STUDY ON EFFECTS OF CO_2 LASER ABLATION CONDITIONS ON CUT PARAMETERS AND MICROSTRUCTURES

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Study on effects of CO_2 laser machining conditions on cut parameters and microstructures

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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This thesis has been submitted for examination with our approval as the university supervisors.

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DEDICATION

This work is dedicated to my dear mum and my lovely husband Mike.

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ABBREVIATIONS

A	Absorptivity
AC	Alternating Current
AI	Artificial Intelligence
Al	Aluminium
Al_2O_3	Aluminium oxide
CAD	Computer-Aided-Design
CNC	Computer-Numerical-Control
CO_2	Carbo-dioxide gas
COIL	Chemical Oxygen-Iodine Laser
CW	Continuous Wave
DC	Direct Current
DLC	Dry laser cleaning
DOF	Depth of focus
E/M	Electromagnetic
FAF	Fast axial flow
HAZ	Heat Affected Zone
He	Helium gas
IR	Infra-Red
K	Kelvin
KCl	Potassium Chloride
LAMM	Laser-Assisted-Mechanical-Micromachining

LASER	Light amplification stimulated by emission of radiation
LBM	Laser Beam Machining
LMJ	Laser MicroJet cutting
LSE	Laser Safety Eyewear
M^2	Beam quality factor
MEMS	Micro-Electro-Mechanical Systems
MLP	Mingle-Laser-Pulse
MOEMS	Micro-Optical-Electro-Mechanical Systems
MPE	Maximum Permissible Exposure
MRR	Material Removal Rate
N_2	Nitrogen gas
NA	Numerical Aperture
NC	Numerical Control
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
NHZ	The Nominal Hazard Zone
O_2	Oxygen gas
OD	Optical Density
OC	Output Coupler
PAH	Polycyclic Aromatic Hydrocarbon
PMMA	Polymethyl methacrylate
PC	Polycarbonate
PP	Polypropylene

PRF	Pulse Repetition Frequency
R	Reflectivity
RF	Highly reflective
SAF	Slow axial flow
SEM	Scanning Electron Microscopy
SiC	Silicon carbide
SLC	Steam laser cleaning
SLP	Single-Laser-Pulse
SOD	StandOff Distance
3D	Three Dimensional
2D	Two Dimensional
TEA	Transverse Excited Atmospheric Pressure
TEM	Transverse Electromagnetic Mode
UV	Ultra-Violet
WJGL	Water Jet Guided Laser
WLC	Wet laser cleaning
ZnSe	Zinc Selenide

NOMENCLATURE

$\boldsymbol{C_p}$	Heat capacity of a material (J/K)
$\mathbf{d}$	Depth to which material is removed (mm)
$\mathbf{D}$	Unfocused laser spot diameter (mm)
$\boldsymbol{d_{min}}$	Minimun spot size (mm)
$\mathbf{E}$	Modulus of elasticity (N/m^2
$\boldsymbol{f}$	Laser focal length (mm)
$\boldsymbol{F}$	Fluence at normal incidence (J/cm^2)
$\boldsymbol{f\sharp}$	f-number
$\boldsymbol{F_{th}}$	Threshold Fluence (J/cm^2)
$\boldsymbol{L_d}$	Length of the laser bore (mm)
$\boldsymbol{N_f}$	Fresnel number
$\boldsymbol{R_a}$	Arithmetic average value of roughness (μm)
$\boldsymbol{T}$	Temperature (K)
$\boldsymbol{Z_R}$	Rayleigh range (mm)
$\boldsymbol{\alpha}$	Thermal diffusivity (m^2/s
$\boldsymbol{\alpha_G}$	Linear thermal expansion coefficient of the glass (K^{-1})
$\boldsymbol{\beta}$	Absorption coefficient of the material (M^{-1})
$\boldsymbol{\kappa}$	Thermal conductivity (W/mK)
$\boldsymbol{\lambda}$	Laser wavelength (μm)
$\boldsymbol{\lambda_m}$	Wavelength of the material where the beam propagates (mm)
$\boldsymbol{\omega_0}$	Beam spot radius size at beam waist (mm)
$\boldsymbol{\omega_z}$	Beam spot radius size at a distance z from beam waist (mm)

$\boldsymbol{\pi}$	Pie = 3.142
$\boldsymbol{\phi}$	Hole diameter (mm)
$\boldsymbol{\rho}$	Density (Kg/m^3)
$\boldsymbol{\sigma}$	Tensile stress (N/m^2)
$\boldsymbol{\tau}$	Interaction time (sec)

ABSTRACT

Laser ablation is a technique that is highly embraced in many applications and especially in Micro-Electro-Mechanical Systems (MEMS) industry. This work focused on development of a Carbo-dioxide gas (CO_2) laser system, a control program to run the system and determination of the effect of machining conditions such as machining time and the number of passes on cut parameters. Effect of compressed air as the assisting gas on hole profiles and glass cracking were also investigated.

The materials experimented with included wood, perspex, ceramics, glass, mild steel and aluminium. These materials were first prepared and the number of passes and machining time varied. It was observed that due to the low power of the laser, mild steel could not be machined. A coating was applied on the surface and left to dry before machining. Cut parameters (kerf widths, inner and outer hole diameters, heat-affected-zone (HAZ), taper, depths machined) and microstructural changes were measured as an indication of the cut quality.

Profile Projector was used for perspex and glass measurements and a traveling microscope on wood. Wood and perspex were easily laser cut although wood produced charred edges. Mild steel was hard to machine due to its high reflectance to CO_2 laser wavelength but visible marks were made after coating. After coating, mild steel specimens were exposed to the beam for 30-500 s and their microstructural changes observed. It was observed that there were microstructural changes on all the cases. Another factor observed was the tapering effect on the holes and cuts made due to the Gaussian nature of a laser beam.

CHAPTER 1

INTRODUCTION

1.1 Background

Most parts and components used in the daily livelihood are produced through material removal processes like machining. Machining is a general term that can be used to imply cutting, drilling, engraving and marking. Machining being a crucial and unavoidable process needs improvement so as to manufacture components cheaply, accurately and at high efficiency. Different manufactured items require different materials and processes and thus different machining tools. There is therefore need to process these items with high accuracy, precision and at low manufacturing cost which necessitates the use of unique machining techniques. Conventional machining techniques are limited by the kinds of materials they can machine and the achievable accuracy and precision.

Lasers have become common in machining due to their unique properties that cannot be easily achieved using conventional machining equipment. Laser machining involves material removal or addition using laser as the tool. Laser ablation involves direct removal of materials by the interaction of the laser light with the target material [1]. In this project, laser ablation technique has been studied using a carbon dioxide (CO_2) laser. Although there are many benefits with laser ablation, the many parameters that have to be considered while machining post a challenge in predicting the output from the input parameters since all these parameters are interrelated but without a universal relationship.

1.2 Laser Ablation

Laser ablation is the direct removal of material by the interaction of the laser light with the workpiece. This process uses a highly focussed laser beam to vaporize and remove a small volume of material. Laser ablation finds applications in processes such as cutting, drilling, etching, stripping, welding and cladding of materials such as plastics, glass, ceramic and thin metals. In processes where machining dimensions range from 1 μm to 1 mm, the process is called laser micromachining. Several types of lasers are used in machining [1, 2].

Laser hole drilling makes about 3 % of the laser material processing market and there are many places within this market each with special requirements. These holes have diameters between 0.005 mm to 1.5 mm and aspect ratios (depth/diameter) from less than 1 to above 50 and they have different requirements with respect to geometrical tolerances and process side effects like thermal side effects such as change of metallurgy, recast, cracks and burrs. These through holes are used as cooling holes, gas, fuel or liquid nozzles, lubrications holes, micro-filters, separators, sieves, guidance holes, et cetera. Laser hole drilling is not limited to just round holes but other shapes can be produced using an appropriate method such as trepanning, in which a focused beam is moved around the circumference of the hole to be drilled by a rotating mirror assembly [3, 4].

Parameters that need to be considered for quality machining to be achieved include [2]:

- Laser parameters - laser power, wavelength, Depth of Focus (DOF), focal length, beam diameter, positioning of the focal point
- Material parameters - thermal diffusivity, thermal conductivity, reflectivity, absorptivity, material thickness, initial temperature and humidity
- Machining parameters- scanning speed, incidence angle, type and pressure of the assist gas.

The many interrelated parameters in laser ablation make it difficult to predict the optimum output parameters required for a particular machining process due to lack of a universal relationship. These output parameters include heat affected zone (HAZ), kerf width, depth machined, taper, entrance and exit hole diameters. This has necessitated the need to have a good understanding in order to simulate the required parameters. Components are normally painted to take advantage of the many benefits of coating. Depainting therefore becomes an occasional necessity where conventional methods of paint removal have had adverse environmental effects among other disadvantages. This has led to the invention of laser paint removal in the recent years. This is a thermal process and thus there is need to determine whether the underlying substrate is at a risk of being damaged through microstructural alterations.

1.3 Advantages of laser ablation technique

- The process is non-contact and therefore has little effect on physical and mechanical properties of the materials [5–7]. Therefore, a laser can cut materials coated with enamel, porcelain or ceramic without damage to the outer coating.

- Hard-to-machine materials such as titanium and diamond can be easily laser cut while maintaining high accuracy and at a relatively low cost as compared to other machining processes.
- Due to the power stability of the laser beam, very tight tolerances can be achieved with laser [5].
- The process is economical since scrap and waste after machining are reduced due to the small kerf widths (up to 0.125 mm). Lasers are capable of doing short runs at a low cost thus advantageous for manufacturing lower volumes with shorter runs as tooling and associated costs are all eliminated.
- It is easy to achieve repeatability since the tool does not change in size or wear while machining making the laser to perform continuously.
- By varying the cutting speed, power, focal spot size, focus position and assist gas pressure, characteristics of the cut such as kerf, taper and surface finish, can be controlled to complement the material type.
- Laser machining is extremely flexible since the operator can change from one part to another within a very short time. This saves on time and thus overall manufacturing cost [5].
- Laser-machined parts are free of distortion because laser cutting requires no physical contact between the work piece and a cutting tool. Dross (burr) from

laser cutting is minimal with most materials giving a good finish and eliminating polishing operations.

- HAZ in laser machining is relatively narrow and the resolidified layer is of micron dimensions making distortion in laser machining to be negligible [5].
- No solvents are used and therefore environmental friendly with operators not exposed to chemicals.
- It is relatively easy to automate, e.g., by using robots.

In addition to the above advantages, a CO_2 laser has the following merits [6]:

- It is relatively cheap and easy to make compared to other types of lasers.
- The beam is prevalent in machining polymers which have wide applications in micro-electro-mechanical systems (MEMS), medical devices, microelectronic and sensor industries where high precision and high quality are required. Polymers have recently replaced silicon and glass in the production of micro-fluidic devices due to their direct methods of fabrication and the relatively low cost of the raw material.
- It has high thermal stability
- It is capable of drilling deep holes through very hard materials
- High power output are achievable for practical machining

- Like other gas lasers, CO_2 laser does not have a big problem of thermal lensing, and thus can be made in big sizes and still obtain a good quality beam.
- Premix gases required for the operation of the laser are readily available [1, 8]. This eliminates problems associated with mixing ratios.
- Gas purity is not very critical
- Although vacuum is required, it is modest of 10-100 Torr which is easily achievable
- Only minimal maintenance is required for real applications.

1.4 Disadvantages of laser ablation technique

- Low energy efficiency
- Laser cutting effectiveness reduces as the workpiece thickness increases
- Generally, laser cutting produces tapered holes especially when drilling deep holes.

1.5 Problem Statement

There are many interrelated variables that control laser interaction with the material. These variables include laser properties, material properties and machining conditions that influence the cut quality. The cut quality is gauged by surface roughness, Material Removal Rate (MRR), kerf width, hole diameters, depths and HAZ. Since these input parameters are interrelated and have no universal relationship, this has made it difficult to predict output parameters from any input parameters. As a result, trial and error method has been the only choice while machining. For any given material, the process parameters need to be adjusted in order to achieve optimum machining performance [9]. With laser paint removal being a thermal process, there is also need to study the effect of exposure time on microstructures so as to be able to determine safe working conditions of underlying materials.

Lasers are also expensive, require high skills for repair and maintenance making laser machining very rare in Kenya. With Vision 2030 in mind, development of laser machining systems would be of great importance for the manufacturing sector. There is therefore need to develop a laser machining system and to study the relationship between process parameters and cut quality characteristics to help in predicting the effects of various input parameters such as number of passes and exposure time on the cut quality.

1.6 Objectives

1.6.1 General objectives

Efficiency, accuracy and costs are important issues considered in manufacturing industries. There is therefore need to be able to predict cut quality from the effect of input parameters so that optimization can be achieved. This work aimed at developing a CO_2 laser system and using it to determine the effect of exposure time and number of passes on depth, HAZ, hole diameters, kerf widths, taper, microstructure and aspect ratios in various materials. With the knowledge from the experiments, it is possible to be able to predict the cut quality from the machining conditions. This will help reduce machining time, increase accuracy and precision, reduce running costs and therefore minimize on overall machining costs of hard-to-machine materials. In order to achieve this overall objective, this was done through the following supporting objectives:

1.6.2 Specific objectives

- Development of a CO_2 laser
- Development of a CO_2 beam manipulation system
- Incorporation of the laser in a machining system to provide accurate holding and automatic movement of the workpiece
- Development of a computer program to achieve x and y motions for the workpiece
- Experimentations on the effect of varying input parameters on output parameters
- Study on microstructural changes in mild steel on laser beam exposure.

1.7 Justification

In Kenya, there are few industrial laser systems for machining. This could be due to their complexity, high costs and maintenance requirements. There is need to develop and implement a cheap and simple CO_2 laser system to be used in local institutions for machining and also for educational purposes. By this, it will be possible to predict how the various input parameters influence cut quality and hence achieve optimization.

1.8 Thesis Outline

This thesis consists of an abstract, an introduction to laser ablation, literature on research done so far in this field, methodology used, results and discussion, recommendation and a comment on future expectation.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Lasers

There are different types of lasers based on the type of the active medium used which can be gas, semiconductor, liquid or insulating solid [5, 10]. Gas lasers such as CO_2 laser, have gas as the active medium and have the following advantages [8]:

- They can be directly excited with electric current
- They are homogeneous in nature
- They allow flexibility in the design of the resonator and can be scaled easily
- Propagation of the beam is unimpeded
- They are relatively inexpensive compared with other high power lasers.

2.2 History of CO_2 Lasers

Although there are many types of lasers in use today [11], only a few of them are widely used in machining, for example, Neodymium-doped Yttrium Aluminium Garnet (Nd:YAG) and CO_2 lasers, as they have the following benefits [11, 12]:

- Wide range of output powers.
- Relatively low running costs.
- High efficiencies (especially with diode-pumped lasers).

- High repetition rates (many tens to hundreds of kilohertz) with pulsed lasers.

The CO_2 laser was invented by C.K.N. Patel in 1964 while working at Bells Labs [5,13]. In his first invention, he used pure CO_2 and produced 1 mW of power with an efficiency of 0.0001%. By adding Nitrogen (N_2), the power improved to 200 mW and when Helium (He) was added, power jumped to 100 W with an efficiency of 6%. Today, CO_2 lasers have a gas mixture of CO_2, N_2 and He at a ratio of approximately 1:1:8 respectively. 100 W CO_2 laser was first marketed by Coherent Company in 1966 and its 250 W version in 1968. Since then, the technology has improved and lasers with even higher power have been developed. Currently, CO_2 lasers with as high as 4 kW are available.

2.3 Methods of laser ablation

Laser ablation technique uses a highly focussed laser beam to vaporise and remove a small volume of material. However, the mechanisms which influence material removal differ depending on the material, gas jet condition and energy density [5,14]. Generally, laser cutting can be categorized into three processes [5]:

- Evaporative cutting where a kerf is created through evaporation of the material by the impinging laser beam. This usually occurs with polymers and composites [15].
- Fusion cutting where a kerf is created by melting the workpiece material and the molten layer ejected using coaxial gas jet. This usually occurs during laser cutting of ceramics and metals.

- Reactive gas cutting where a kerf is created through a combination of melting and chemical oxidation under laser heating, with the oxidation effect as the primary mechanism.

Generally, a laser machining system consists of the laser system, beam delivery system, control system and the workpiece mounted on either a movable or stationary table to generate the desired profile as shown in Figure 2.1, [5].

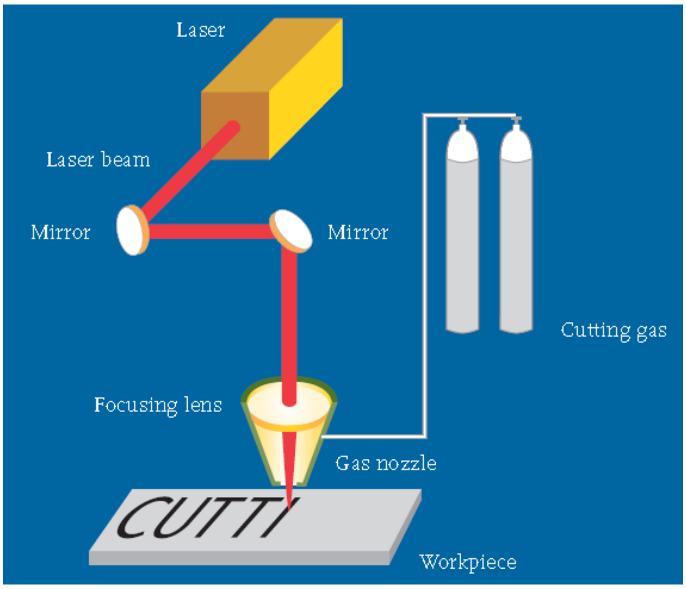


Figure 2.1: How a laser machining system generates a profile

During the cutting process, power densities ranging from 10^5 to 10^8 W/cm^2 is absorbed by the material in the zone of focus and gets transformed into heat [10]. This heat locally provokes a quick increase of the temperature of the piece where the fusion and/or the vaporization of the interaction zone determine the formation of a hole. A typical laser cutting process is shown in Figure 2.2, [8].

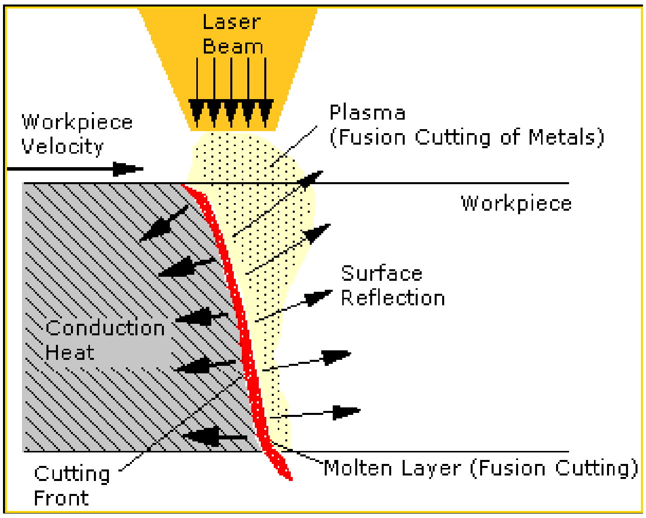


Figure 2.2: An outline of a laser cutting process

There are known relationships involved during a laser ablation technique, one of which is the rate of mass removal from kerf width during machining expressed as

$$\mathrm{Lim}_{\Delta t\longrightarrow 0}\frac{\Delta m}{\Delta t}=\frac{dm}{dt}=\frac{d}{dt}(\rho A h) \tag{2.1}$$

where ρ is the material density, A is the kerf area removed and h is thickness removed.

Increasing laser power increases the kerf width which implies increased MRR and vice versa. Kerf width increases slightly with an increase in material thickness. High assisting gas jet velocity reduces required power in laser machining. In engineering processes, the properties of the manufactured products dictate the performance of the products. For instance, the surface finish attainable has been found to affect the part accuracy, requirement for post processing and the functionality [8]. In other cases, machining time or the efficiency of the process is the concern of the manufacturer.

2.4 Parameters affecting laser ablation techniques

The parameters influencing a laser cutting process determine the quality of the end product and thus have to be considered for quality machining to be achieved. Since there are many parameters to be considered, this increases the complexity of laser machining process making it impossible to predict the output parameters from the input laser and material parameters [16, 17]. Another important issue in laser machining is the optimization of the parameters for the best parameter combination in terms of surface roughness, kerf width, HAZ and MRR that directly influence machining time and accuracy.

2.4.1 Laser parameters

Generally, laser parameters affecting machining performance include laser output power, beam spot size, DOF and wavelength. Other influencing factors include [10, 18]:

- Mode: In laser descriptions, a mode refers to the cross-section of the beam profile. Transverse Electromagnetic Mode (TEM) mode relates to the beam's ability to be focused and is comparable to the degree of sharpness of a cutting tool. The lowest order or reference mode is TEM_{00}, of which the beam's profile simulates a Gaussian distribution curve. Modes that approach this energy distribution can be focused down to the laser's theoretical minimum spot size and give the sharpest energy density. TEM_{00} has the highest beam quality $\text{M}^2 = 1$, gives the sharpest spot size, has highest power density and lowest divergence with a

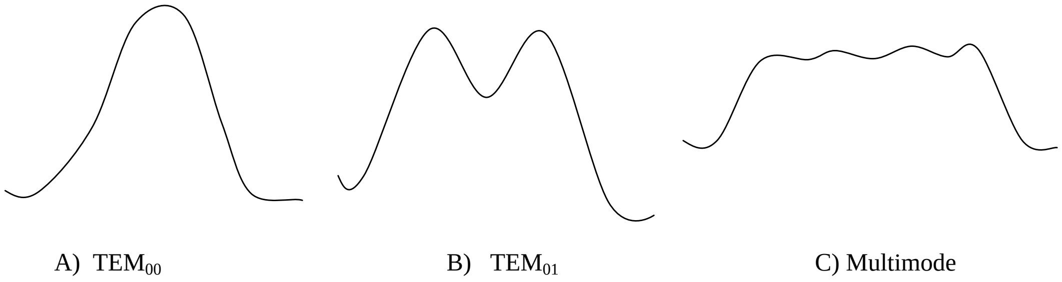


Figure 2.3: Laser beam profiles for various modes of lasers

profile as shown in Figure 2.3.

TEM$_{01}$ has medium beam quality with $M^2 = 1.7$, gives a larger spot size and results in wider kerf widths. A multimode beam has poor quality with M^2 greater than 5, gives the largest spot size and is accompanied by insufficient power density for cutting. If all the beams have the same power and spot size at the focusing lens, the focused spot sizes will vary as shown in Figure 2.4.

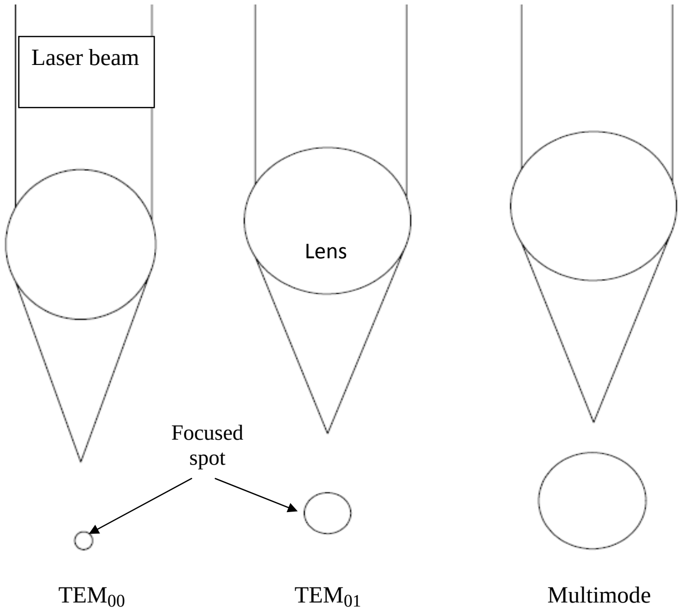


Figure 2.4: Comparable focal spot sizes for different laser modes

- Output power: Holding all the other machining considerations constant, increased power allows for faster processing speeds and the ability to cut thicker sections of materials at high MRR.
- Stability: Since quality results are obtained by the application of consistent energy, the stability of the laser's output is a key feature in cutting. This includes maintaining unwavering output energy (power stability), consistent beam quality (mode stability) and fixed energy concentration (pointing stability).
- Polarization: Uncontrolled or random polarization can affect the relative degree of absorption of the beam's energy that is coupled into the material at a given moment.

2.4.2 Material parameters

Generally, the following material properties influence laser machining process [19, 20].

- Absorptance: Laser wavelength determines the transparency or absorptance of materials being machined. The higher the absorptivity of a material to a certain wavelength, the higher the machinability of the material by the laser and vice versa.
- Reflectance: Reflectance is the ratio of the power reflected from a surface to the power incident on it. Generally, metals have high reflectivities to long wavelength lasers such as CO_2.
- Thermal conductivity: A high thermal conductivity of the processed material

causes the formation of molten edges and will make the resolution of the projection process worse.

- Thermal expansion coefficient: Large thermal expansion coefficients cause the formation of cracks in brittle materials with low thermal conductivity because of high thermal gradients and high mechanical stress.
- Quality of the surface: Smooth unirradiated surfaces mostly have a lower absorptance than already ablated surfaces, so that for the initialization of the ablation process a higher laser fluence is necessary. Impurities or water films at the sample surface can cause higher ablation thresholds too.

Another important material parameter that appears often in the laser machining analysis is thermal diffusivity α. This is related to material properties; thermal conductivity (κ), the materials density (ρ) and specific heat (C_p) as follows , [10].

$$\alpha = \frac{\kappa}{\rho.C_p} \tag{2.2}$$

Absorption depends on reflectance and transmittance of the material as given by Eq. 2.3.

$$A = 1 - R - T \tag{2.3}$$

where R is the reflectivity, A is the absorptivity and T is the transmissivity. For opaque materials, $T = 0$ and thus Eq 2.3 reduces to :

$$A = 1 - R \tag{2.4}$$

Reflectivity, absorptivity and transmissivity of a material depend on the laser wavelength. High reflectivity and transmissivity of a material to a certain wavelength don't favor the machining process.

2.4.3 Beam delivery and optics parameters

Even if the best laser and material parameters are considered in a laser machining process, best quality and efficiency will not be achieved if beam delivery and optics parameters are ignored. The range of the laser wavelength determines the types of optics to be used. CO_2 laser uses infrared (IR) optical materials such as [21]:

- Germanium (Ge) with high refractive index n = 4.0, exhibits poor transmission qualities at high temperatures greater than 200 ^{0}C.
- Zinc Selenide (ZnSe) with refractive index n = 2.4, scratches easily, requires AR coating.
- Sodium Chloride (NaCl) with low refractive index, water soluble and has good transmission.

It has been found that focusing lens controls the spot size and DOF as given in Eq. 2.5 and Eq. 2.6.

$$DOF = 2.44\lambda M^2(\frac{f}{D})^2 \tag{2.5}$$

$$d_{min} = \frac{4fM^2\lambda}{D\pi} \tag{2.6}$$

where d_{min} is the minimum spot size, λ is the laser wavelength, M^2 is the beam quality factor, f is the lens focal length and D is the unfocused beam spot size. Smaller beam spot size allows higher travel speeds, produces smoother surface and cuts narrower kerfs [1].

2.4.4 Other parameters

In addition to the above parameters, laser machining is influenced by other factors like the assist gas, scanning speed, laser beam angle and presence or absence of coating or lubrication on the sample to be machined. With an assist gas, factors to be considered include the type, flow rate and purity [22]. These influence the speed of machining and surface finish. For instance, when oxygen is used as an assisting gas, the exothermic reaction results in reduction of machining time. It has been noted that some gaseous impurities can modify the characteristics of the beam generated by a CO_2 laser and cause some nonreproducible performances such as loss of power, reduced stability of the laser beam and shorter service life for electrodes and delivery mirrors [19].

These impurities can occur from the gas used to fill the resonator or from chemical and/or physical reactions during the operation of the laser. In experiments to produce CO_2 laser, addition of small quantities of O_2, H_2, Ar, H_2O resulted in dampness that destabilized the discharge. Moreover, absorption of water by the mirrors adversely affected the optical properties of the mirrors.

2.4.5 Beam propagation characteristics

Along the optical axis z of a propagating Gaussian beam, spot size *w(z)* varies as

$$w^2(z) = w_0^2[1 + (\frac{z}{z_0})^2] \tag{2.7}$$

where w_0 is beam spot size at the waist. A Gaussian beam radius or beam waist w_0 is the radius at which the intensity has decreased to $1/e^2$ or 0.135 of its axial or peak value. A typical Gaussian beam with brightness intensity is as shown in Figure 2.5.

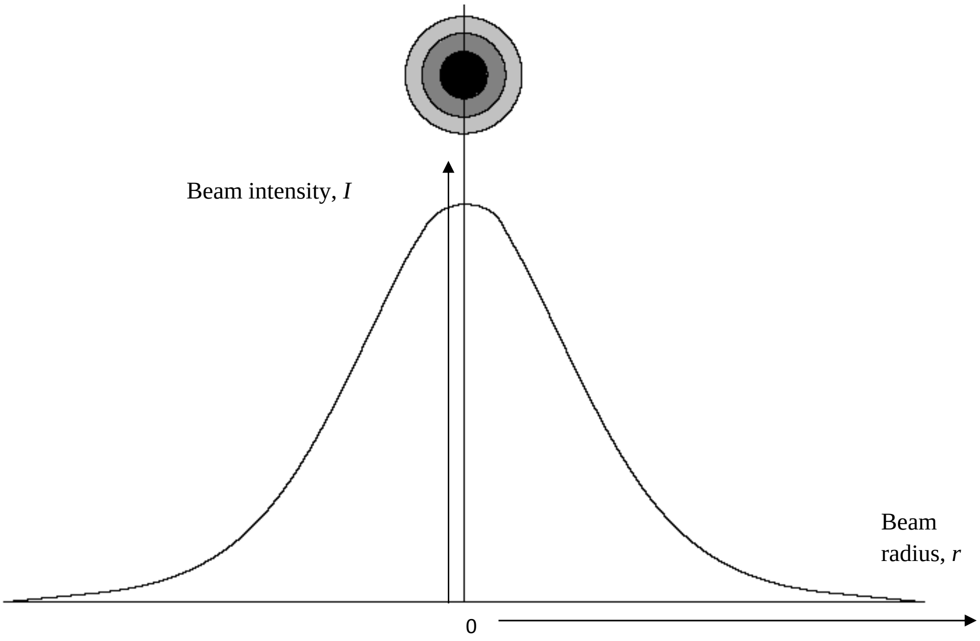


Figure 2.5: Spatial intensity distribution of a Gaussian Beam

2.5 Interaction of high-power laser beams with materials

The input of energy or energy deposition process from a laser beam into the near-surface regions of a solid involves electronic excitation and de-excitation within an extremely short period of time [1, 10, 23]. This means that laser-matter interaction within the near-surface region achieves extreme heating and cooling rates in the range of 10^3 - 10^{10} K/s, while the total deposited energy (typically, 0.110 J/cm^2) is insufficient to significantly affect the temperature of the bulk material. This allows the near-surface region to be processed under extreme conditions with little effect on the bulk properties. The resulting temperature profile depends on the deposited energy profile and thermal diffusion rate during laser irradiation.

Only part of the laser power is useful for cutting while the rest is wasted through reflection by the workpiece surface or transmitted through successive partial reflections. Absorption of laser radiation [18] in materials is generally expressed by Beer's Lambert Law :

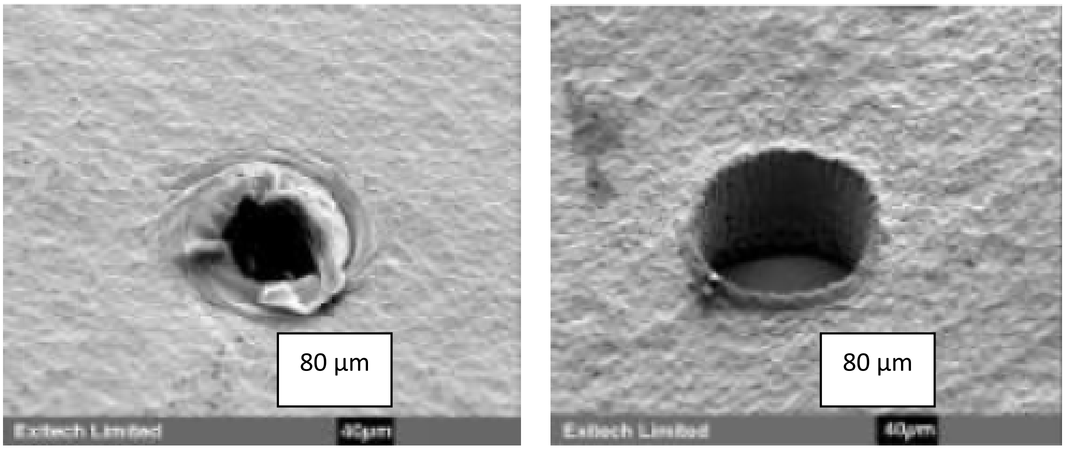
$$I(z) = I_o e^{-\beta z} \tag{2.8}$$

where *I(z)* is the laser intensity at depth z, I_o is the incident laser intensity and β is the absorption coefficient of the material. Laser power influences cutting quality and performance where lower power and high speed result in improved surface roughness and kerf width [18].

2.6 Performance optimization for laser machining applications

Dutta et al. [23] noted that there are major hurdles that restrict wider use of lasers in routine material processing applications such as limitation of beam size with respect to the component size/dimension, high installation and replacement cost, additional and expensive accessories, and need for skilled manpower. However, the high productivity, precision and versatility of laser material processing can easily overcome the above limitations, if areas are identified where laser offers unmatched advantages in terms of end properties and product quality in comparison to those achieved by conventional techniques.

Malcolm [6] investigated on industrial applications of laser micromachining in microvia, ink jet printer nozzle and biomedical catheter hole drilling, thin-film scribing and MEMS fabrication. In hole drilling, the combination for high-resolution, accuracy, speed and flexibility allowed laser micromachining to gain acceptance in many industries. Laser drilled holes showed better profiles and geometrical accuracy than traditionally-machined holes as shown in Figure 2.6, [6].



a) Mechanically drilled hole

b) Laser drilled hole

Figure 2.6: Difference between mechanical and laser drilled holes

In another paper, Malcolm et al. [7] investigated in excimer laser drilling of microvia holes in circuit interconnection package. They found that the higher the machining speed was, the lower the costs of production became. Further investigation resulted in the knowledge that increased printer quality was achieved by simultaneously reducing the nozzle diameter, decreasing the hole pitch and lengthening the head.

Berrie et al. [24] experimented on the effect of lens, position and focal plane, speed of cut and power on the cutting and drilling rates of Polymethyl methacrylate (PMMA). It was found that PMMA/perspex degraded to 100% monomer (methyl methacrylate) when heated, the rate of degradation being independent of the molecular weight of the polymer. They developed a model for cutting and drilling by vaporisation based on a heat balance and the Gaussian mode of propagation with the following assumptions:

- The laser energy was absorbed in a thin layer at the surface of the material
- Energy losses due to radiation and conduction were negligible
- No absorption of light occurred in the vapour plume
- The laser beam propagation could be described by Gaussian optics
- Any changes in the intensity at the surface resulted in changes in the temperature, and hence in the evaporation rate.

They also found that an increase in power increased the rate of drilling. Another point noted was that holes drilled with different lenses differed only superficially with the short focal lengths producing shallower, wider holes, whereas with the longer focal lengths, tapering was more pronounced. At low speeds or large depths there was little or no dependency of depth of cut on the focal length of the lens.

Pietro et al. [25] used model-based optimization process in laser machining and noticed that as speed increased, the amount of power lost through the kerf decreased. This indicated that the cutting process was more efficient at higher processing speeds due to better beam coupling with the workpiece material. It was shown that although transmission and reflection mechanisms were identifiable during the reactive gas cutting of steel, reflection losses were minimised at high processing speeds.

Larson et al. [26] examined CO_2 laser cutting of holes in kevlar laminates with different thermal properties and thicknesses. They noticed that the kerf width reduced with increasing cutting speed for all the workpiece thicknesses. This is because the irradiated laser power scans the surface at high rates with increasing cutting speed. In this case, the rate of energy consumed in cutting reduced, since the laser power remained the same for all the cutting speeds. Consequently, sideways burnings were minimized and kerf width enlargement suppressed with increasing cutting speed. Kerf width variation with workpiece thickness was small due to laser power intensity at the workpiece surface, which was just sufficient to proceed with the cutting process.

Vijay et al. [27] studied UV laser micromachining of a biodegradable polymer for applications in biomedical engineering. Parametric studies were conducted on Polyvinyl Alcohol (PVA), a biodegradable polymer, to produce micro channels and micro holes. They showed that the relation between the etching depth and intensity of the laser, for F greater than F_{th}, is given by :

$$L = \frac{1}{\alpha}\ln(\frac{F}{F_{th}}) \tag{2.9}$$

where, L is etch depth per pulse, α is absorption coefficient, F is the induced fluence and F_{th} is threshold fluence of the material, below which there is no etching. In their study, they also found out that for photochemical ablation to occur, energy of the photons at that wavelength should overcome the intermolecular bond energies of the polymer. The relation between the photon energy of light and laser wavelength is given by

$$E = \frac{1.245}{\lambda} \tag{2.10}$$

where, λ is the light wavelength (μm) and E is the energy of photons (eV). This shows that as the wavelength increases, the photon energy decreases. From the equation, a UV laser with a wavelength of 266 nm has photon energy of 4.66 eV. Typically the C-C bond energy is 4.6 eV and C-H bond energy is 4.2 eV in polymers. It can be seen that for photochemical ablation to occur in polymers, the photon energy of the light should be greater than the bond energy of the material.

Yilbas [28] assessed cutting quality and thermal efficiency of a laser gas assisted cutting process. He found that increasing laser beam scanning speed reduced the kerf width and that the kerf width increased with increasing laser output power. The main effects of all the parameters employed had significant influence on the resulting cutting quality.

Another major factor in laser machining is in the optics where very high optical cleanliness is required. Any dirt/dust on optical surfaces can either absorb or diffuse laser energy. To obtain the right conditions for laser optics, the optic should not be mechanically damaged by scratching or chemically damaged by etching or other chemical attack. Scratching or etching would remove the coating on optical surfaces thus reduce the effectiveness of the surfaces.

Carroll et al. [29] while experimenting on materials processing performance of a Chemical Oxygen-Iodine Laser (COIL) found that for a given cut depth, power and spot size, COIL was cutting steel approximately three times faster than a CO_2 laser using an inert gas assist. However, the capital and operating costs of today's COIL devices make them economically uncompetitive devices in the low to middle power level markets.

The experimental and theoretical studies of Avanish et al. [30] showed that process performance can be improved considerably by proper selection of laser parameters, material parameters and operating parameters. In their review, they made these four conclusions:

- Laser Beam Machining (LBM) is a powerful machining method for cutting complex profiles and drilling holes in wide range of workpiece materials. However, the main disadvantage of this process is low energy efficiency during production.
- Apart from cutting and drilling, LBM is also suitable for precise machining of micro-parts. Holes of very small diameters with high aspect ratio of more than 20 can be drilled accurately using nanosecond frequency tripled lasers. Cutting of thin foils of up to 4 mm thickness has been done successfully with micro-range kerf width.

- The performance of LBM mainly depends on laser parameters (e.g. laser power, wavelength, mode of operation), material parameters (e.g. type, thickness) and process parameters (e.g. feed rate, focal plane position, frequency, energy, pulse duration, assist gas type and pressure). The important performance characteristics of interest for LBM study are HAZ, kerf or hole taper, surface roughness, recast layer, dross adherence and formation of micro-cracks.

- The laser beam cutting process is characterized by large number of process parameters that determine efficiency, economy and quality of whole process. Researchers have therefore tried to optimize the process through experiment based, analytical, and Artificial Intelligence (AI) based modelling and optimization techniques to find optimal and near optimal process parameters. However, modelling and optimization of laser beam cutting with multi-objective and hybrid approach are nonexistent in the literature.

Tuan et al. [31–33] designed a series of experiments to give an insight into the potential capabilities of the Laser MicroJet (LMJ) where they coupled a laser beam into a water jet. Their results showed that the LMJ is undoubtedly an appropriate machining technology for various applications. The cuts are clean, reliable, accurate, and show negligible heat damage. In particular, the cutting of complicated shapes such as spirals and pillars provide excellent results, achieving consistent pattern transfer. The principle of LMJ is as shown in Figure 2.7, [32, 33].

Steyn et al. [34] prepared and experimented tool steel on improvement of the surface

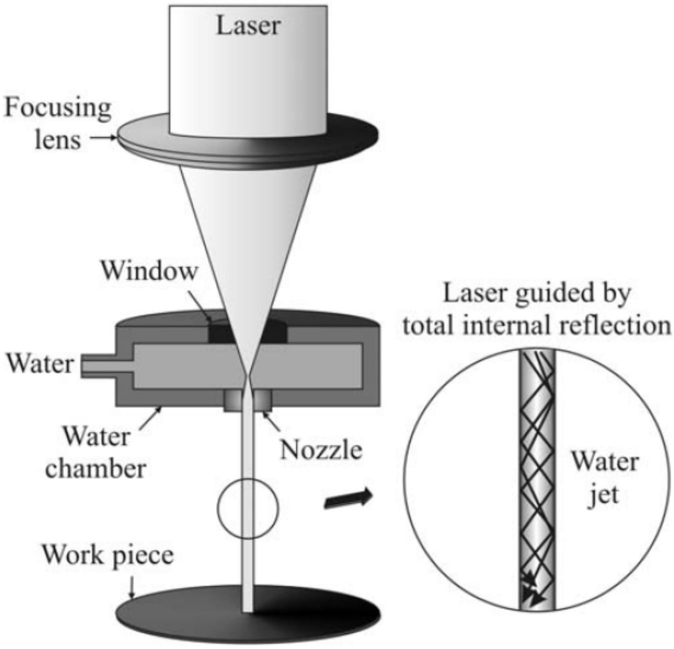


Figure 2.7: The principle of Laser Micro Jet (LMJ) Cutting

finish obtained by laser ablation. They noted that by adjusting a number of laser and process parameters, for example, laser frequency, power, scan speed, track displacement, laser defocus, the number of layers machined and spot size, the surfaces either improved or deteriorated depending on the combination of parameters.

Tantra [35] in his laser cutting research found that most non-metallic materials are highly absorptive at CO_2 laser wavelength. There are three main types of laser cutting processes [35]:

- Melt shearing (mostly for thermoplastic) which cuts very quickly with high quality edges
- Vaporization which is usually for acrylic

- Chemical degradation characterized by slow cutting, high temperature, flat and smooth result.

At constant laser power, cutting speed decreased with increasing material thicknesses but higher power meant higher cutting speeds for the same sheet thickness.

Pham et al. [36] carried out an experimental study to identify the relationship between surface finish and the laser parameters such as current, pulsing frequency and scanning velocity on a micro tool. The surface was first polished to a roughness Ra = 0.2 μm and layer thickness maintained at 2 μm each. To obtain a true representation of the attainable surface finish throughout the experiment, the scanning direction of the laser beam was restricted to only the x- and y-axes. They noted that lower lamp currents, speeds, and frequencies were more appropriate when the surface finish was a concern although this meant longer machining times and thus increased manufacturing costs. Copper revealed better accuracy than steel due to their differences in physical properties and in particular the thermal properties. They had the following conclusions to make:

- Laser milling is capable of producing adequate surface finish for micro tools.
- Features with an aspect ratio of 2.5 are achievable with the laser milling process.
- Accuracy is directly influenced by laser-material interaction.
- Material properties have to be considered in order to improve process accuracy.

- Thin walls down to 40 μm can successfully be produced while the smallest groove machined was 120 μm.
- Shorter pulse durations offered highly improved surface finish and accuracy when employed in the laser milling process.

Naeem [37] investigated the machineability of polymer based composites, metal based composites, ceramics and silicon wafers with CO_2 and Nd:YAG lasers and concluded that:

- CO_2 laser is best suited for cutting polymer composite materials.
- Both CO_2 and Nd:YAG can be used for cutting ceramic and metal based composite material.
- CO_2 laser cutting of polymer composites is dependent upon the fibre reinforcement and the composite thickness.
- For carbon fibre reinforced composites, it was difficult to achieve cuts in material thickness over 4 mm.
- Cutting of ceramic materials was affected by cracking due to thermal shock which can be reduced by pre/post heating.
- Composite materials can be cut by using laser but the quality is not as good as with the water jet cutting.

Ramesh et al. [38] researched on Laser-Assisted-Mechanical Micromachining (LAMM) and found that by integrating thermal softening with mechanical micro-cutting processes, thermal softening of workpiece resulted in low cutting forces and overcame limitations of tool stiffness, bending strength and low material removal rate. This has an overall improvement on dimensional accuracy.

Ahn et al. [39] investigated the effects of laser power, cooling rate, scanning speed and assist gas pressure on the quality characteristics of laser cut 316L stainless steel. In their determination of optimum parameters of laser cutting on the material, they observed that laser power, scanning speed and assist gas pressure did the major effects on kerf width. Smallest kerf widths were achieved with low laser power,high scanning speeds, low gas assist pressure and moderate cooling rates.

Yilbas [40] investigated the effects of laser cutting parameters (output power, cutting speed, and oxygen assisting gas pressure) on kerf size variations of thick sheet metals. A factorial analysis was carried out to identify the main effects and interactions of the parameters and thermal efficiency of cutting and liquid layer thickness formulated. Optical microscopy and Scanning Electron Microscopy (SEM) were carried out to examine the cutting defects and the kerf size variation. It was found that laser output power and oxygen gas pressure had significant effect on the percentage of kerf width variation.

Yilbas [41] studied parameters involved in laser hole drilling of sheet metals that affect hole quality in terms of internal form and taper and related geometrical features, and the extent of HAZ. He observed that main effects of laser parameters as well as their interactions, had significant effects on all features of hole geometry. Drilling medium pressure was found to be a very effective factor, since its interactions with the other parameters in any order were significant.

2.6.1 Laser machining of nonmetals

In general, non-metallic materials are good absorbers of infrared energy produced by a CO_2 laser. Likewise, they are generally poor conductors of heat and have relatively low boiling temperatures. As such, the energy intensity of a focused beam is almost totally absorbed by the material at the spot and will instantly vaporise a hole [35]. This has made CO_2 laser to be the most commonly used laser in machining of nonmetals.

2.6.1.1 Laser machining of wood

The laser offers a number of attractive advantages for the cutting of timber, plywood, and particleboard. In particular, it provides narrow kerfs of 0.3-0.8 mm, the absence of sawdust, the ability to contour cut in any direction and minimum or no noise. While the use of a laser eliminates rough, torn-out, and fuzzy edges which are evident with conventional sawing techniques, it is characterized by burned edges produced by the laser heat. Greater amounts of charring will result when the material thickness is increased, thereby slowing the cutting feed-rates. CO_2 laser has been very efficiently and successfully used to machine most non-metallic materials like wood because these materials highly absorb the CO_2 laser wavelength of 10.6 μm.

Nukman et al. [42] investigated the effects of CO_2 laser cutting parameters on the cut quality of several selected Malaysian wood. The processing variables taken into investigation were laser power, nozzle standoff distance (SOD) or focal point position, nozzle size, assist gas pressure, types of assist gas, cutting speed and delay time. The wood properties observed were thickness, density and moisture content of the wood. The analyses considered were of the geometric and dimensional accuracy (straight sideline length, diameter of circle, kerf width, and percent over cut), material removal rate, and severity of burns of the matters upon machining with compressed air or any assist gases. They made the following conclusions:

- Selection of cutting parameters for laser cutting of wood was governed by materials moisture and air content, workpiece thickness and density
- For material thickness of 10 mm for all wood samples, it was not possible to achieve a successful cut using laser power of 100 W at 1.2 m/min cutting speed
- Due to exothermic reaction, cutting with compressed air exhibited severe burns and charring with larger kerf width, over cuts and higher portions of material loss
- Use of nitrogen was proven to be reliable in reducing material loss and over burning due to the compensation of heat accumulation by offering cooler and inert environment to the cutting process

- Closer dimensional accuracy and acceptable surface finish in laser cutting of wood were obtained when nitrogen was used in assisting the cutting process as compared to the use of compressed air instead

Richard et al. [43] investigated on novel cutting techniques in wood machining processes by evaluating three new approaches to kerfless wood cutting namely cutters, high-velocity liquid jet and laser beam. It was apparent that the high-velocity liquid jet and laser beam offer great potential in secondary manufacture, in particular for cutting of intricate contours and complex computer-controlled operations.

2.6.1.2 Laser machining of composites

In alloys, assist gases are used in industrial laser machining to protect the laser optics by blow back of ejected debris and to allow a chemical reaction between the substrate and assist gas in order to generate more energy as noted by Voisey et al. [44]. These authors investigated the effects of using assist gases in the drilling of different substrates with the aim of investigating whether assist gases are beneficial to the laser drilling of superalloys. The effectiveness of the drilling process was monitored by the mass loss of the sample and calculation of the volume of material removed per hole. They found that assist gases brought no great benefit to the laser drilling process as they had little effect on the drilling of the ceramic top coat. The final surface of the top coat at the end of the process was however affected by the use of assist gas.

No noticeable variation in the mass of substrate removed per hole was observed for either assist gas used to drill both the blind and through holes. Changing from an oxidising (oxygen) to an inert assist gas (nitrogen) did not have any discernable effect, indicating that the superalloy, as well as the zirconia top coat, do not have any chemical interaction with the oxygen assist gas. The lack of reaction between zirconia and oxygen was expected since zirconia was already an oxide. There exists a wide range of materials that has been laser machined including several types of rocks [45].

2.6.1.3 Laser machining of glass

Conventional glass cutting is done by scoring and breaking which produces micro-cracks and splinters, and leaves cutting oil residues. These influences lead to lowered strength and pollution of the glass sheets. If the glass has to be bent or tempered, further grinding, polishing and washing processes become necessary.

Using the laser-cutting method, a certain temperature is generated at each point of the planned scoring line. The following cooling creates the score exactly with high precision, giving a smooth and polished-like edge [46]. As opposed to quartz, most types of glass are prone to thermal shock and are therefore generally not suitable candidates for laser cutting. The instantaneous heat of the laser's beam provides cutting action by both vaporisation and the blowing away of molten glass from the cut zone [47].

Christoph [48] in his paper on laser cutting of glass, with an aim of producing high quality cut on glass, separated glass by laser induced tensions. This was done by preheating the glass surface by a locally precise laser beam followed by cooling through high temperature gradient within the same local limitations. This induced thermal extension and tensile stress resulting in a crack along a defined contour. The absorption of the CO_2 radiation through glass was by pure surface absorption where 90% of the laser beam energy was directly converted to heat at the glass surface with typical penetration depths of 10-50 μm. CO_2 laser is the most appropriate among other industrialized laser types for glass cutting application due to its high absorption characteristics. Results showed no micro-cracks, no chipping and a clean process, thus showing characteristics certainly superior to the conventional method.

Abramov et al. [49] investigated a non-ablating CO_2 laser scoring process based on thermal induced stress that generates a high-quality clean glass edge without splinters and micro cracks. Conventional glass cutting has been accomplished by using mechanical tools for scoring followed by bending separation. An alternative scoring process uses CO_2 laser radiation to heat the glass and then rapidly cooling it to create transient tensile stress via temperature gradient. They found that tensile stress, σ, produced during the process was proportional to

$$\sigma \approx \alpha_G \times E \times \Delta T \tag{2.11}$$

where α_G is a linear thermal expansion coefficient of the glass, E is a modulus of elasticity and T is a temperature difference between the radiated surface of glass and the glass surface under the cooling nozzle. The generated stress had to be higher than the molecular bonds of the glass. The lower the thermal expansion of the glass, the lower the tensile stress and subsequently, the lower the scoring speed can be achieved.

Laser separation of glass with zero width could be summarised by the following steps

[50]:

- The glass surface was heated by laser beam
- Compressive stress built up in the surface layers, but there was no surface damage
- When a coolant was applied, this cooled the surface on the cutting line
- Steep temperature gradient generated high tensile stress on the glass surface
- This caused propagation of the developing crack in the glass sheet.

2.6.1.4 Laser machining of polymers

Perriere et al. and Davima et al. [15, 51] did some experimental studies on CO_2 laser cutting to evaluate the effect of the processing parameters (laser power and cutting velocity) on the quality of the cut for several polymeric materials. A plan of experiments was established considering CO_2 laser cutting with prefixed processing parameters in several polymeric materials with different thicknesses. In evaluating the quality of the cut, the presence of burr and dimension of HAZ were considered. Laser cutting workability of the polymers/composites under investigation was found to be very high for PMMA, high for Polycarbonate (PC), high/medium for Polypropylene (PP) and lower for reinforced thermoset plastics.

In another paper, Davima et al. [52] did an evaluation on cutting quality of PMMA using CO_2 lasers. The quality of cutting was evaluated in terms of surface roughness, dimensional accuracy and HAZ in linear and complex 2D cutting. The results also showed good repeatability. From their experiments, they drew the following conclusions:

1. Generally, HAZ increased with laser power and decreased with the cutting velocity
2. The surface roughness increased with a decrease in laser power and an increase in cutting velocity
3. PMMA in complex 2D cutting presented dimensions of HAZ between 0.12-0.37 mm, without burrs and low surface roughness less than 1 μm.

2.6.1.5 Laser machining of ceramics

Ceramics have many desirable properties, such as excellent wear resistance, chemical stability, and high strength even at elevated temperatures. In spite of all these characteristics, the difficulty in machining has been a major obstacle that limits the wider application of these materials since they have strong bonds which are either covalent or ionic in nature [36]. Fortunately, with the discovery of laser machining technology, these and many more materials have been machined successfully.

Yung [53] invented a technique for machining brittle ceramic materials by first softening them with heat from a laser to find out whether this would significantly reduce the manufacturing cost of components. The technique was expected to be especially critical for certain kinds of ceramic components that are not produced in large enough quantities to justify the expense of designing costly dies. This is because, components made in small lot sizes might be produced far more economically by machining instead of being formed with dies. The method was found to be successful but the position and strength of the laser had to be controlled precisely so that it heated only a tiny portion of the material just before it was machined.

2.6.2 Laser beam interaction with metals

Physical properties of metals such as thermal conductivity and material viscosity influence quality, productivity, profitability and safety of laser cutting operation [54]. A laser beam is a flexible heat source whose intensity and interaction with materials can be controlled by varying the power, beam size or the interaction time.

For any material, a minimum amount of energy has to be absorbed for the material to be ablated by the laser beam [45]. This absorbed radiation is converted to energy that raises the temperature of the substrate. The resulting temperature profile depends on the deposited energy profile and thermal diffusion rate during laser irradiation. Reflectivity of most metals is high at low beam intensities but much lower at high intensities. This reflectivity reduces with increasing temperatures [45]. It is also good to note that cutting of thicker materials requires high laser power intensity. The optimum incident power is established during procedure development because excessive power results in a wide kerf width, a thicker recast layer and an increase in dross while insufficient power cannot initiate cutting.

For the range of operation conditions tested, it was observed that power had a major effect on kerf width and the size of HAZ, while feed rate effects were secondary. On the other hand, surface roughness and striation frequency were affected most by the feed rate. At low power levels, the smallest kerf width and HAZ are obtained and the effect of feed rate is moderate. Low feed rates gave good surface roughness and low striation density. For optimum cut quality, kerf width, HAZ and surface roughness were kept at a minimum. However, operating conditions that satisfy these requirements while maintaining high productivity could not be identified [11].

Most metal surfaces reflect IR light at 80 % and above at room temperature. The 20 % light is absorbed and converted into heat that initiates melting [54]. The nature of interaction of laser radiation with metal surface depends upon physical and metallurgical properties of the metal and all the process parameters involved. This means that to each kind of material, including its thickness and surface finishing, there will be a different collection of process parameters that will optimize a determined feature of the cutting product. Generally, metals are more difficult to machine using CO_2 laser due to their high reflectivity to this wavelength. However, this does not mean that CO_2 laser machining of metals does not exist.

Cadorette et al. [55] investigated productivity characteristics of a 4 kW CO_2 laser cutting system for 0.25 inch mild steel. They found that laser cutting operations generally produced regular patterns in the cut surface, known as striations whose severity (frequency and amplitude) had a direct impact on surface quality. Incomplete cuts resulted from low oxygen pressure, focus lens deterioration, and/or trying to cut at a rate exceeding the power rate required for maintaining complete cutting. They controlled some parameters such as feed rate, power, assist gas pressure and laser pulse frequency while focus lens condition, nozzle gap and assist gas purity remained uncontrolled. They made the following general observations:

- A surprising amount of variation between observations of experimental runs resulting to either the cut surface being very well within the acceptable limits established (Ra. less than 18 μm), or very poor;
- The greater the roughness values were, the wider the variations among the individual measurements became.

In order to successfully machine hard-to-wear materials, Armitage et al. [56] made innovations in LAM which combined laser technology with traditional machining methods such as turning and milling. The laser was used as a heat source with the beam focussed on the unmachined section of the workpiece directly in front of the cutting tool as shown in Figure 2.8, [56]. In their LAM of hard-to-machine metals, optimum operating parameters were expected to provide minimum surface roughness, subsurface defects, tool wear, tooling costs, machine time and maximum MRR, precision and accuracy.

Preheating the material to be machined softened it resulting to less force required by the conventional tool while cutting. This had the advantage of minimizing tool wear and thus grinding or diamond machining which accounts for about 60-70 % of manufacturing cost of the final product. In LAM technique, temperature of the workpiece

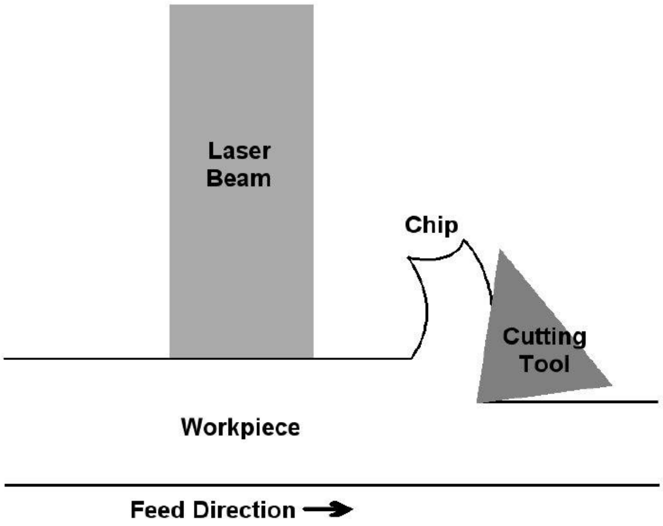


Figure 2.8: Laser Assisted Machining (LAM) Principle

is very important so that ductile deformation occurs during cutting. However there is to be no melting of the material, heat treating of the bulk workpiece or softening of the cutting tool, as these are all detrimental to the surface integrity of the finished workpiece. For this reason heating should be localized as much as possible to the surface layer of the material to be removed before substantial heat is conducted into the bulk of the workpiece.

Ignatiev et al. [57] investigated the influence of LAM parameters variations on surface heating temperature to determine the most sensitive LAM parameters. They noted that the surface temperature was slightly affected by cutting speed variation, but it depended strongly on the value of laser power. The optimum ranges for the cutting temperature were determined from the tool wear resistance tests at conditions of high quality of machining.

Uslan [58] investigated on kerf width variation during a CO_2 laser cutting of mild steel where the influence of laser power and cutting speed variations on the kerf width size was examined. A lump parameter analysis was introduced when predicting the kerf width size and an experiment conducted to measure the kerf size and its variation during the cutting process. It was found that the power intensity at the workpiece surface significantly influenced the kerf width size. The variation in the power intensity resulted in considerable variation in the kerf size during the cutting, which was more pronounced at lower intensities.

Yanga et al. [59] did a numerical and experimental investigation of the HAZ in a LAM process of a titanium alloy (Ti-6Al-4V). In their thermal modelling, they made the following assumptions:

- The laser beam was assumed to be base mode Gaussian and vertically directed at the workpiece.
- The workpiece moved in the - Y direction with a constant velocity U.
- The thermo-physical properties were dependent on temperature.
- The treated material was homogeneous.
- The ambient temperature was 295 K.
- Air convection coefficient was 50 $\mathrm{W/m^2}K^1$

A typical model of the laser system is as shown in Figure 2.9, [59]. A good agreement

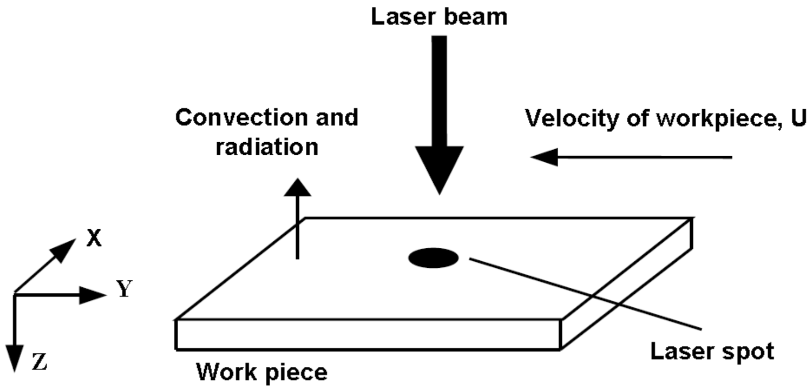


Figure 2.9: Schematic model of a laser heating system

between theory and experiment was obtained and the size of the HAZ was found to be a function of the laser power, speed and spot size.

2.6.2.1 Laser machining of aluminium and copper

It is well known that laser cutting of aluminum or aluminum alloy is difficult because of the high reflectivity and heat conductivity of aluminum and low detachability of aluminum dross. However, aluminium alloys fall second behind steel in terms of the volume of industrial laser cutting applications due to their high demand in automotive, castings, extrusions and forgings [54].

Armon et al. [60] investigated on aluminium drilling with a CO_2 laser beam. The penetration time, crater top radius and melted zone for aluminum plates drilled were measured and analyzed on the basis of various assumptions concerning absorptivity of the liquid metal, attenuation by the metal vapor and heat exchange with the vapor. Comparison with the experimental data showed that each of the interaction parameters must lie within a predetermined range in order to correlate all the experimental measurements.

O_2 assist gas results in higher cutting speeds than neutral or inert gases due to the generation of energy from the exothermic reaction [54] between aluminium (Al) and oxygen (O_2) as shown in

$$2\mathrm{Al} + 3/2\mathrm{O}_2 \longrightarrow \mathrm{Al}_2\mathrm{O}_3 + \mathrm{Heat} \tag{2.12}$$

This aluminium oxide (Al_2O_3) forms a protective coating around the molten aluminium resulting in rougher edge finish appearance than in steel laser cut edge.

Lasers can cut copper in pure or alloyed form. Pham et al. [36] considered important characteristics in laser milling such as surface finish, aspect ratio, dimensional accuracy and minimum feature size on copper and H13 tool mild steel. They made the following conclusions:

- Laser milling was capable of producing adequate surface finish for micro tools
- Features with an aspect ratio of 2.5 were achieved with the laser milling process
- Accuracy was directly influenced by laser-material interaction
- Material properties had to be considered in order to improve process accuracy.

Petkov et al. [61] investigated the effects of machining duration on surface quality and material microstructure when ablating a material commonly used for manufacturing micro tooling inserts. They found that with short machining time, some heat was transferred into the bulk, but it was not sufficient to trigger significant structural changes. Therefore, heat penetration was small and grain refinement minimal and that these were the issues that had to be taken into account when considering the trade offs between high removal rates and the resulting surface integrity.

VanderWert [62] investigated laser drilling for medical device manufacturing where he found that material properties with the greatest influence on the interaction were:

- absorptivity of the material surface at the laser wavelength
- melting and vaporization temperatures and
- thermal diffusivity.

He also found that MRR was a good predictor of the edge finish that could be achieved since high MRR indicated poor edge finish and vice versa.

2.6.2.2 Laser machining of steels

Different types of steels exist and due to their different properties, they are machined using different processes. Wandera et al. [63] investigated laser cutting of austenitic stainless steel with a high quality laser beam. They reported that the energy used in cutting was independent of the time taken to make a cut but the energy losses from the cut zone were proportional to the time taken. Therefore, the energy lost from the cut zone decreased with increasing cutting speed resulting into an increase in the efficiency of the cutting process. A reduction in cutting speed when cutting thicker materials led to an increase in the wasted energy and the process became less efficient. The levels of conductive loss, which was the most substantial thermal loss from the cut zone for most metals, rose rapidly with increasing material thickness coupled with the reduction in cutting speed. They also found that the kerf width was smaller when the focus position was on the workpiece surface and above the surface.

Nowakowski et al. [64] investigated laser beam interaction with materials for microscale applications. They observed material modifications around the hole which can be either of thermal (HAZ), mechanical affected zone (MAZ), or chemical affected zone (CAZ) nature. Depth, diameter and amount of material damage as well as geometry depended on pulse energy, laser pulse characteristics, power density, intensity distribution across the beam on the target and optics involved in the process.

When cutting thick plates of mild steel, O_2 assist gas was used to take the advantage of the exothermic reaction occurring between iron (Fe) and oxygen (O_2) at 2240 ^{o}C before melting starts [54] as shown in Eq. 2.13. The heat energy generated (260 kJ/mol in this case), depended on material thickness, O_2 flow rate and feed rate.

$$\mathrm{Fe} + 1/2\mathrm{O}_2 \longrightarrow \mathrm{FeO} + \mathrm{heat} \tag{2.13}$$

Oxygen-assisted laser machining resulted in an exothermic reaction especially with carbon steel and stainless steels allowing higher machining speeds to be achieved. In a related study, Smith [65] had the aim to determine the maximum speed achievable for a certain material thickness, laser power and with increasingly higher oxygen purity using a CO_2 laser. He found out that the higher oxygen purity resulted in cleaner cuts and better edges quality at high cutting speeds. However, oxygen purity alone does not dictate the speed and cut quality since other factors like laser power and material thickness also play an integral role in the resultant speeds and quality.

Shuja et al. [66] investigated the influence of gas jet velocity in laser heating of a moving steel substrate. Simulation was repeated for three assisting gas jet velocities (100, 10, 1 m/s) and a constant workpiece speed (0.3 m/s). It was found that the effect of assisting gas jet velocity on the surface temperature was more pronounced in the cooling cycle than in the heating cycle of the laser heating process. The workpiece movement affected the location of the maximum temperature at the surface, which moved away from the initially irradiated spot center in the direction of motion of the workpiece.

Chen [67] investigated the effects of gas composition on CO_2 laser cutting of mild steel. In his research, gas-composition variation and the gas pressure were selected as the dominant factors and their effects on the cut quality investigated, with particular reference to small variations in gas composition. He used gas mixtures composed of oxygen, argon, nitrogen and helium. From the experimental results, it was found that a high purity of oxygen was required for the high-performance CO_2 laser cutting of mild steel. Only a tiny oxygen impurity (1.25 %) reduced the maximum cutting speed by 50 % in 3 mm thick mild steel under low pressure (up to 6) bar-inert gas cutting.

2.7 Checking efficiency

After making any laser system, it is important to determine the efficiency of the laser [68] . Fresnel number, N_f, is used to determine the efficiency of a laser system. This is the number of fringes expected at the output aperture for uniform illumination [8]. A large Fresnel number (well above 1) of a resonator means that diffraction losses at the end mirrors are small for typical mode sizes and hence high efficiency. Conversely, a small Fresnel number (below 1) means that diffraction losses can be significant particularly for higher-order modes [69].

$$N_f = \frac{\phi^2}{4\lambda L_b} \tag{2.14}$$

where ϕ is the bore diameter of the tube, λ is laser wavelength and L_b is the length of the bore. Up to a point increasing the radius of curvature increases power output because the available excited gas volume is used more efficiently. Larger radius also has the disadvantage of increasing the difficulty of mirror alignment roughly in proportion to the radius. Also, if the radius is so large as to increase the 1/e beam diameter to larger than the actual bore size, then the output beam may break into higher transverse modes.

2.8 Other applications of laser technology

Laser technology is applied in other cases such as cleaning. For instance, Bauerle et al. [70] did a study on laser cleaning of solid surfaces from either tiny particulates or extended contamination layers. They demonstrated that, under certain conditions and with certain systems, laser cleaning enabled efficient removal of micron and submicron particles from solid surfaces. Dry Laser Cleaning (DLC) is performed in vacuum or dry atmosphere. If on the other hand the removal of particulates is assisted by the evaporation of a thin liquid film, the technique is denoted as Steam Laser Cleaning (SLC). If laser cleaning is performed in an atmosphere of high relative humidity, for example in water vapor, the term Wet Laser Cleaning (WLC) is used.

2.9 Laser optimization techniques

The best possible productivity can be ensured by optimizing all the parameters influencing laser machining [19]. In order to improve laser machining technology, Richerzhagen et al. [32,33,71] invented Water-Jet-Guided-Laser (WJGL) cutting for fine cutting and grooving.

Sulaiman et al. [26] investigated laser machining facts with the aim of optimizing the process. They made the following statements:

- When O_2 was used as an assisting gas, it resulted in exothermic reactions with the material being machined enabling penetration of thick and reflective materials.
- When cutting with non-reactive (inert) gases such as nitrogen or argon, the material was melted solely by the laser power and blown out of the cut kerf by the kinetic energy of the gas jet. As nonreactive gases do not react with the molten metal, and no additional heat is generated, the laser power required is usually much higher than in oxygen cutting of the same thickness. Cutting with nonreactive gases is often referred to as clean cutting or high-pressure cutting.

- The cutting speeds obtainable in pulsed cutting are much lower than with continuous wave laser beams since average power normally has to be reduced to some hundred watts in order to achieve a significant increase in cutting quality by pulsing.

- Laser intensity determines the thickness that can be cut. The thicker the material to be cut, the higher the intensity required. Higher intensities can be reached by increasing laser power or by using a focusing lens with a shorter focal length.

- Cutting speed is determined by the average power level. The higher the average power, the higher the cutting speed although high-power lasers do not automatically deliver high intensity beams. The lens used to focus the beam is very important in the context of the cutting speed.

- A lens with a short focal length produces a small spot size and a short DOF, generally resulting in high speed and good cutting quality of thin sheet metal. However, careful control of the distance between the lens and the workpiece is necessary. When thicker materials are cut, the depth of focus must be adapted to the materials thickness by selecting a lens with a longer focal length.

- Laser beam mode affects the size of the focused spot and the intensity of the focused beam. It also affects intensity distribution in the beam focusing and thus the cut quality.

- The focal point of the focusing lens must be positioned accurately with reference to the surface of the workpiece, and the position must be kept constant during processing.

- The surface condition of mild and low alloy steels is important in laser cutting. Oxygen-cutting of sheets with rust, for example, may cause dross and notches. Likewise, painted surfaces can also cause problems.
- Cutting of aluminium with CO_2 lasers is considered difficult on account of its high reflectivity and thermal conductivity. Aluminium alloys, however, are usually easier to cut than pure aluminium at a higher cutting speed.

Chen et al. [72] investigated parameter optimization of non-vertical laser cutting. They showed that in some cases, in order to avoid interference during 3D laser cutting of thin metal a laser head could not be kept vertical to the surface of a work piece. In such situations, the cutting quality depended not only on typical cutting parameters but also on the slant angle of the laser head. Traditionally, many tests had to be done in order to obtain the best cutting results.

Delphine et al. [73] investigated on the fracture strength of dies produced through laser microjet machining process. The basic principle was to focus a laser beam into a nozzle while passing through a pressurized water chamber. The low-pressure water jet emitted from the diamond nozzle guides the laser beam by means of total internal reflection at the water/air interface, in a manner similar to conventional glass fibers as shown in Figure 2.7. The water jet has three process-critical functions namely:

- Guiding the laser beam to the work piece;
- Removing molten material and

- Cooling the work piece, and thus the HAZ is negligible.

Unlike in conventional laser machining where the kerf shape is V-shaped, laser micro-jet machining has parallel kerf widths.

2.10 Challenges encountered in laser machining

Wollenberger [74] investigated the challenges of laser cutting and methods of overcoming some common obstacles. Some of the challenges encountered were:

- Laser cutting became less effective when material thickness increased
- Material's thermal conductivity being too high as in aluminum, where much of the energy was transferred laterally into the material, resulting in inefficient cutting and reduced cutting speeds
- Part geometry. Certain part geometries were affected more than others by the thermal process. For instance, corner or smaller areas of a part absorb more heat, and consequently the probability of thermal runaways or violent reactions like blowouts increased.
- A HAZ formed in metals when the temperature rose above the critical transformation point. In laser cutting, this is localized near the cutting zone. In carbon steel, the higher the hardenability, the greater the HAZ.

Some of the remedies include:

- Thick materials can be machined by using a more focused beam and even more improvement on the cutting process can be achieved by focusing the assist gas
- Use of a pulsed beam rather as opposed to a CW beam to avoid thermal problems
- Where the machining results in burrs and recast layers, secondary operations may be required to remove the recast.
- A laser can dwell in the start position until the material reflectivity changes and before the motion system begins to move the laser
- Cracks can be eliminated in certain cases with high-pressure nitrogen cutting
- In most cases, the HAZ can be eliminated by post-heat treating the part, but there is a risk of distortion.

2.11 Summary and conclusion from literature

From this literature, it is clear that good research has been carried out in laser machining showing that the many parameters influencing the process are closely interrelated but without a universal relationship. This means that even if only one parameter is altered the cut quality will change implying that there is so much yet to be studied since any alteration leads to different results during laser machining. This calls for further experiments to be able to predict the cut quality from machining parameters. It is also clear that the laser parameters are strong influencing factors since the researchers quoted in this section used different laser types and ratings. With experimental data, it is possible to select and determine right combination of parameters for a desired cut quality

It has also been shown that lasers have been used in cleaning and in paint removal. Since this is a thermal process, there are chances that the underlying material may be damaged depending on machining conditions involved. Alterations on underlying material may be in the form of color or even microstructural changes. The changes are not always desirable since they may be adverse causing early and unexpected failure of components and systems and thus increase repair and maintenance costs. There is therefore need to come up with a lab-built laser system to be used to study the effect of laser, material and machining parameters on cut quality. The same laser system will be used to remove paint from surfaces of mild steel specimens and microstructures observed before and after laser beam exposure. With the observations from experiments, it will be possible to make conclusions on safe working conditions to maintain material properties. It is also possible that changes could improve the material rather than deteriorate its properties. This calls for more work to be done using different set of parameters as will be discussed in the following chapter.

CHAPTER 3

METHODOLOGY

3.1 Overview of the methodology

Laser machining involves many parameters that are interrelated and which need to be considered. There being no universal relationship involving all of them, this makes the process difficult leaving trial and error the only alternative. As a result, there was need in this study to investigate the effect of laser and material parameters on cut quality defined by depth machined, diameters of holes, taper and kerf widths.

Painting of components helps prevent corrosion, adds on aesthetics and provides camouflage. Depainting becomes an occasional necessity during the lifetime of the painted component where several methods have been used although they all have their limitations. To counteract these disadvantages, laser depainting has been introduced where incident power, which is usually lower than the threshold of the material, is applied on the surface. Any damage to the underlying substrate may lead to shortened lifetime and can even be dangerous in case of unexpected failure. It is therefore important to ensure that depainting is done effectively with no damage to the underlying material. To achieve this, the beam was focused on painted surfaces of mild steel for a certain period of exposure time and the effect of the beam on the microstructure investigated.

In addition, it was important to determine the point at which glass cracks as one way of understanding the properties and behavior of glass under a laser beam. In order to achieve these, this research consisted of the CO_2 laser generation system, beam delivery system, control system for X and Y motions of the workpiece and experimentations where machining conditions were varied and their effect on the cut quality investigated. The first step was to align the CO_2 laser in order to generate the beam. The next step was to develop beam delivery system and control program to manipulate laser beam to achieve X and Y motions. Since a lens is very delicate, a lens holder was machined for support and a fan fitted in the system to assist in cooling, debris removal and lens protection from smoke. Workpieces for laser machining experiments were then prepared before commencing on machining. During the experiments, only one parameter was altered at a time while holding all the others constant and the effect of the altered parameter on cut quality investigated. The cut quality was defined by depths, hole diameters, microstructural behavior, glass cracking, kerf widths, taper and aspect ratios.

3.2 Experimental assumptions

In this study, the following assumptions were made:

- Each glass specimen experimented on had homogeneous properties across the whole surface.
- The time taken by the beam to hit the target was negligible.
- Paint coating on mild steel specimen was of the same thickness across the painted portion and in all the specimens.

3.3 CO_2 laser construction features

The CO_2 laser consisted of a glass tube, two electrodes; one made of steel and the other made of stainless steel, vacuum pump, gas mixture supply, a step-up transformer, water cooling system, piping, valves and two end mirrors. The mirrors consisted of a total reflector at one end, and an output coupler made of a semi-reflective coated zinc selenide at the output end. The reflectivity of the output coupler is typically around 5-15% [68]. A schematic generation of lasers is as shown in Figure 3.1.

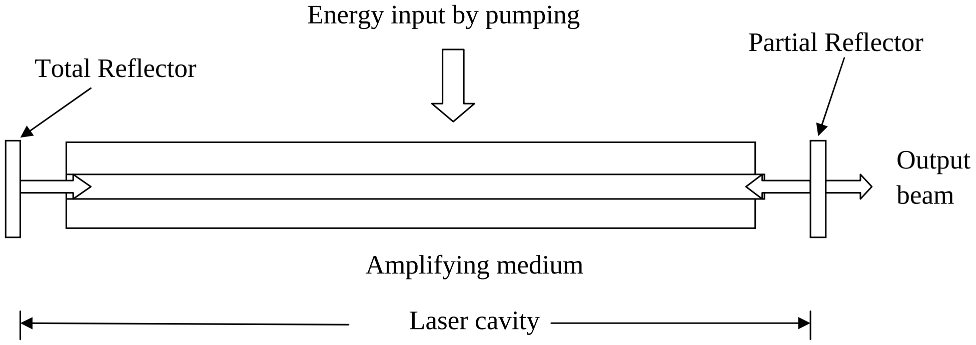


Figure 3.1: CO_2 laser system

3.3.1 Gas supply

To avoid complication associated with achieving the correct mixing of the gases, a premixed gas supply was used consisting of CO_2, N_2 and Helium in the ratio of 10, 13 and 77 respectively. A flowmeter was used in the system to control the gas flow rate. In this system, CO_2 is the lasing medium, N_2 increases the efficiency of excitation by facilitating the absorption of energy which is subsequently transferred to the CO_2 molecule while helium speeds up cooling and allows the CO_2 molecules to return to ground level for re-excitation [14].

3.3.2 Vacuum pump

Generally, a suitable vacuum pump is required to evacuate the laser tube. CO_2 lasers operate at optimum pressures of between 8-20 Torr though high gas pressures will allow lasing if the excitation voltage is sufficiently high. Good air evacuation was indicated by the formation of rings in the laser tube.

3.3.3 Cooling system

Flowing tap water was used for cooling the laser tube and thus preventing the operation temperatures from rising and possibly to cause cracking of the glass tube. Also, laser efficiency is affected by temperature. The system maintained the glass temperature at around the room temperature.

3.3.4 High voltage power supply

For lasing to occur, high voltage is required to allow pumping of gas molecules from the lower to higher energy level. To achieve this, a transformer rated 15 kV D.C. voltage, 30 mA supply was used.

3.4 CO_2 laser design

The CO_2 laser generation setup is as shown in Figure 3.2. There are several CO_2 laser designs such as slow axial flow (SAF), sealed lasers, fast axial flow (FAF) lasers and transverse excited atmospheric pressure (TEA) lasers [68]. CO_2 lasers can also be either pulsed or continuous. In this work, CW slow axial flow (SAF) mode was used. A SAF CO_2 laser uses relatively high amount of helium to facilitate cooling and

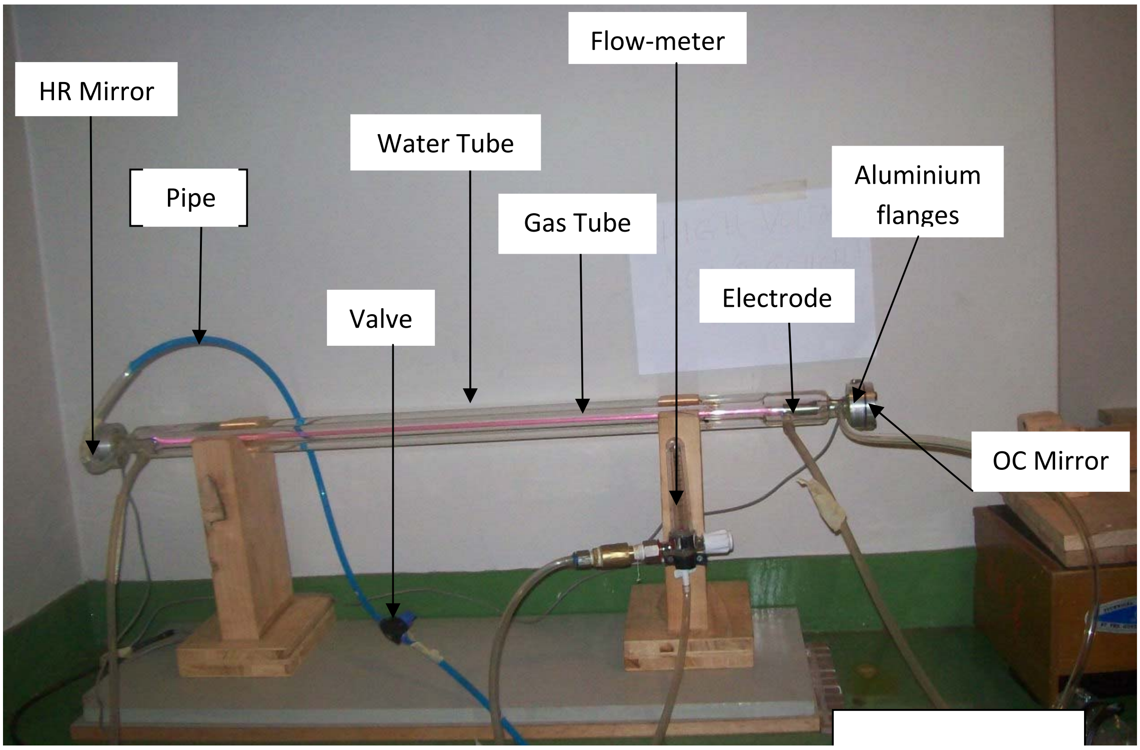


Figure 3.2: A setup for CO_2 laser

the gas flows relatively slowly to allow pollutants generated in the discharge region to be removed. The low flow rate allows laser gas to be heated quickly, which reduces start-up time but the temperature must be kept below 250 ^{0}C to maintain gain in the resonator. In SAF lasers, excitation is normally achieved with DC sources where output power increases with increasing discharge current up to a point at which the heating effect becomes significant. Optimum discharge current depends on gas pressure and tube diameter. In this work, SAF CO_2 laser design was preferred due to the following advantages [68]:

- The design is simple resulting to low running and maintenance costs
- It is an ideal source for fine cutting, scribing, precision drilling and other similar

applications

- Since the gas flow and light generation are coaxial, the beam propagates in the direction of mean thermal gradients and vibrations are averaged out along the beam path thus producing a stable beam mode
- This construction together with a stable mirror alignment and limited tube diameter, enable high quality TEM_{00} beam to be generated.

3.5 CO_2 laser optical alignment

In CO_2 laser optical alignment, the objective is to make the centers of the two mirrors at the ends of the laser cavity reflect a beam back-and-forth numerous times without striking the walls of the tube as shown in Figure 3.3. There are challenges in aligning this particular laser since even the slightest misalignment might throw it out of alignment. The best alignment occurs when the line joining the centers of curvature is coincident with the geometrical axis through the mirror centers and the laser medium. A reliable laser beam was obtained only after precise alignment was achieved. Laser optical alignment is a critical step and was carefully done step by step as follows:

1. An optical table was used to eliminate vibrations and achieve desired flatness during optical alignment
2. An appropriate wooden cradle was made to hold the CO_2 laser tube in a horizontal position. At this point, the tube was open on both sides without the mirrors.

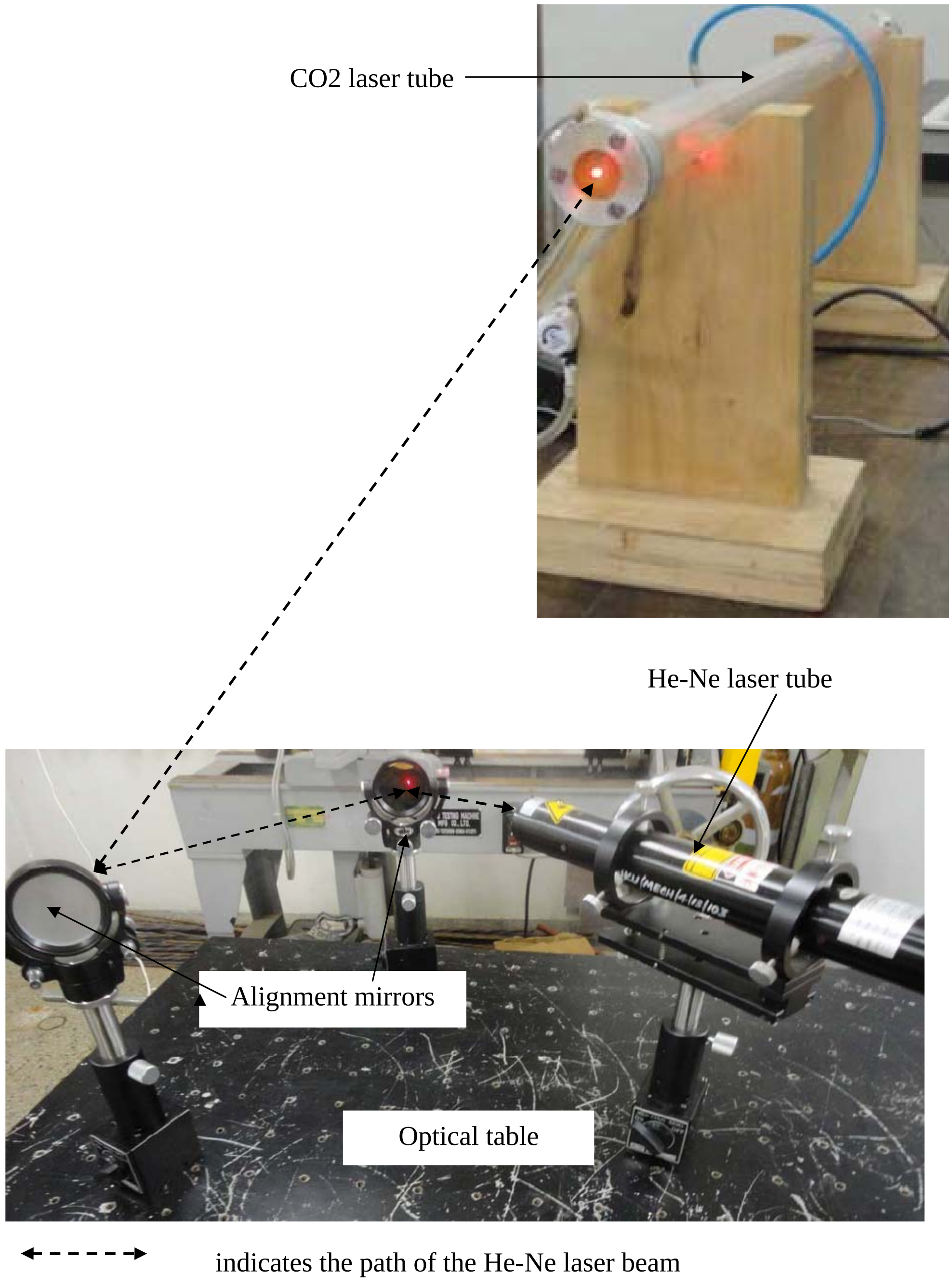


Figure 3.3: CO_2 laser alignment setup

3. The CO_2 laser system and He-Ne laser were placed about 2 m apart and in the same horizontal axis. A meter rule and a spirit level were used for linear measurements.

4. A pin-hole was made through a plain paper and the paper mounted on a holder and placed along the axis of the beam between the two laser tubes.
5. He-Ne laser was switched on and the beam passed through the CO_2 glass tube through the output coupler side by varying the mirror orientations. To ensure only the central part of the beam passes through, a pin hole was made through a masking tape and placed to coincide with the center of the tube using a pair of compasses and a heated pin. This step is critical and took quite some time before any success.
6. A fitting O-ring was placed at the rear end groove of the tube with a lot of care not to move the tube in any way.
7. The highly reflective (HR) mirror was carefully put in place while ensuring that the reflected beam traces the same path to the source. Adjustment screws were fine tuned to achieve the tracing of the same path. Soft tissue was used not to contaminate the mirror surface with the fingers.
8. The other O-ring was put in place at the front end groove of the tube.
9. On successful completion of the first alignment, output coupler (OC) was similarly placed in position to compress the O-ring and the reflected beam ensured it traces the same path.

The Fresnel number N_f for this arrangement was determined using Eq. 2.14, with ϕ = 22 mm, λ = 10.6 μm and L_b = 955 mm. This was found to be 11.95, and since it well above unity, the performance of the laser is good.

3.6 Beam manipulation system

For machining to be done, the laser beam had to be directed from the source to the workpiece. Silicon coated mirrors were used for beam delivery and a ZnSe lens to focus the beam to a small spot in order to increase the power intensity. Beam manipulation system involved location of the invisible beam, delivery and focusing. Beam delivery system is shown in Figure 3.4.

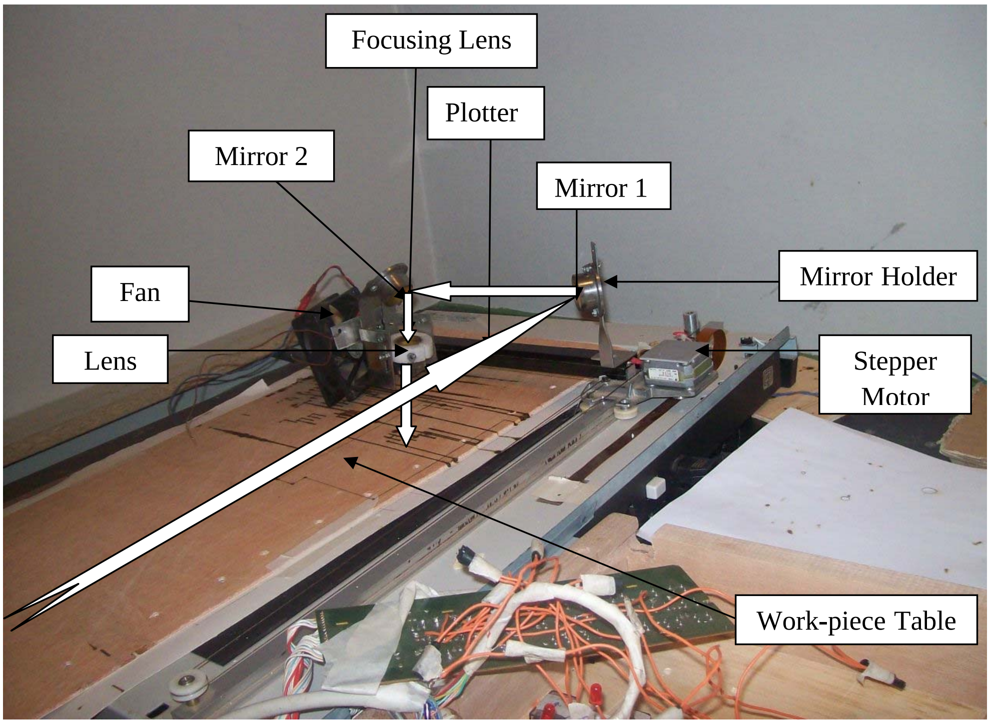


Figure 3.4: CO_2 laser beam delivery system

3.6.1 Detecting and locating the CO_2 laser beam

Since a CO_2 laser beam falls in the far infrared part of the spectrum which is invisible to the naked eye, there was need to determine the beam location. Although there are various methods used in CO_2 laser detection [68], a simple method was adapted as follows:

- The laser was switched on and a paper placed along its axis. Once a burnt spot was observed on the paper, the paper was moved to a different position
- This was repeated all the way to the lens surface
- The paper was also used to ensure that the beam was always at the center of the optics

3.6.2 CO_2 laser orientation

Once the CO_2 laser was aligned and gas flow rate fine tuned to give the maximum power. Since a power meter was not available, estimation of orientation for maximum power was through visual observation of the brightness of the spot produced by the laser when directed onto a workpiece. He-Ne laser was again used for this orientation using the following procedure:

- A spirit level was used to ensure both the CO_2 and He-Ne laser tubes were horizontal.
- Using a meter rule for linear measurements, the heights of the two laser centers were made the same.
- He-Ne laser was switched on and aligned along the CO_2 laser axis to ensure that the beam was reflected back through the same path to the He-Ne laser source.
- He-Ne laser was turned through $180\ ^0$ and directed to the beam delivery system through the first mirror M1, see Figure 3.4.

- With the He-Ne laser at this position, the mechanism for beam motion and workpiece was adjusted to ensure that the beam was focused on the workpiece.
- The program for the X and Y motions was run to ensure that the beam was always focused on the workpiece from one end of the plotter plate to the other.
- He-Ne laser was switched off and removed from this axis and CO_2 laser switched on ready for machining.

3.7 Beam focusing system

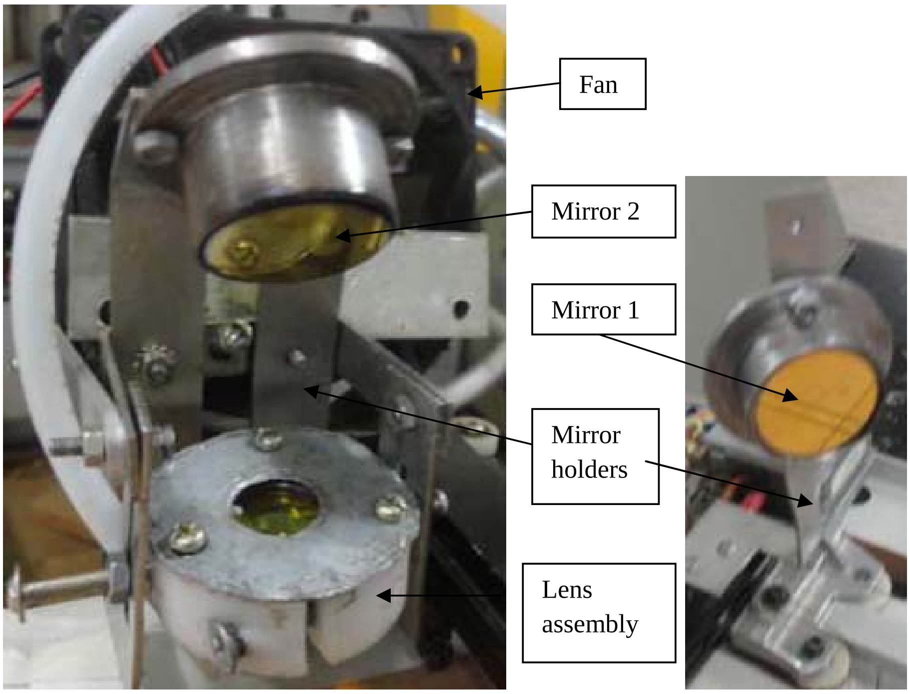


Figure 3.5: Mirrors and lens setup

For beam focusing, mirrors and lenses were used. These were secured as shown in Figure 3.5. Lens manufacturers normally indicate the specifications of the lens in terms of the coating and focal length. However, the value of the focal length lies in the range of ± 5% and thus there is need to confirm the exact value especially in precision machining. It was therefore necessary to determine the focal length experimentally. A simple method for measuring the focal length was used as illustrated in Figure 3.6 [36].

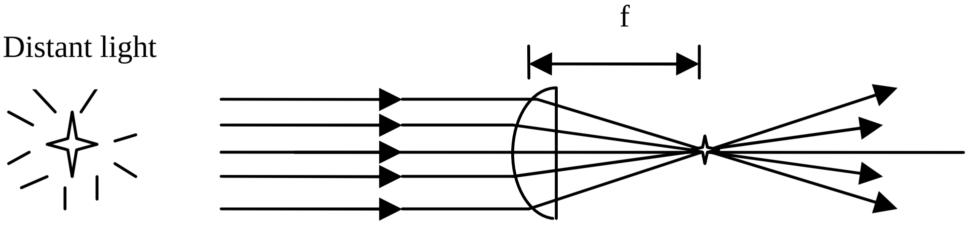


Figure 3.6: Verifying the focal length of the lens

1. Bright lighting bulbs hanging on the laboratory's roof were chosen as distant objects to be focused by the lens
2. Laboratory windows were closed and curtains put on to eliminate light from outside the room
3. The lens was held using a lens tissue and light from the bulbs allowed to fall on the convex side of the lens to reduce abberation effect
4. A smooth laboratory table surface was used as the screen where the focused image was formed
5. The lens was finely moved along the light source to create the sharpest image on the screen
6. Distance between the lens center and the sharpest image location was measured as the lens focal length

To confirm the focal length given, a piece of target material was put at the f=38 mm and machining glare was observed to be brightest and with the sharpest burnt area.

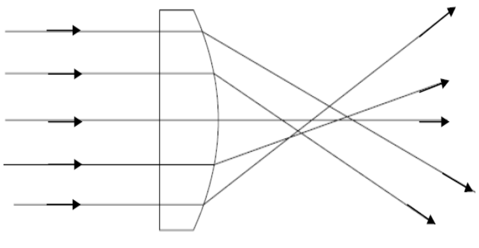
3.7.1 CO_2 laser focused spot size

It is important to focus the beam at the point of machining in order to obtain the benefit of maximum power density. Even if the laser, the lens and all mirrors were perfect, one cannot focus a beam to a size smaller than its wavelength. The wavelength of CO_2 laser is 10.6 micron (0.0106 mm) making this the smallest diameter of the circle it can be focused on to. A suitable lens was required to focus the beam to the sharpest spot size possible. In this study, a plano-convex lens was used for focusing the laser beam. A plano-convex lens has one convex surface and one flat (plano) surface. This type of lens was used due to the following benefits [75]:

- it is cheaper than other types of lenses
- it has a positive focal length close to the optimum shape for use as focussing lenses for collimated beams
- it is possible to achieve a low spherical aberration effect.

To achieve low spherical aberration as illustrated in Figure 3.7, the lens was orientated with the incident beam entering through the convex side and leaving through the plano side. The power of a lens, P_{lens} in Diopters, is determined by its focal length f (in meters) [75] which in this case was calculated to be as shown in Eq. 3.1.

$$P_{lens} = 1/f = 1/0.038 = 26 \tag{3.1}$$



a) Laser incident on the plano side

b) Laser incident on the convex side

Figure 3.7: Orientation of the lens to reduce spherical aberration

The focal-number or f-number (f$\sharp$), of a focusing optic characterizes its focusing ability and defines the convergence of the beam as shown in Eq. 3.2

$$f\sharp = \frac{f}{D} = 38/0.8 = 47.5 \tag{3.2}$$

where f is the focal length of the optic and D is the diameter of the beam. Low f-number optics are limited in performance due to uneven thermal expansion across the lens and increased spherical aberration which alter the focal length and the focused spot size. A high f-number of 47.5 implies acceptable optics performance. D was obtained by directing the beam on perspex for about 3 seconds and measuring the diameter of the hole made. This was repeated for about five times and the average obtained.

3.7.2 Cleaning of CO_2 laser optics

Optics should be kept free from dust or any form of dirt/damage since contamination absorbs the heat energy resulting to thermal damage. The best method of having clean optics is to avoid contamination in the first place. Dust should be simply blown off with a jet of compressed dry air or nitrogen. In this work, there was need to clean the output coupler where the following procedure was used [68] as illustrated in Figure 3.8.

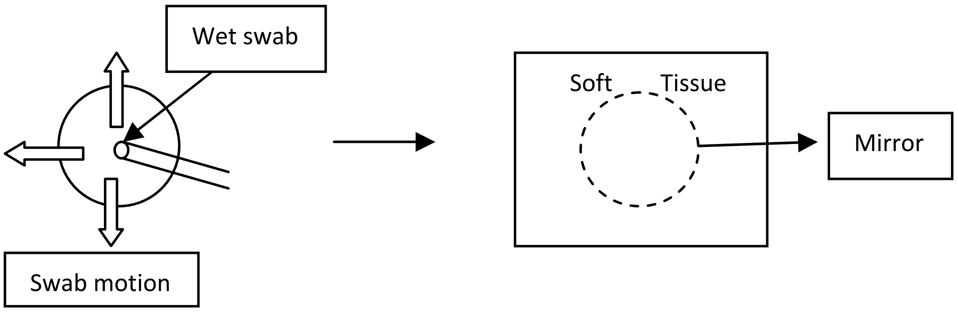


Figure 3.8: Procedure for cleaning the optics

1. Since skin oils are difficult to remove and can permanently damage some optics, the hands were thoroughly washed before working with optics to minimize contamination.

2. Finger cots were worn to protect both the hands and the optics

3. Cotton-tipped swabs were dipped in isopropyl alcohol and lightly dragged from the center of the coupler toward the edges

4. A high quality lens tissue was lightly dragged in one direction to absorb the excess reagent. This was done under the swab's own weight only and slowly across the optic.

After cleaning, the mirrors and lens were always left covered with clean polythene bags when not in use to avoid contamination or damage to the surfaces.

3.8 Lens holder machining

Since the zinc selenide lens is very delicate, firm support was required for it. Off-axis aberrations were eliminated by ensuring the beam was centrally located through the lens by making the lens flat on the holder base and ensuring that the whole lens system was parallel to the workpiece table. A brass holder was used to support the lens and the combination of the lens and brass holder supported in a plastic holder. To ensure the lens holder was firmly supported with no chances of falling off, a washer was specifically made with internal diameter less than the lens diameter and screwed on the plastic lens holder. The lens and the parts used in supporting it are as shown in Figure 3.9.

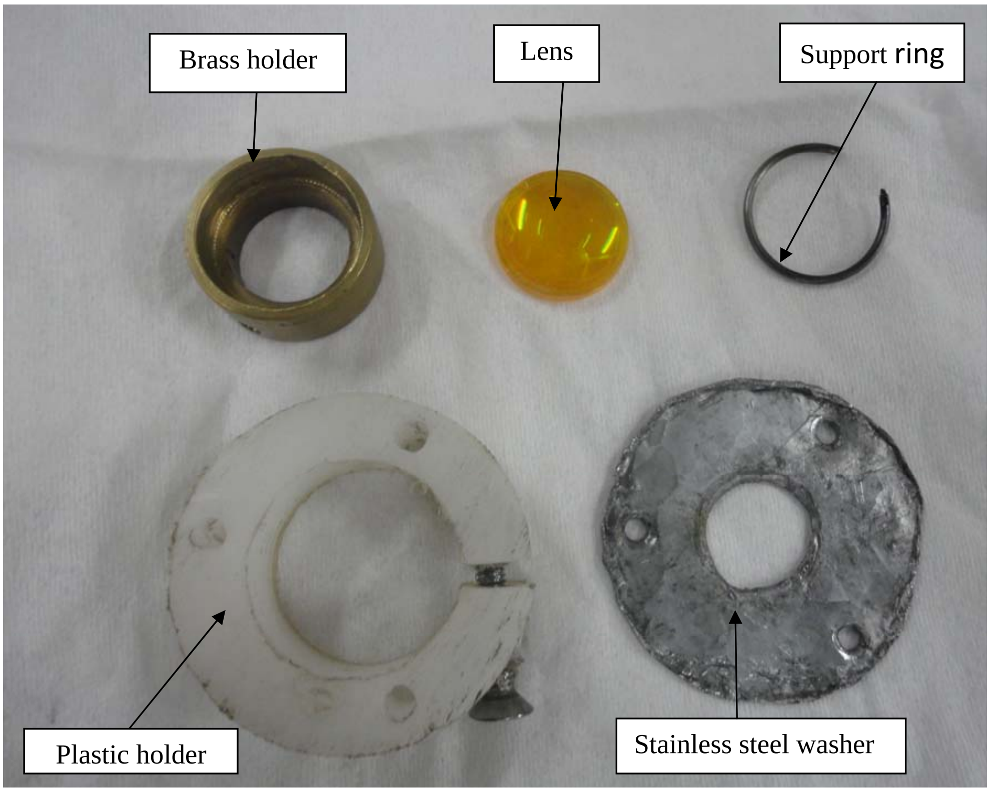


Figure 3.9: The lens and its holders

3.9 Washer machining

A washer was machined by drilling a central hole with a diameter slightly less than the lens diameter. Three other smaller holes were drilled and used to screw this aluminium washer to the plastic lens holder for firm support of the lens. An assembly of the lens in the holder is as shown in Figure 3.10.

a) Lens in the plastic holder

b) Washer on lens assembly

Figure 3.10: Lens assembly

3.10 CO_2 laser machining

Materials experimented on during this work include wood, perspex, paper, plastics, ceramics and mild steel. To eliminate the possibility of the CO_2 light being diffused by dirt/dust particles on the surface of the materials being experimented on, thorough cleaning of the surfaces was done and these were left to dry before use. Several pieces of each material were prepared and used as specimens.

In the machining processes, the aim was to focus the beam on the workpiece so as to

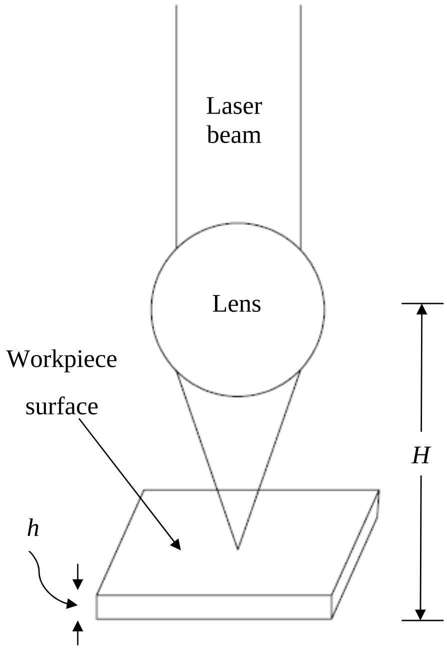


Figure 3.11: Positioning of the lens above the workpiece

concentrate the beam to the minimum spot possible and thus achieve maximum power density which would consequently increase the MRR and reduce the HAZ. The laser beam was always positioned at the surface of the workpiece. This was done by first measuring the workpiece thickness h and adjusting the position of the focusing lens H as shown in Figure 3.11.

With the focal length of the lens as 38 mm, Eq. 3.3 was used where H and h are in mm.

$$H = h + 38 \tag{3.3}$$

The average speed of the machining system was found to be uniform and 11.2 mm/s in both the X and Y directions. In one set of the experiments, machining time was varied and the effect on HAZ, depths, hole diameters and aspect ratios investigated. In the other set, the number of passes were varied at constant scanning speed and their effect on HAZ, depths, taper, kerf widths and aspect ratios investigated. For each set of machining conditions, several experiments were done and an average calculated for accuracy reasons. The measurements were done on either a Profile Projector (PJ 311) or a traveling microscope.

3.10.1 Taking of measurements using a Profile Projector

The following procedure was used in measurement of kerf widths, depth, HAZ, and diameters as illustrated in Figures 3.12 and 3.13.

1. Profile Projector was switched on
2. The specimen to be measured was placed on the machine table and its height adjusted to focus the upper surface
3. The specimen orientation was adjusted to be parallel with the alignment lines and then the machine zeroed
4. The Y direction handle was rotated until the alignment line was on the other side of the measurement being taken and the reading on the machine taken.

3.10.2 Effect of the position of the focal length on CO_2 laser machining

In order to investigate the importance of machining with the workpiece at the focal point of the beam, the workpiece was moved so that the beam was either at the surface (B), above (A) or below the surface (C) as shown in Figure 3.14.

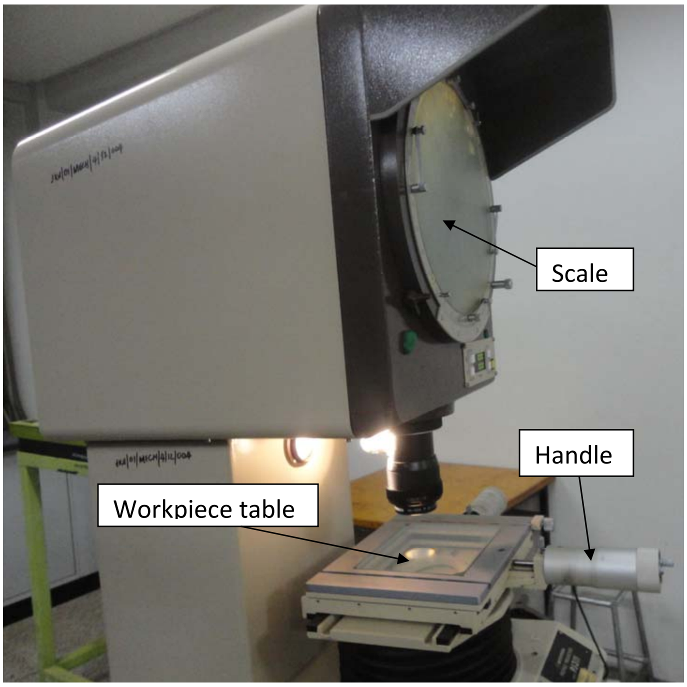
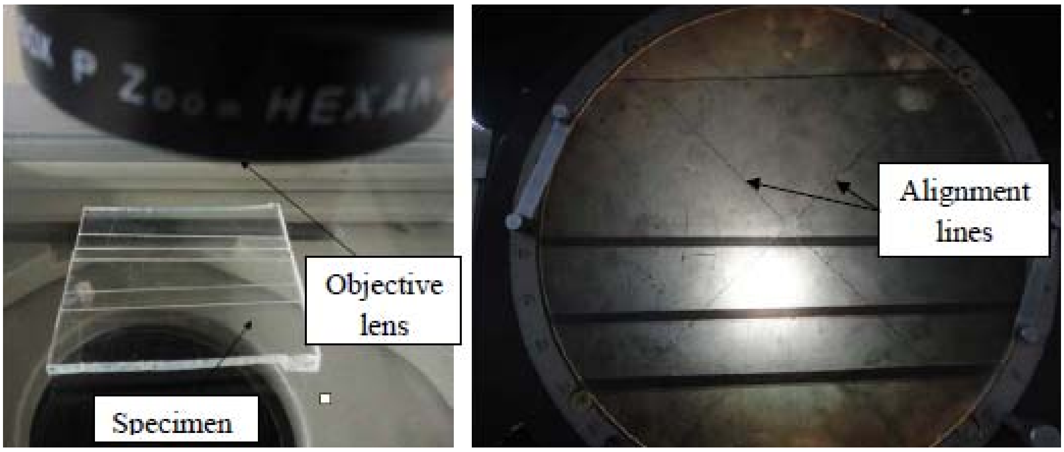


Figure 3.12: Taking of measurements using a Profile Projector

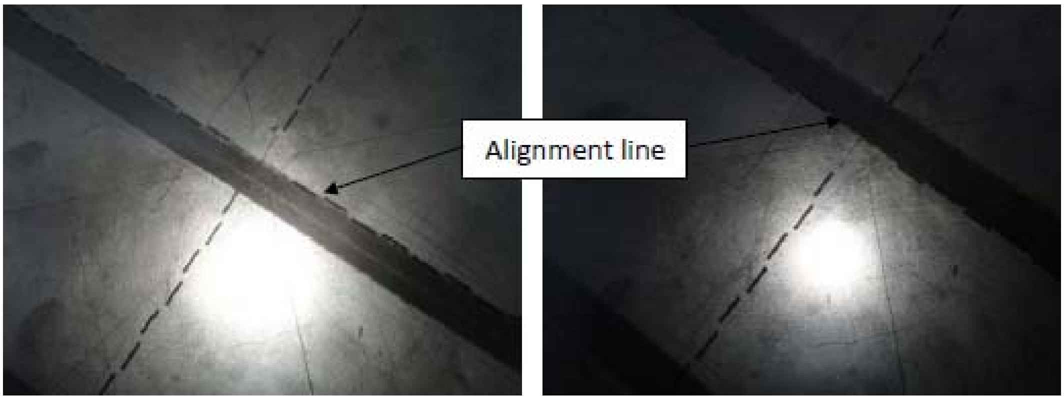
3.11 CO_2 Laser drive system

The CO_2 laser drive system consisted of an electronic circuit using a ULN 2803 as the microcontroller. ULN2803 is a high-voltage, high-current Darlington driver comprised of eight NPN Darlington pairs with pin configuration as shown in Figure 3.15, [59]. Pins 1-8 receive the low level signals, pin 9 was grounded, while pin 10 is the common on the high side and was connected to the positive of the voltage being applied to the relay coil. Pins 11-18 are the outputs where pin 1 controls pin 18, pin 2 controls pin 17 and so on. To achieve the mechanical motions, hybrid stepper motors with a step size of 0.9 degrees/step were used due to the following advantages:

- A high accuracy of motion is possible even under the open-loop control
- It is cheap since large savings in sensor and controller costs are possible with the



a) i) Placement of specimen ii) Focused specimen



b) Specimen orientation

Figure 3.13: Taking of measurements using a Profile Projector

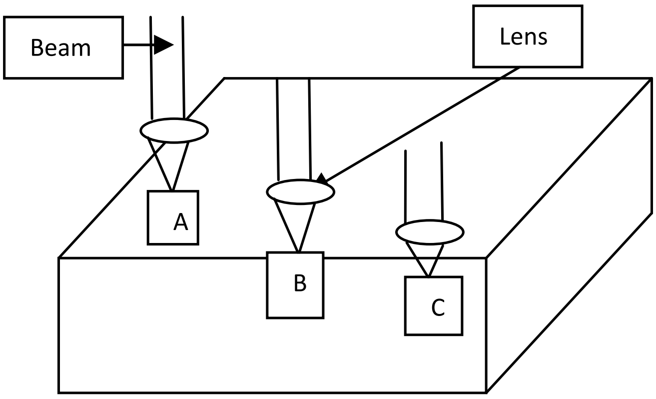


Figure 3.14: Positioning of the focal point while machining

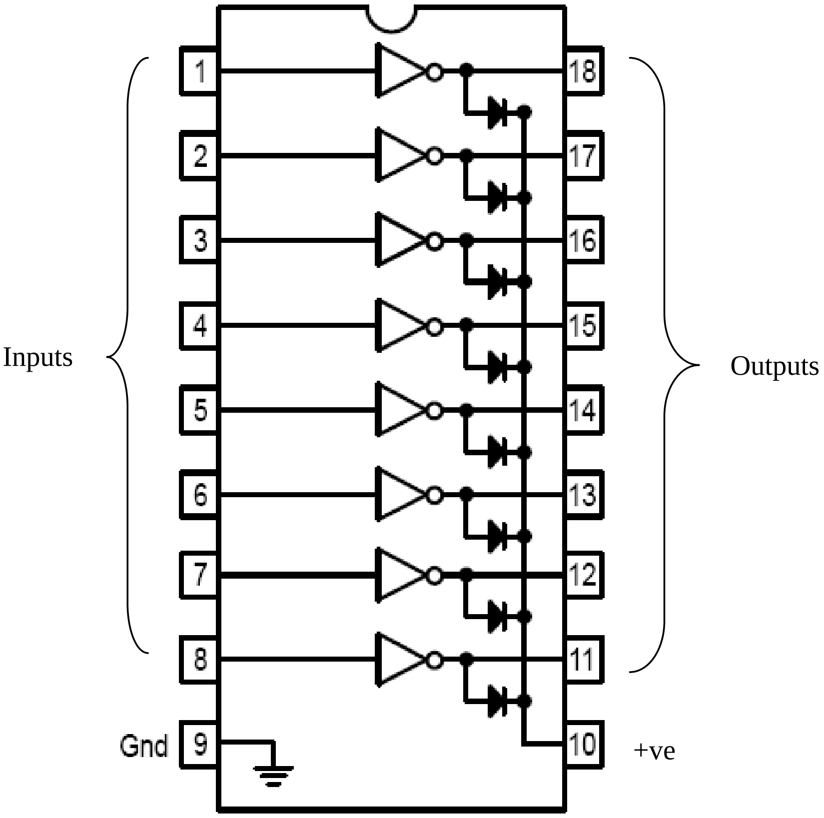


Figure 3.15: ULN2803 pin configuration

open-loop mode

- Because of the incremental nature of command and motion, stepper motors are easily adaptable to digital control applications
- Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 - 5% of a step and this error is non cumulative from one step to the next
- Excellent response to starting/stopping/reversing.

3.12 CO$_2$ laser ablation analysis

When a laser beam is focused on a workpiece, some of the power is reflected, some transmitted and some absorbed. It is the absorbed power that is used for machining. Assume a laser beam with an initial power P whose small portion, P$_{Lost}$, was lost through the above mentioned processes. Assuming that the beam shape is circular and that the focal point of the focusing lens is on the surface of the workpiece, this means that the minimum laser spot size d$_{min}$ hits the workpiece surface and radiates on an equal dimension d$_{mtl}$ i.e.

$$d_{mtl} = d_{min} = \frac{4\lambda f M^2}{\pi D} \tag{3.4}$$

However, d_{mtl} is a factor of the machining time t, material thermal conductivity κ and thermal diffusivity α. Power intensity $P_{Intensity}$ is given by

$$P_{Intensity} = \frac{P_{Actual}}{Area} = \frac{P_{Actual}}{\pi r^2} \tag{3.5}$$

where $r = d_{min}/2$ is the beam radius at the workpiece surface. This means that $P_{Intensity}$ can be increased four-fold by quadrupling the power or by halving the beam radius. However, the beam radius cannot be smaller than the laser wavelength. It is this $P_{Intensity}$ that determines the peak surface temperature attained and thus the principal mechanism of material interaction [64]. Assuming the beam scans at a speed V in mm/sec over the distance d_{min}, it means that the interaction time τ is

$$\tau = \frac{d_{min}}{V} \tag{3.6}$$

where d_{min} is the beam minimum diameter. Depth machined d is determined by this interaction time and materials thermal diffusivity α as given by

$$d = \sqrt{4\tau\alpha} \tag{3.7}$$

The above assumption applies to the workpiece surface where the beam size is d_{min}. However, as the beam penetrates the workpiece, it diverges with half-beam divergence θ given by

$$\theta = \frac{M^2\lambda}{\pi\omega_0} \tag{3.8}$$

where ω_0 is beam waist radius.

3.13 Operation and optimization of CO_2 laser

To ensure safety both for the operator and the system, a systematic procedure of switching the CO_2 laser ON was followed. A reverse of the procedure was used to turn OFF the laser as shown in Figure 3.16 . Performance of CO_2 lasers may be optimized in several ways by controlling the parameters involved. In this research, the gas flow rate was adjusted using the flowmeter as indicated in the following steps:

1. A piece of wood was placed near the OC at the beam path to be used as the beam locator
2. The flow rate on the flowmeter gauge was adjusted to the minimum possible value for the laser beam to be obtained and the burnt area measured
3. The flow rate was precisely incremented while the brightness of the burning process and the burnt area being either observed or measured within every 5 s.

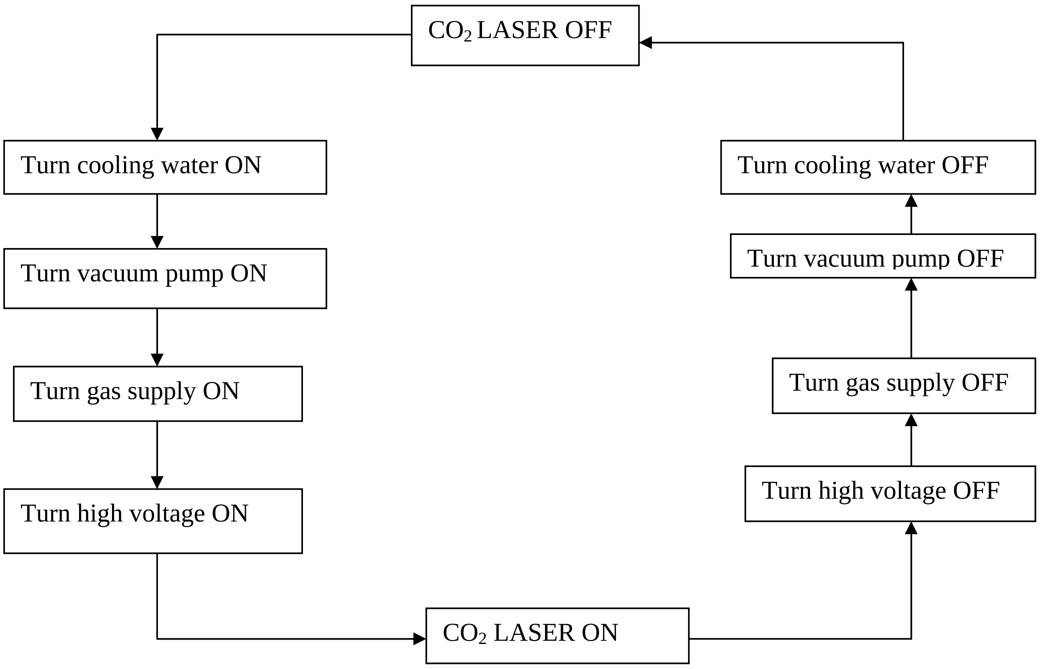


Figure 3.16: Turning the CO_2 laser ON and OFF

4. The flow rate with the highest brightness while burning and the most defined burnt area was taken to be the optimum of 420 kPa

5. This flow rate was set fixed and the flowmeter was not adjusted again in the course of all the experiments.

3.14 Preparation of mild steel

In order to have a flat and smooth surface for laser machining, mild steel was prepared as outlined by Munyazikwiye [76]. In this process, the section to be examined is sawed, then manually filed and surface ground using a universal surface grinder. Small samples are mounted using resins and ground using progressively finer silicon carbide (SiC) waterproof papers. The specimen are then polished using 6 and 1 μm granulation diamond paste and etched in dilute acid (2% Nital= 2ml HNO_3: 98ml

Ethanol CH_3CH_2OH). Finally it is washed in alcohol and dried.

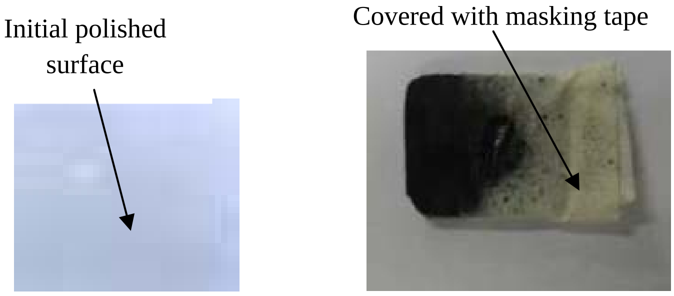
After this preparation, a thin coating of paint (ABRO ^{TM}) was sprayed on the shiny surface of some mild steel samples and left to dry in air.

3.15 Preparation of polished mild steel surfaces

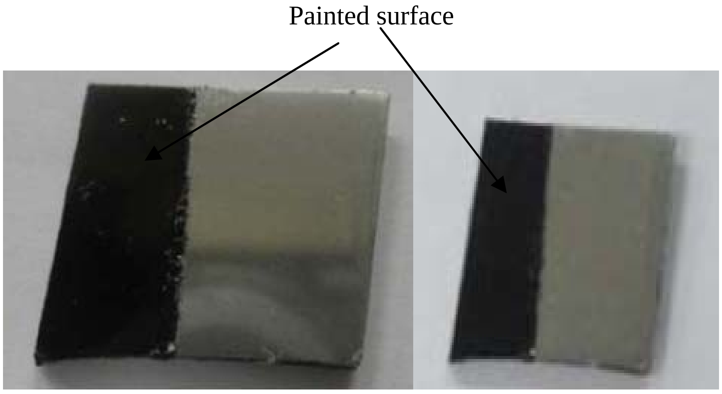
Laser paint removal is a thermal process and thus may damage the underlying material. As a result, experiments were done on coated mild steel specimens to investigate the effect of the laser beam on microstructure. The following procedure was used in preparation of the specimens:

1. Mild steel specimens were spray painted and left to dry.
2. The thickness of each specimen was measured using a micrometer screw gauge and the laser beam focused on the coated surface for a an exposure time of between 30-500 seconds.
3. Each part of the specimen (both the painted and the unpainted) had its microstructure observed under a microscope and a photo taken for comparison.

An illustration of the specimen before and after painting is as shown in Figure 3.17. One of the limitation was that it was not possible to measure the thickness of the paint layers and thus uniformity could not be ascertained. The laser beam was switched on and focused at a point on the surface of the material for a defined exposure time and



a) Unpainted specimen b) Painted specimen



c) After removing masking tape

Figure 3.17: Coating of the specimens

then switched off.

3.16 Observation of the microstructures

After exposure of the beam to the surfaces, the specimens had their microstructures observed. The microscope used had a resolution of 1.7, eyepiece of 8 times magnification, MN11065 model and manufactured by Cooke Traton. The following procedure was used in observing the microstructure of each specimen under the microscope:

1. The specimen was focused under 544 times magnification and the microstructures observed.
2. The eyepiece of the microscope was replaced with the camera, the shutter closed

and the photo taken.

3.17 Laser machining of glass

In order to determine the point at which glass cracks, the following procedure was used:

1. The glass thickness was measured to be 2.95 mm.
2. The lens height from the plotter table was adjusted to be 43.18 mm in order to achieve good beam focusing on glass surface.
3. The glass specimens were wiped clean with a tissue paper to avoid contamination.
4. Each piece was placed under the focused beam and the time it took either to crack or give a cracking sound measured using a stopwatch.
5. The pieces were later observed and hole diameter, crack length and thickness measured using the profile projector.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Laser machining parameters

The cutting ability of the CO_2 laser depended on several factors which include:

- Laser output power: Due to the limited power available, only a few materials could be processed such as wood and glass while mild steel, aluminium and ceramics needed more power. This power also limited the MRR achievable and increased the HAZ which is expected to be negligible in laser machining as compared to conventional processes. Maximum kerf width to HAZ ratio in wood was found to be less than 1:6.

- Laser beam width: At the beam waist where the beam width was minimum, finest marks and greatest depth were achieved and the inverse was true for a wide beam.

- Mobility: For a stationary laser beam, more heat was absorbed into the material causing significant melting and material removal unlike when the work table was moving at 11.2 mm/sec.

- Thickness of the material. Due to the limited DOF of the beam, only a limited thickness of a particular material could be machined.

- Machining time: Short machining time meant less interaction time and hence less material removal. Only adequate machining time resulted in measurable depths.

- Material properties: Materials with low melting point such as perspex were easily machined unlike materials with high melting point such as glass. Wood does not melt but rather decomposes chemically.
- Position of the focal point: With the focal point of the beam on the surface of the workpiece, maximum power density could be achieved which resulted to highest MRR. With the focal point either far below or above the surface, limited or no burning at all occurred.

4.2 CO_2 laser machining of different materials

Laser ablation was observed to be influenced by many interrelated parameters. This meant that even the same material behaved differently under a variation of laser parameters and other machining conditions.

4.2.1 CO_2 laser cutting of wood

The following advantages were evident while machining wood using the CO_2 laser:

- No sawdust
- Minimal noise and narrow kerf widths
- Ability to contour in any direction
- Elimination of rough, torn-out edges obtained with conventional sawing technique. However, charred edges were observed which in this thesis have also been

represented as HAZ.

For the holes or slots made using the CO_2 laser, HAZ was evident and defined as a darkened area around the holes or slots where the beam intensity was not sufficient for a clean cut. The holes were also tapered, due to the Gaussian power distribution of the beam, as shown in Figure 4.1. An increase in machining time resulted in an increase in the charred region, depth, hole diameter and aspect ratio upto a certain value above which any increase in machining time resulted in limited increase in these dimensions as shown in Figure 4.2. Aspect ratio was calculated as shown in Eq. 4.1, where AR is the aspect ratio, d is the depth machined and ϕ is the hole diameter. An increase in the number of passes resulted in an increase in both the charred region and kerf widths as shown in Figure 4.3.

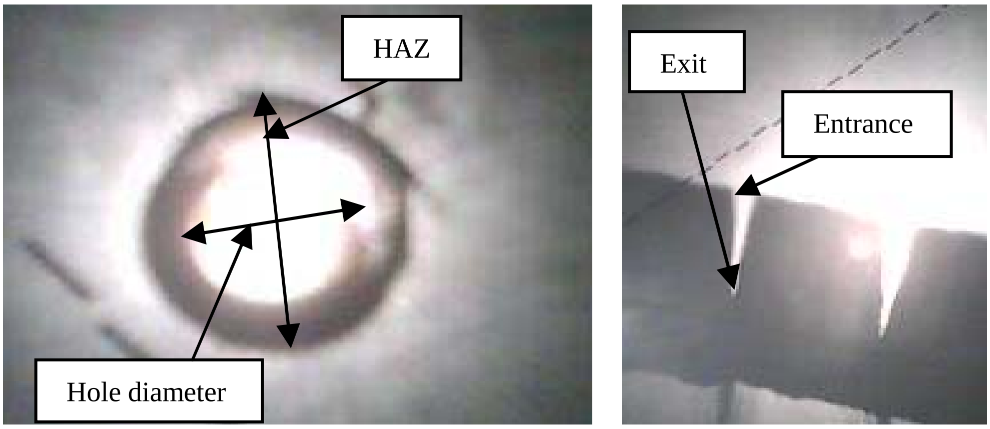


Figure 4.1: Characteristics of the laser-drilled holes and slots in wood

$$AR = d/\phi \tag{4.1}$$

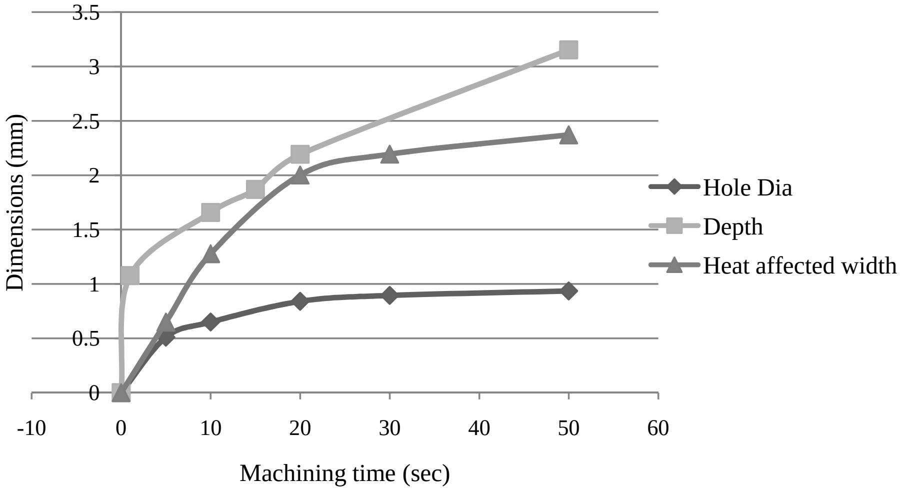


Figure 4.2: Influence of machining time in wood drilling

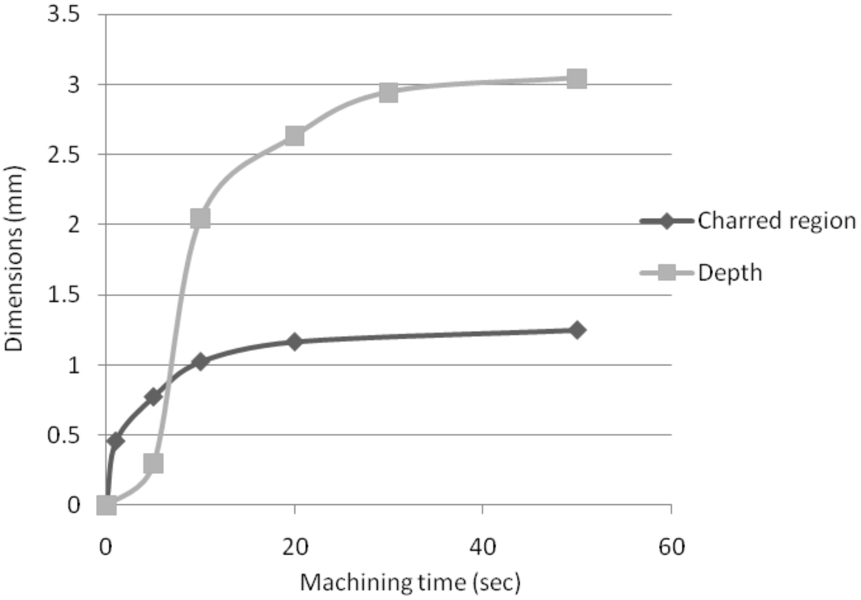


Figure 4.3: Influence of machining time on charred region and depth in wood cutting

4.2.2 CO_2 laser cutting of mild steel

Due to the high reflectance of mild steel to CO_2 laser wavelength, no visible marks were made on the polished surface of steel. When paper was placed along the reflection path of this beam from the mild steel surface, the paper was evaporated immediately as evidence that the beam must have been reflected rather than absorbed. Plastic placed along the same path was observed to be melting. This explains why no marks were made on the polished steel surface.

4.2.3 CO_2 laser cutting and drilling of perspex

Strong fumes were produced during laser machining of perspex and this necessitated good ventilation in the laboratory by keeping the windows wide open for air circulation. An increase in the number of passes resulted in an increase in HAZ, kerf widths and depths as shown in Figure 4.4.

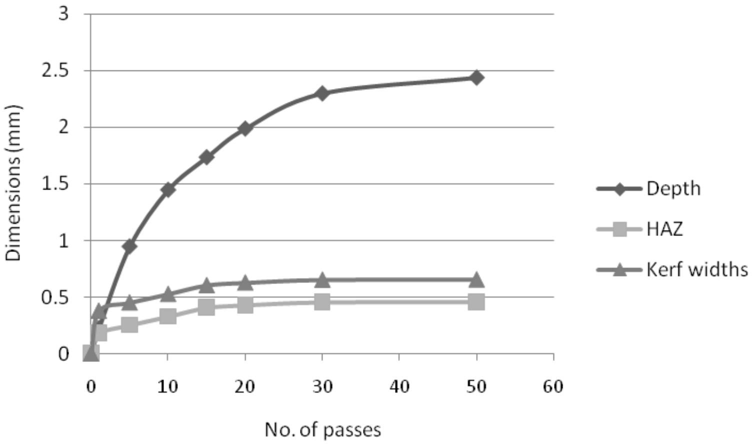


Figure 4.4: Influence of the number of passes on dimensions in perspex cutting

4.2.4 CO_2 laser cutting of aluminium

There were no visible marks on aluminium surface. This was due to the high reflectance by the material for CO_2 laser wavelength. It was also observed that a paper placed along the line of reflection of the beam from the aluminium surface were seen burning as evidence of reflection from the aluminium surface just as observed while cutting mild steel.

4.2.5 CO_2 laser cutting of ceramics

Due to the low power available with the CO_2 laser used in this work, it was possible to only make marks on ceramics that could not give data for analysis due to the limitation in measuring equipment available.

4.2.6 CO_2 laser cutting of glass

There was no sign of cracking as a result of thermal shock for the first few passes. Machining was possible but to a less extent than with wood and perspex. This can be associated with the higher melting point of glass as compared to perspex which meant more heat energy requirements. An increase in machining time resulted in increase in hole diameters and HAZ as shown in Figure 4.5. An increase in the number of passes resulted in an increase in kerf widths but this increase reduced with time as shown in Figure 4.6.

4.3 Effect of paint/coatings in laser machining

It was observed that when the polished mild steel surface was coated, marks were made on the surface since the coating improved absorption of the surface by reducing reflection. However, these marks could not give enough data for analysis.

4.4 Effect of focal point position and DOF

The position of the focal point was observed to be very crucial in the laser machining process since it dictated the achievable spot size and thus the greatest irradiance

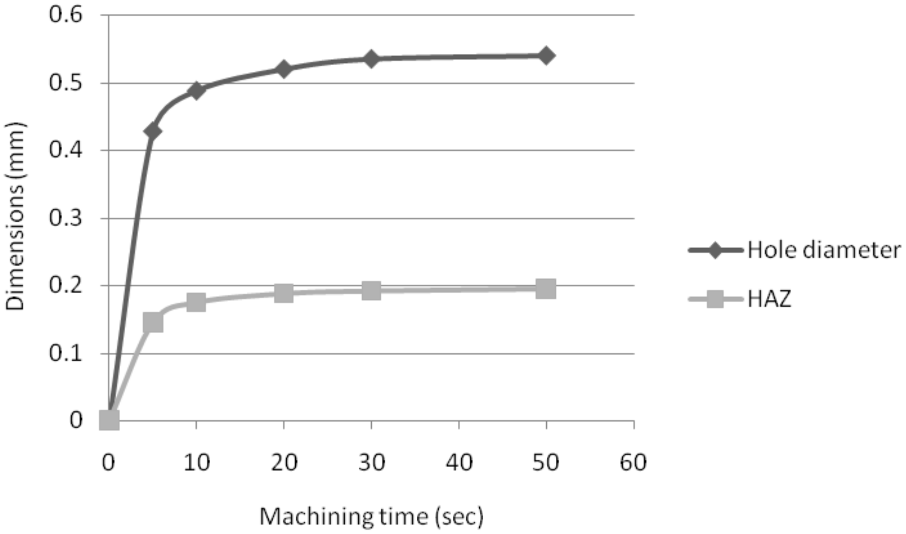


Figure 4.5: Influence of machining time on hole dimensions in drilling of glass

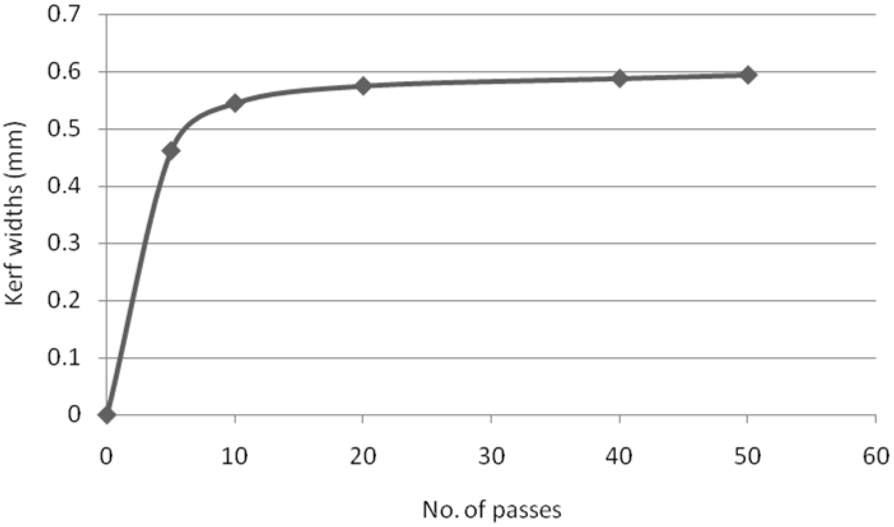


Figure 4.6: Influence of the number of passes on kerf widths in glass cutting

delivered. It was observed that machining at the focal point of the beam resulted to minimum spot size achieved, maximum power density resulted to highest MRR and least HAZ. With the workpiece not at the focal point of the beam, only faint marks or no marks at all were made.

4.5 Effects of CO_2 laser machining on cut quality

Some of the output parameters considered in this work are: kerf widths, taper, depth machined, hole diameter machined and surface finish.

4.5.1 Effect on kerf widths

From the experiments, it was evident that kerf widths increased with the number of passes for any particular material. This is due to the increase in heat supplied and hence the amount absorbed by the material from the subsequent passes. It was also observed that, across the materials, kerf widths varied for the same number of passes. The ascending order in terms of kerf widths achieved was: mild steel, glass, wood and perspex. This can be associated with the respective decrease in melting point of the materials since energy required to break bonds is directly related to melting/decomposition points of the materials for constant machining speed and time. A comparison of the effect of the number of passes on kerf widths for different materials is as shown in Figure 4.7.

4.5.2 Effect on taper

It was evident that the entrance diameter was always larger than the exit diameter resulting in a taper as shown in Figure 4.8. This was as a result of the beam having a Gaussian power distribution profile. A simple analysis of the taper was done by approximating the slots cut as follows 4.9. From trigonometry,

$$\tan\beta = \frac{y}{x} \tag{4.2}$$

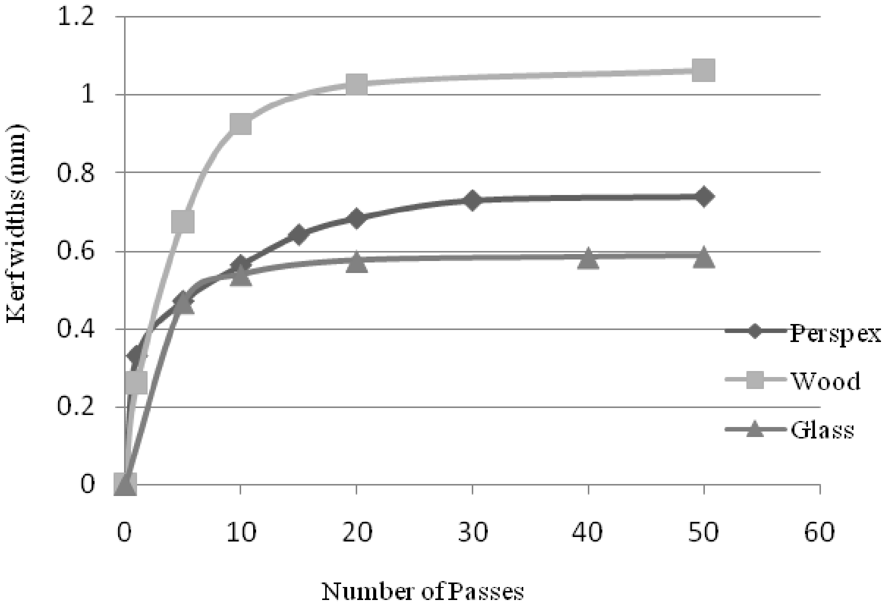


Figure 4.7: Effect of the number of passes on kerf widths for different materials

Figure 4.8: Tapered holes

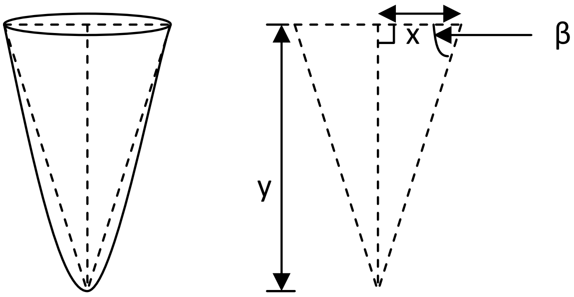


Figure 4.9: Taper analysis

This implies that :

$$\beta = \tan^{-1}(\frac{y}{x}) \tag{4.3}$$

It was not possible to obtain the measurements for glass due to equipment limitations. However, minimum taper for perspex was 8° and 22° for wood.

4.5.3 Effect on depth attainable

Depth machined increased with the number of passes and interaction time but not infinitely since the maximum depth a stationary laser can machine depends on its DOF. It was found that depths attainable for perspex and wood could be predicted as shown in Figures 4.10 and 4.11 while their comparison is as shown in Figure 4.12. It was also clear that prolonged machining time resulted in a saturated depth.

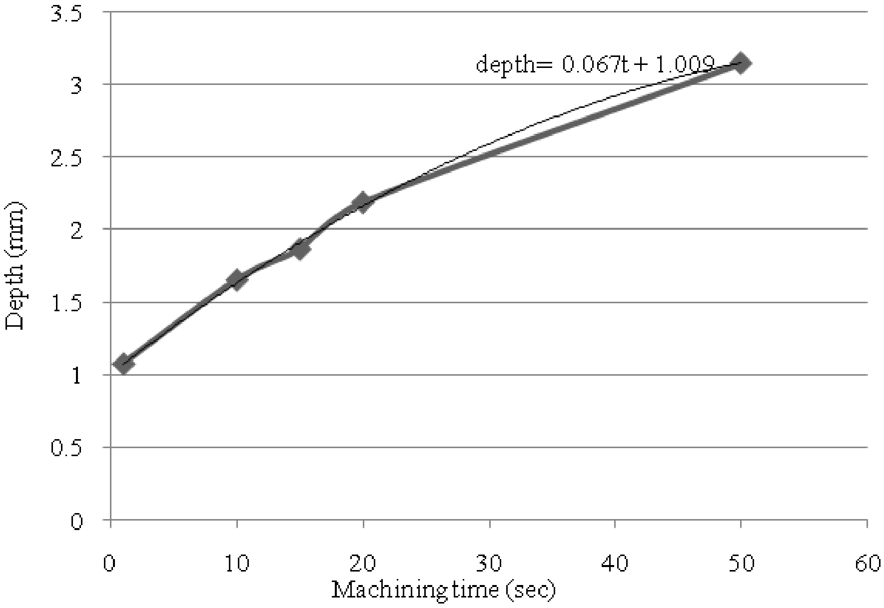


Figure 4.10: Prolonged machining time results in a saturated depth in perspex

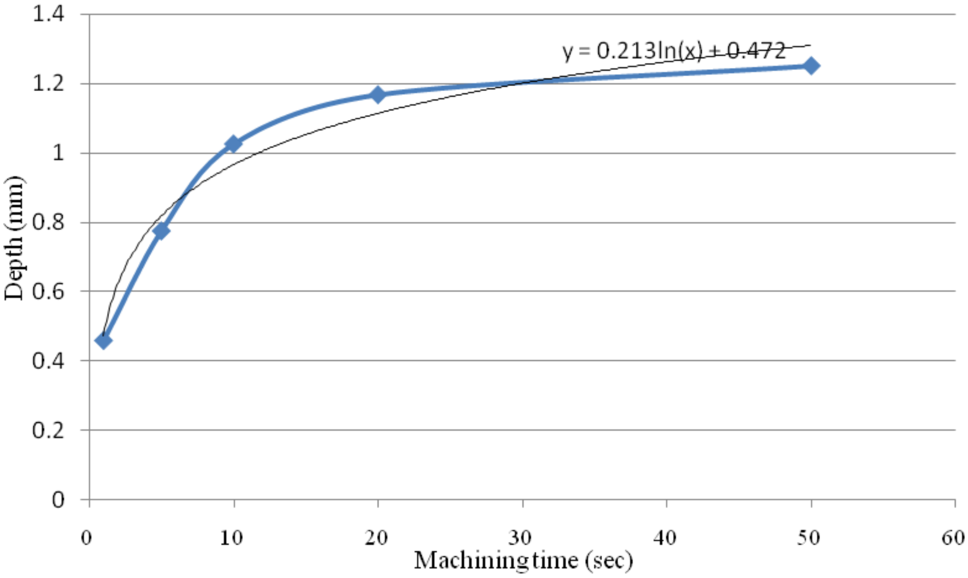


Figure 4.11: Prolonged machining time results in a saturated depth in wood

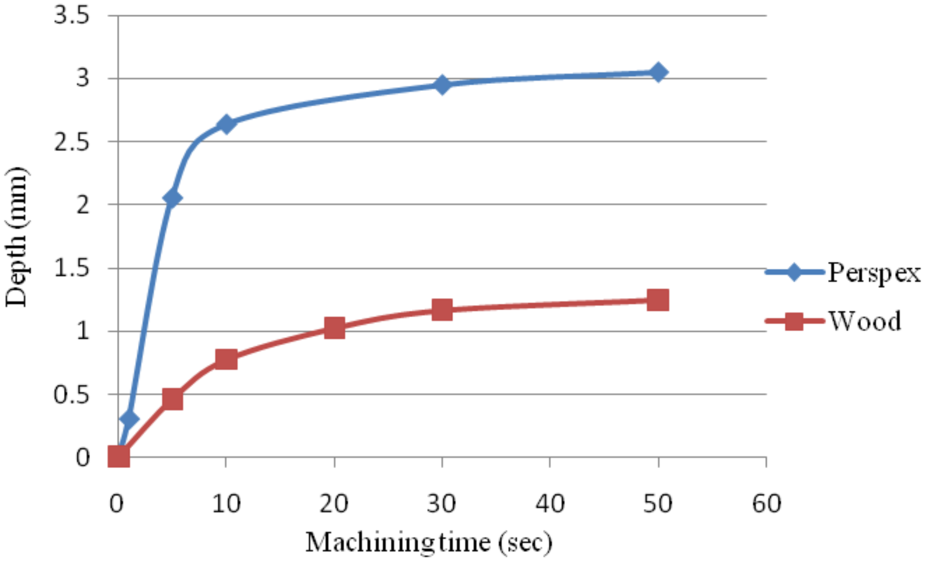


Figure 4.12: Comparison of depth attained in wood and perspex

4.5.4 Effect on hole diameter

Hole diameter machined increased with an increase in interaction time as shown in Figure 4.13.

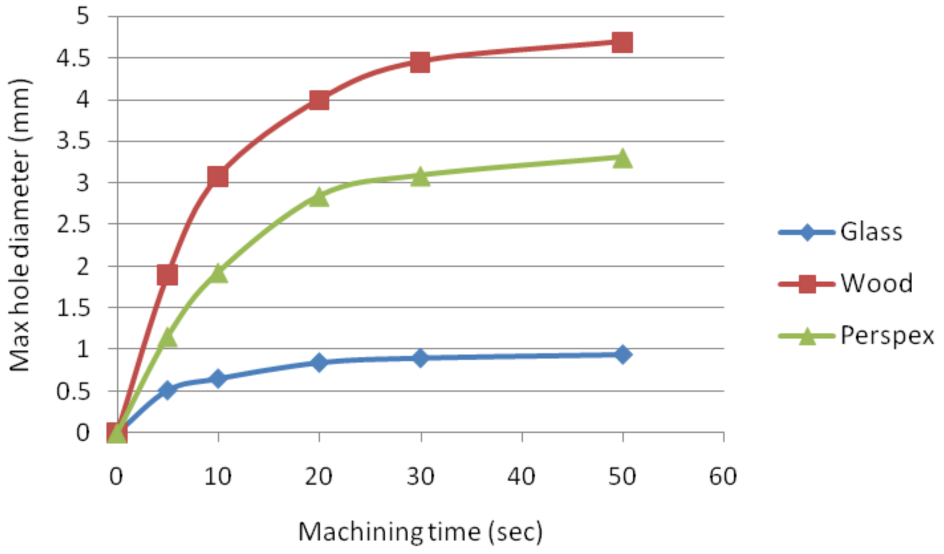


Figure 4.13: Effect of machining time on hole diameter

4.5.5 Effect on HAZ

In all the materials machined, a HAZ was observed where the beam power density was not enough to make a cut but could just alter the colouration of the region. This region was observed to be a dependent on machining time and the number of passes. Wood had a larger HAZ (of about 15 % of the machined width) than perspex. Effect of the number of passes on HAZ for different materials is as shown in Figure 4.14. It can thus be deduced from this figure that perspex is more suitable for CO_2 laser machining as compared to wood.

4.5.6 Effect on aspect ratio

The hole diameters varied in the different materials machined due to differences in heat requirements and the holes had aspect ratios (depth/diameter) from less than 1 to about 3.4 as shown in Figure 4.15.

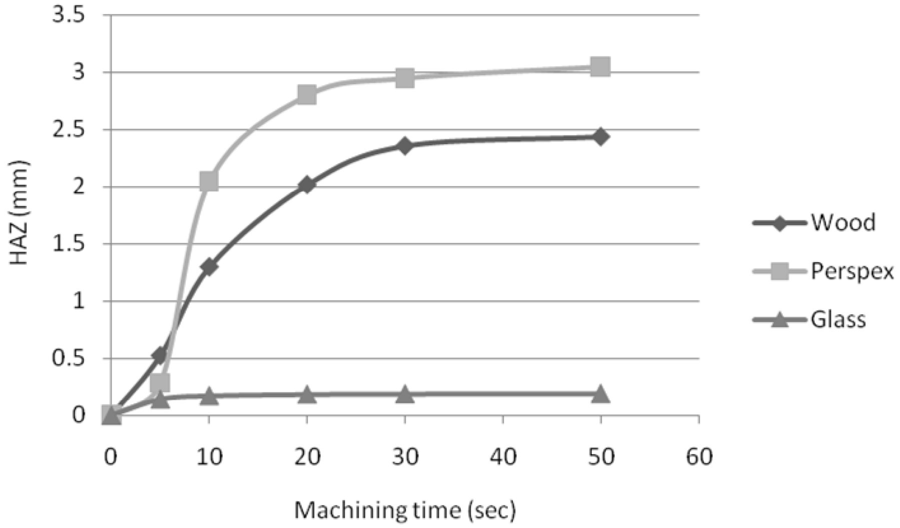


Figure 4.14: Effect of the number of passes on HAZ for different materials

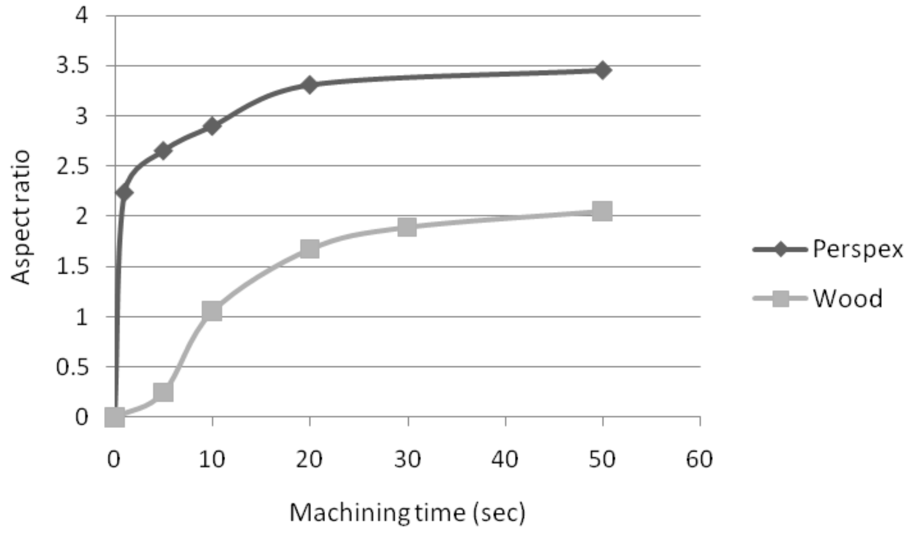


Figure 4.15: Effect of the number of passes on aspect ratio for wood and perspex

4.6 Effect of CO_2 laser on microstructure

It was noted that exposure of the CO_2 laser on unpainted shiny surfaces yielded no marks, but on the painted surfaces, marks were visible. This could be attributed to the fact that the shiny surfaces reflected a big percentage of the beam while the paint improved the absorption of the beam. This is due to the fact that a laser beam is reflected or absorbed depending on the surfaces of the materials. To be certain that the observed microstructure after the laser effect had no interference from the paint, a smooth painted surface was observed under the microscope as shown in Figure 4.16. For the unpainted surfaces, there were no changes in microstructures since the laser energy was reflected by the shiny surfaces resulting in no or negligible absorption, which is liable for any changes. Microstructural examination of the exposed specimens revealed that the microstructure changed on exposure. The microstructure changes are as shown in Figures 4.17 - 4.20 for different exposure times. Before exposure of the specimens to the laser light, the specimens consist of more ferrite and less pearlite structures. The ferrite can be seen in these figures as light polygons while pearlite are the dark lamellar structures. After exposure, more pearlite structures and less ferrite structures are observed in all cases. This is because, on exposure, laser energy is absorbed by the incident surface and diffusion of alloying elements occurs which changes the ferrite and pearlite ratio in the structure. We can approximately estimate the amount of carbon by the amount of structures such as ferrite, pearlite and cementite. In pure iron, only ferrite exists while at 0.1% and 0.2 % carbon steel,

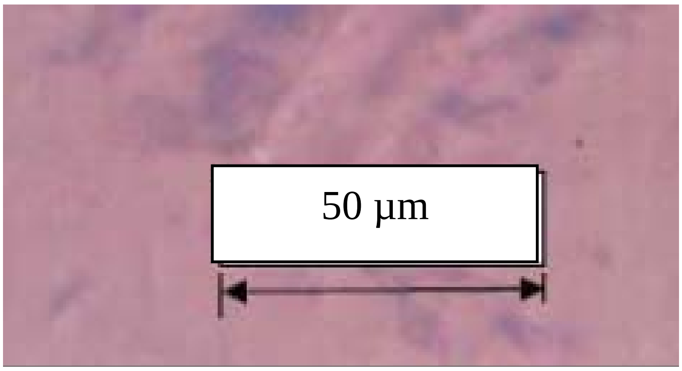
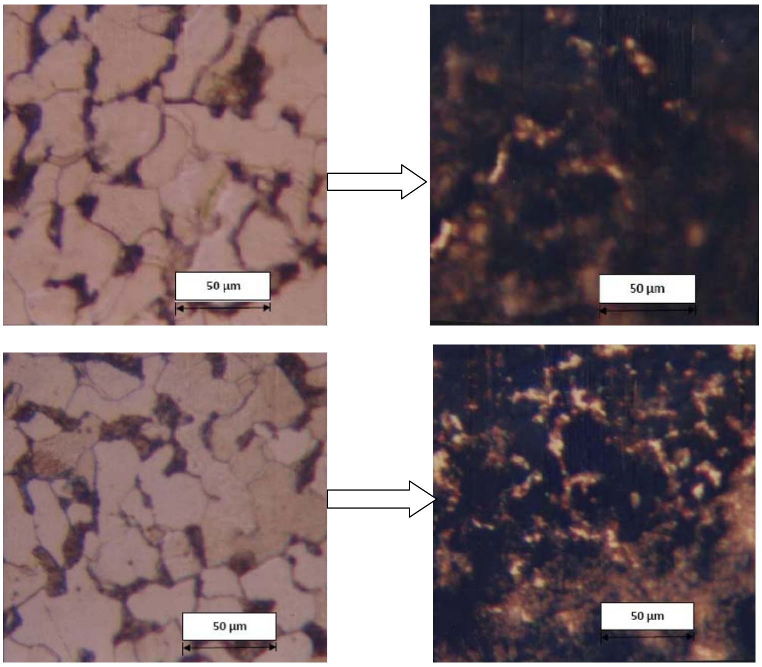
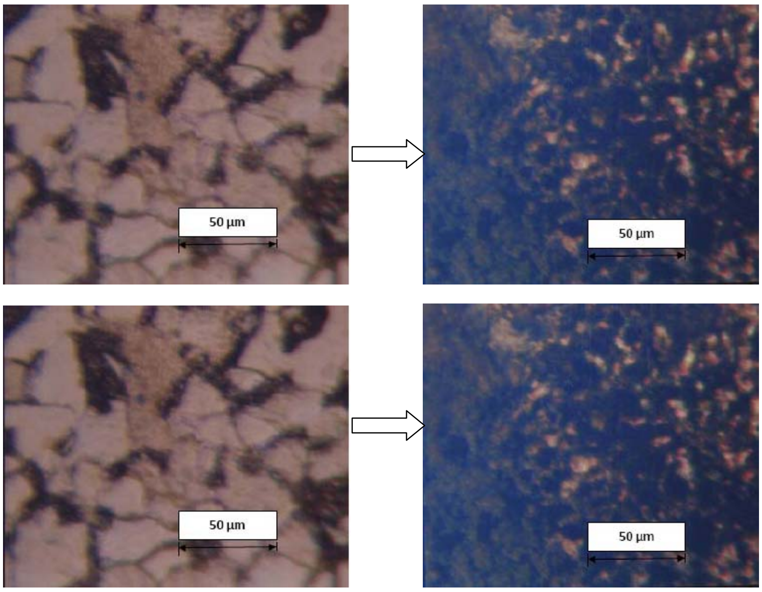


Figure 4.16: Appearance of the paint surface under the microscope



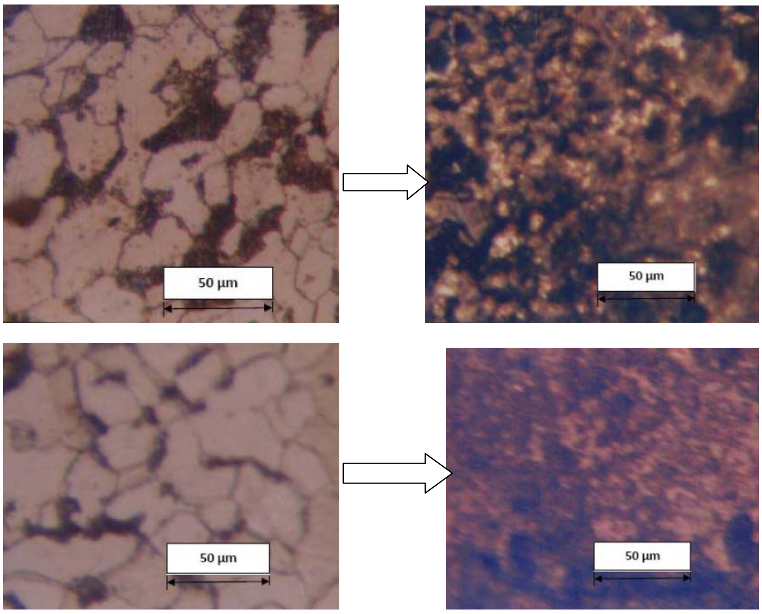
Before exposure After exposure

Figure 4.17: Microstructure changes after exposure for 60 seconds



Before exposure After exposure

Figure 4.18: Microstructure changes after exposure for 100 seconds



Before exposure

After exposure

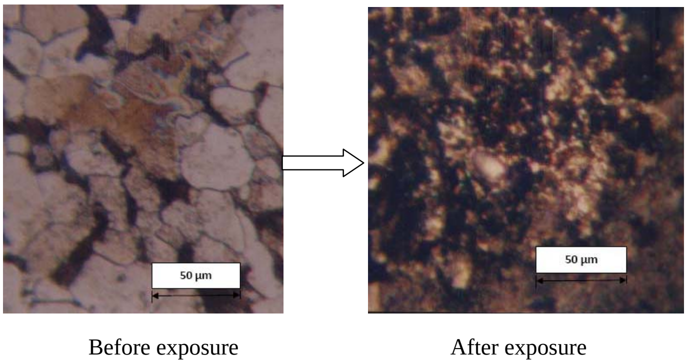
Figure 4.19: Microstructure changes after exposure for 500 seconds

pearlite appear at the boundary of ferrite. Pearlite increases still more in place of ferrite with increasing amount of carbon content and the whole domain is occupied by pearlite in 0.8 % carbon steel. Mechanical properties such as hardness and tensile strength increase while elongation and impact value decrease with increase in amount of pearlite [77].

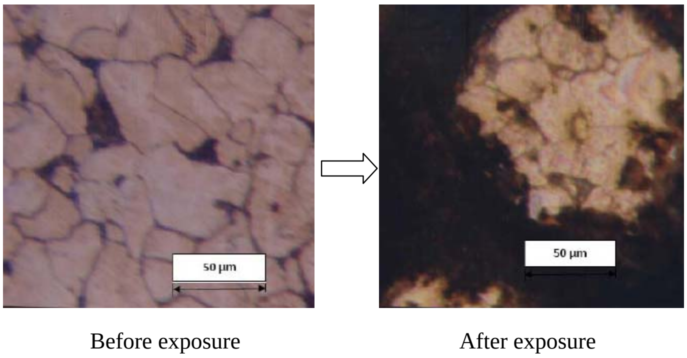
4.7 Observations on glass cracking

From the experiments done on glass, the following observations were made:

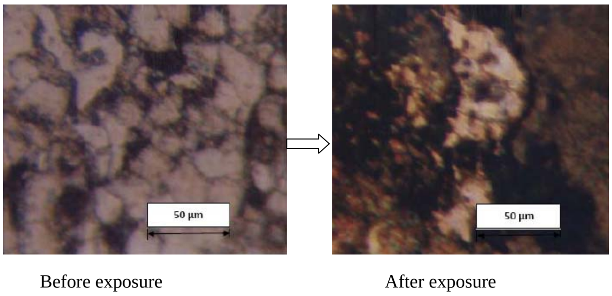
1. It was observed that although machining conditions (same beam, focal positioning) were constant and the material was from the same sample of glass, all the pieces cracked or gave the cracking sound and some even separated after a wide range of time (from 6-60 seconds).



(a) exposure for 30 seconds



(b) exposure for 200 seconds



(c) exposure for 300 seconds

Figure 4.20: Microstructural changes for various exposure periods

2. Some of the pieces gave the sound but with no visible cracks seen using the profile projector (PJ 311).
3. Other pieces even separated and were thrown far away from the machining area.
4. Other pieces separated along the full width of about 45 mm.
5. Crack thickness varied from a minimum to a maximum.
6. Hole diameters also varied (from 0.998-1.6 mm).

4.8 Effect of compressed air in glass cutting

To investigate the effect of an assisting gas in glass cutting, one set of experiments was done without any assisting gas while the other was done with compressed air as the assisting gas. Beam-glass interaction was varied from 5-25 seconds and the effect on beam diameter measured. Three different experiments were performed on the specimens as follows:

- experiments without any assisting gas
- experiments with assisting gas at 10 mm above the workpiece surface, at 45 degrees and at 3 kgf/cm^2
- experiments with assisting gas at 3 mm above the workpiece surface, at 45 degrees and at 3 kgf/cm^2.

For the experiments without an assisting gas, the first breaking of glass was noticed at less than one minute while another similar piece did not break even for two and half minutes. With no assisting gas during machining and with the beam focused at 10 mm from the edge, breaking occurred after close to two minutes. Separation of the glass piece also occurred. With compressed air as the assisting gas, cracking was not obvious since the gas also acted as a coolant and thus reduced thermal stresses. There was therefore no crack or separation even after about 20 minutes.

Another observation is that holes drilled with the assisting gas had more circular profiles while those without had irregular profiles as shown in Figure 4.21. This is as a result of the compressed air being able to remove debris and blowing them away preventing solidification around the holes. Another reason is associated with the fact that compressed air acted also as a coolant and thus reduced thermal stresses. This subsequently prevented formation of microcracks around the holes and thus the regular and smooth surface. This has therefore shown the importance and advantage of using assisting gas in laser machining to achieve precision. Components produced with microcracks are prone to early failure thus expensive to maintain since frequent replacement becomes an occasional necessity. This has shown that the use of compressed air as an assisting gas improves on profile accuracy in laser machining.

a) without compressed air b) with compressed air

Figure 4.21: Effect of compressed air on hole profile

4.9 Accounting for discrepancies

A few discrepancies were observed in the graphs as points away from the expected line as a result of some imperfections in the system such as:

- Imperfect output coupler due to dirt and thus damaged which might have altered the beam right from the output and the same imperfection manipulated through the delivery system to the machining process.
- The beam might have been multimode rather than TEM_{00} as assumed. This means that there might have been excess divergence resulting to larger size than a perfect beam would.
- Presence of spherical aberration which acts to increase the focal spot size.
- Materials inhomogeneity especially in glass which however, was ignored in this work. The effect of this is in producing irregularities in the kerf widths, cracking behavior and hole diameters obtained.
- Pollutants might have resulted during the lasing process resulting to degradation of the system efficiency.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this study, a CO_2 laser system and a delivery system were developed and used to determine the effect of machining conditions such as machining time and the number of passes on cut parameters. In addition, effects of compressed air as an assisting gas on hole profiles and glass cracking were investigated. Finally, the effect of laser beam exposure time on microstructures was investigated in mild steel surfaces. From the study, the following conclusions can be made:

- Increase in machining time and/or number of passes results in increase in depth, taper, kerf width, hole diameter and HAZ.
- Assist gas improves geometrical accuracy by blowing away debris and preventing solidification around the holes.
- Use of assist gas reduces the chances of glass cracking by cooling the glass surface to reduce thermal shock.
- There is a minimum exposure time below which laser beam cannot remove the paint. In this case, minimum exposure time was found to be 30 seconds.
- Laser beam has some effects on the microstructure of the underlying materials in mild steel. It is therefore good to check for this changes so as not to compromise with the integrity of the underlying materials especially in aircraft paint

stripping.

- Painting improves the surface absorptivity of the laser beam by the underlying material.

Materials with low melting point like perspex are easily machined than those with high melting points like mild steel and glass.The fact that laser is capable of machining brittle materials like glass has been one of the major advantages with laser machining. This advantage was also confirmed true since there were no microcracks along the cut edge when an assist gas was used.

5.2 RECOMMENDATIONS

In order to be able to machine a wider range of materials and make deeper cuts, a high power laser system is recommended. Other parameters such as laser power, optical parameters (focal length) and scanning speed should be varied and their effects on cut parameters investigated. Though paint removal using laser has several advantages, the integrity of the substrate may be compromised. Further investigation needs to be done on the effects of laser on physical properties, such as strength, of the laser-exposed surfaces to determine whether the change on the underlying material was positive or adverse.

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Appendix A

CO_2 Laser Safety

A.1 Dangers in the CO_2 laser system

Although a CO_2 beam falls in the IR range and cannot be focused on a human's retina [68], several precautions needed to be done since the system has other dangers unusual with most types of lasers. Safety precautions were thus extremely important for this small CO_2 lasers for a variety of reasons [78]:

- The high voltage supply required the operator to be more careful to avoid electrocution
- Due to the water cooling system and the high voltage associated with this type of laser, great care was required to avoid short circuiting
- Cutting of some materials produced undesirable fumes that necessitated good ventilation. The by-products of laser processing of organics generally include very hazardous materials. Carcinogens such as benzene and PAH's (polycyclic aromatic hydrocarbons) are typically generated in reasonably significant quantities.
- Although CO_2 laser has a long wavelength which cannot be focused on the retina to evaporate it, due to the high power associated with CO_2 laser, it can literally burn the surrounding areas and thus access the retina. This can cause permanent blindness since the cells in the retina form the central nervous system which do not regenerate.

- The beam is totally invisible and thus one may assume it is safe to cross or stare without any awareness [68]. Eye-blink reflex responds only to visible wavelengths making CO_2 laser hazardous as it can burn the eyes before they blink.

- Other hazards involve those of moving machinery that can either be damaged.

- Gas poisoning may occur. The gas used in CO_2 lasers is a mixture of helium, N_2, CO_2 and sometimes others like O_2 and neon. These gases must not leak as they cause ventilation problems like nausea. A leakage meter was used to ensure no leakage along the piping and the glass tube.

- Poisoning from materials may also occur. Although the ideal mirror recommended for use as the output coupler is a zinc selenide mirror, it is a toxic material and harmful to the body in a cumulative effect when exposed to it for long durations.

A.1.1 CO_2 laser safety concerns

To counteract the above risks, only well insulated screw drivers were used, a safe distance was kept from the high voltage areas, suitable eye goggles were used and tight fittings were ensured to avoid water or gas leakages. To strengthen on the above laser safety measures, the following guidelines were adhered to

- It was a habit not to point the laser at another person, especially their face by working in a dark room with a restricted access.

- Never under any circumstances to look directly into the laser beam not to take chances with the eyes

- Always to be conscious of and aware of reflective surfaces such as mirrors, polished metal, watches, necklaces, ear rings or glass since a reflected beam can harm the eyes

- Not to let other people use the laser unless they are fully aware of the dangers of lasers

- Wearing of safety goggles at all times

- Avoidance of wearing jewelery since they might be reflective with the reflected beams having almost as much power as the original beam

- Adequate ventilation in the room was ensured by opening windows while working due to the flowing gas and fumes generated while machining

- An appropriate laser safety and electrical safety warning was put near the laser emission aperture and on the power supply component

- Everyone who came/visited the laser system environment was advised on laser hazards and safety guidelines

Appendix B

CO_2 laser eye protective wear

CO_2 lasers are in group IV and thus the right eye wear in terms of the correct choice of lens density and color were selected based on the wavelength and power of the specific laser being used.

The eyes were protected from maximum anticipated exposure and at the same time the greatest amount of light possible was allowed to enter the eye to ensure proper sight. There are two important technical considerations for laser safety eyewear (LSE):

1. Maximum permissible exposure (MPE) which is the level of laser radiation to which a person may be exposed without hazardous effects or biological changes in the eye. MPE levels are determined as a function of laser wavelength and exposure time. The MPE is usually expressed either in terms of radiant exposure in J/cm^2 or as irradiance in W/cm^2 for a given wavelength and exposure duration.
2. The Nominal Hazard Zone (NHZ) which is the physical space in which direct, reflected or scattered laser radiation exceeds the MPE. LSE was worn within the NHZ.

In selecting the specific eyewear, the following were considered:

1. Laser wavelength at which protection was required and
2. Optical density (OD) of the LSE for the wavelength being used

OD refers to the ability of a material to reduce laser energy of a specific wavelength to a safe level below the MPE given by :

$$OD = Log_{10} \frac{E_i}{E_t} \tag{B.1}$$

where E_i = incident beam irradiance (W/cm^2) for a worse case exposure, E_t = transmitted beam irradiance (MPE limit in W/cm^2). The required OD for any given laser is usually determined by either of the following methods:

- calculation
- consulting nomograms or tables (e.g., ANSI 136.1 guidelines)
- consulting the laser manufacturer.

Even with a very good eye wear, it is good to note that any damage to the LSE will reduce the OD and thus interfere with its protective capability. A safety eye wear of OD 6 was used while carrying out the experiments.