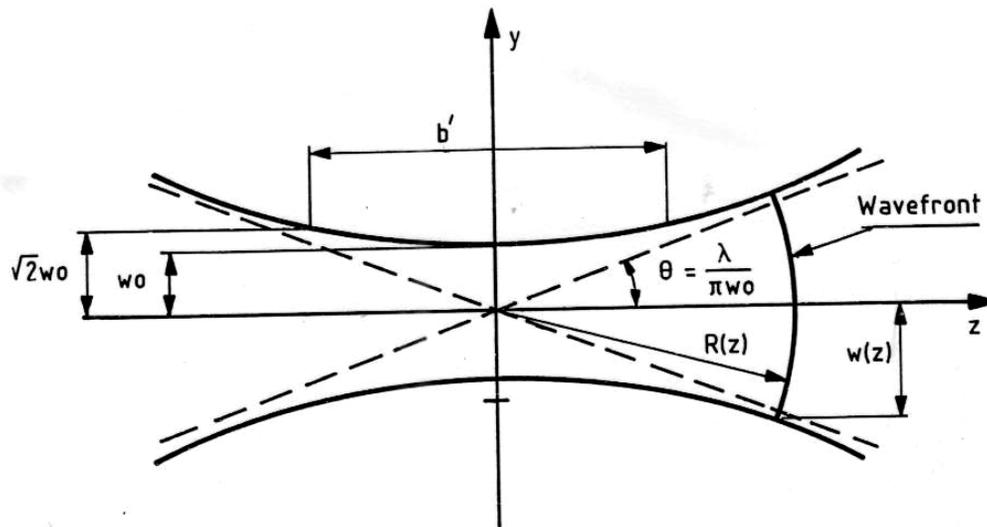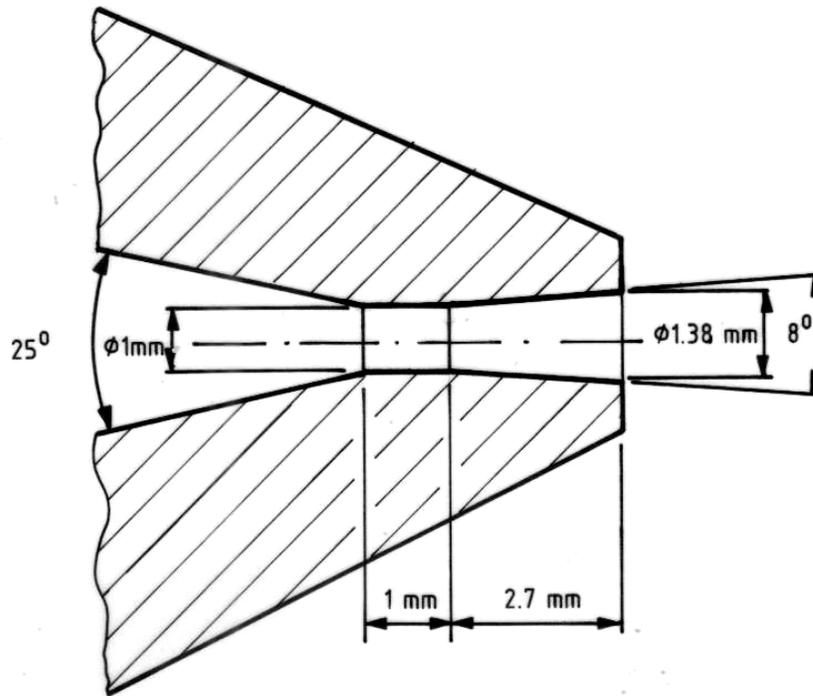

Fig. 3. 2. Beam depicting approximate solution of beam divergence.

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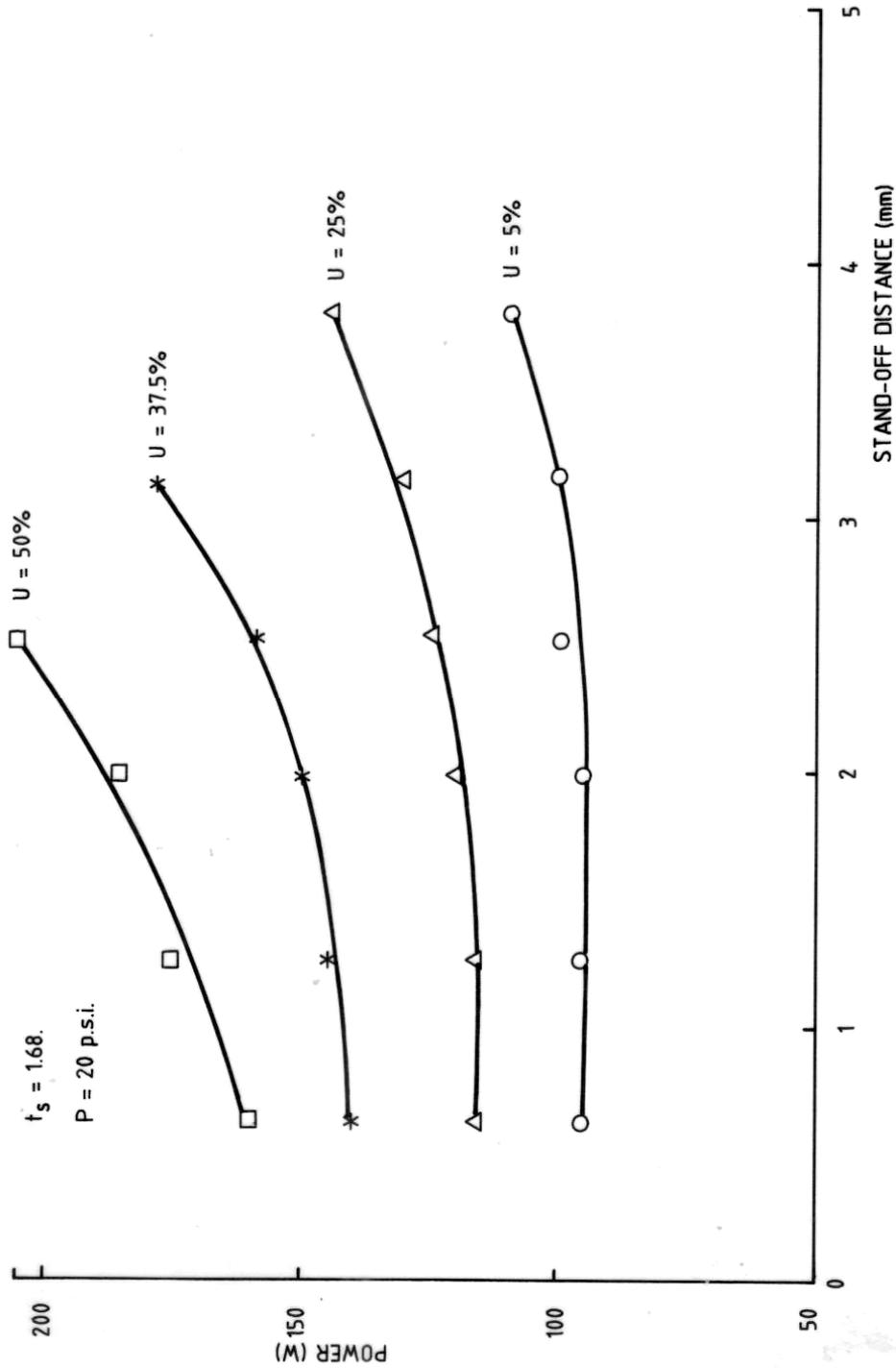in metal –cutting with "CO₂ laser –gas jet"
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1

(b) CONICAL EXIT NOZZLE

Fig. 4. 4. Design of different nozzles.

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Fig. 5. 4. Relationship between laser power and stand-off distance

Fig. 5. 5.   Relationship between laser power and stand-off distance

Fig 4 :

The Role of Nozzle and its Stand off distance
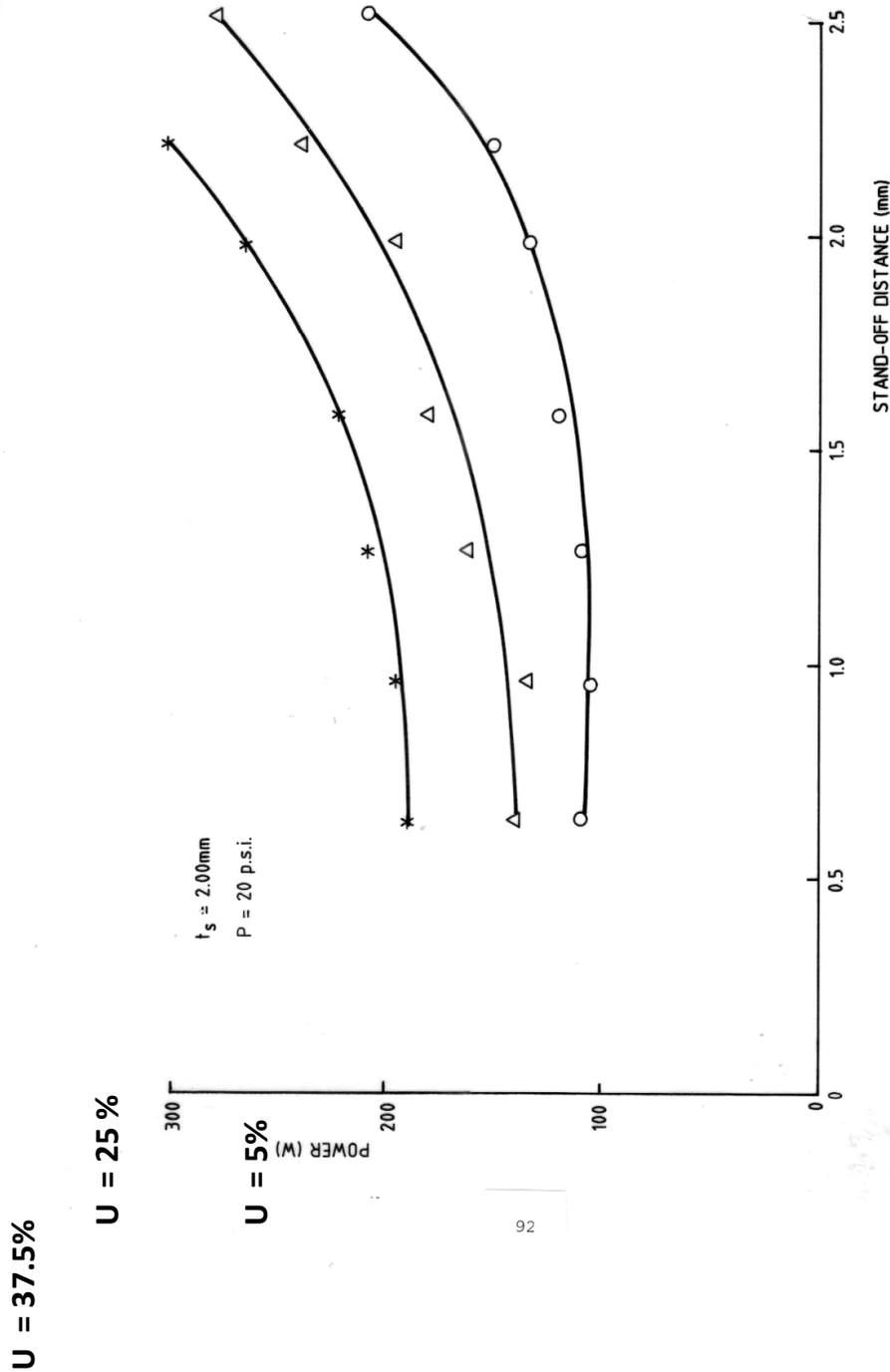in metal –cutting with "CO₂ laser –gas jet"
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