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Precision Cutting of Hardwoods by using a High Energy Carbon Dioxide Laser

presented by

Mondher Cherif

has been accepted towards fulfillment
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Master's degree in Materials Science

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PRECISION CUTTING OF HARDWOODS BY USING A HIGH ENERGY CARBON DIOXIDE LASER

By

Mondher Cherif

A Thesis

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

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1990

ABSTRACT

PRECISION CUTTING OF HARDWOODS BY USING A HIGH ENERGY CARBON DIOXIDE LASER

By

Mondher Cherif

In traditional cutting of wood a valuable portion of the material is lost due to the wide saw kerf and cross cutting to cut around defects present in the lumber. In the present work laser beam machining is proposed as an alternative method of processing wood. A systematic study on the feasibility of using a high energy laser to cut hardwoods was conducted. In this study a 3000 watt CO_2 laser was used to perform high speed cuts in basswood, soft maple, black cherry, black walnut, and hard maple. The relationship between various laser processing parameters, thermophysical properties of wood and the quality of cut was investigated. To determine the environmental safety of laser wood cutting, the smoke produced during the cutting process was also analyzed by gas chromatography. The results show that high speed, clean, and narrow cuts can be made in various types of hardwoods.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

In wood industry a large and valuable portion of a tree is wasted in the production of furniture parts and other wooden products. Only about one sixteenth of the original tree is used in the finished product for the above mentioned industry. In conventional rough milling most of the material loss results from cross cutting and material ripping to cut around the defects present in the lumber(1). Such defects are worm holes and knots. Further material loss is due to the wide saw kerf. Kerf represents the amount of material removed by saws. Since the supply of more expensive types of wood such as black walnut, black cherry, and soft maple has decreased, the need for a tool which can cut large boards of wood with a small kerf has become more imperative. Presently, in the market several tools, which can be used to make high speed precise cuts with relatively small kerf, are available. The most important candidates for high speed precision cutting are a focused electron beam, a high velocity water jet, or a high energy focused laser beam.

The use of electron beam requires vacuum, thus large vacuum chambers are needed in electron beam wood cutting which poses a major problem. Although water jet technique is used for cutting metals and ceramics, it is not adopted to cut wood due to several disadvantages. One of which is the fact that the wood cut surface can absorb water. Also the water jet technique is not completely adaptable to precise numerical control, hence complicated shapes are difficult to cut.

Lasers, with an enormous potential for material processing, are routinely used for cutting, joining, heat treating, cladding, and for drilling of metals, ceramics, and plastics (2-5). Even though several types of lasers, such as carbon dioxide, Nd:Yag, eximer and other types of lasers have been developed for materials processing applications, carbon dioxide laser is the most widely used for such application because its 10.6 micron wave length is better absorbed and hence more efficient for many materials including wood (6).

The rapid success of the carbon dioxide laser is due to its ability to provide a coherent, high energy focused laser beam. The other advantages are complete control of the beam power, narrow kerf (one eighth of saw cut) (7), no tool wear due to absence of mechanical contact with the workpiece (6,8), ability to make cookie cuts which is due to the fact that the laser beam can be started and stopped anywhere in the workpiece and ability to make contour cuts (9), and ability for complete automation. Hence, high speed laser cutting with little human involvement can be performed.

As with any other new technology wood industry has been rather slow in accepting laser as a cutting tool, it is still skeptical about the use of lasers. For the last few years, most of the commercial use of lasers in wood industry is restricted to cut die boards, fancy furniture parts and for art work (10). In early 70's, Mcmillan made cuts in pine wood samples of different thicknesses using a 250 watt carbon dioxide laser, he found an inverse relationship between cutting speed and sample thickness (11). In 1976, Peters et. al., investigated the possibility of cutting wood and wood base products by using a multi-kilowatt carbon dioxide laser (12). They also found that the cutting speed decreased with the increase in wood thickness and density.

As laser manufacturers and wood industry managers become more familiar with the materials processing potentials of lasers, it is likely that many more important applications will be developed. The major problem is a more complete understanding of the complex interactions between the laser beam and wood. The various parameters of the laser interaction with the material can be classified into three major areas: (1) characteristics of the laser beam; (2) equipment and processing variables; (3) properties of the work material. Important beam characteristics include beam power, beam mode, polarization, and stability. Major equipment and processing variables involve the design of the beam delivery optics, location of the focal point, feed rate, design of the gas jet assist system, type of the gas used, and gas pressure. Factors related to the material include thickness, density, and moisture content. In addition, for composite wood products, the quantity of additives and the shape and orientation of the particulate elements are also important.

This document discusses the experimental results pertinent to the effects of various laser and material parameters on high speed laser cutting of hard woods. Five different types of 2.2 cm (7/8 inch) thick hardwoods such as Basswood, Soft Maple, Black Cherry, Black Walnut, and Hard Maple were cut under a wide range of laser power, feed rate, type and flow of the cover gas, and optical focussing conditions. Limited experiments were also performed to determine the composition of gases/smoke produced during laser cutting of hardwoods. Data on different permanent gases and hydrocarbons was collected. This data is essential to (a) understand the thermodynamics and kinetics of evaporation and combustion associated with high energy laser interaction with wood, (b) develop vital information about the potential health hazards of combustion products produced during laser cutting of hardwoods. The details of the experimental results are discussed in the following chapters.

CHAPTER 2

LASER WOOD INTERACTION

In laser wood cutting, a high power laser beam whose energy is concentrated in a very narrow spot interacts with the wood surface. The laser beam of high power density can instantly vaporize the mass exposed to it. In the case of wood, a rapid combustion of cellulose and other constituents of wood leads to a rapid material ablation. A coaxial cover gas is also provided along with the focused laser beam to assist in the removal of vapors and particles from the cut region and away from the laser beam.

With a laser beam the energy available for cutting is related to the thermal and optical properties of the material. When the laser beam strikes the surface of the workpiece, reflection of photons causes energy losses. While metals may reflect up to over 90 percent of the laser energy, losses for wood are relatively small. After energy has been absorbed, further losses are due to the conduction of heat into the bulk. Again, since the thermal conductivity of wood is very small compared to metals, only a little absorbed energy is lost by conduction. In a very simplified form the maximum cutting rate can therefore be related to the laser power by the following equation:

$$P = Q.W.L.F \qquad (2.1)$$

where, P : laser power (watt)

Q : energy required to evaporate a unit volume of wood (J/cm^3)

W : kerf width (cm)

L : thickness of wood (cm)

F : feed rate (cm/sec)

From the above equation, it can be seen that for a fixed value of evaporation energy, wood thickness, and kerf width, the feed rate is directly dependent upon laser power.

One of the main advantages of using lasers for cutting hardwoods is the fact that kerf width of laser cut wood is much smaller than the width of cut made by conventional saw (13). An economic study conducted by Huber (13) has shown that by using laser to cut hardwoods, at least five percent of the material can be saved. However, for an economically feasible transition in the cutting operation, it is necessary to cut Basswood at a feed rate of 12.7 cm/sec (300 ipm). This desired feed rate can be obtained, as can be seen from equation 2.1, by increasing the laser power. But, one should be aware of the higher cost of cutting operation due to the use of the high power lasers. Also the input laser energy can not be increased indefinitely due to the limitations of the machine and also due to the fact that it is not known how much and how the input energy is actually consumed. It is therefore necessary to develop an understanding of the cutting process on scientific bases.

Laser wood cutting is mainly a combustion process in which intense heating causes irreversible chemical reactions which result in the removal of the material. This process consists of three different mechanisms; (1) entrapped water evaporation, (2) gas heating, and (3) chemical reactions.

2.1 EVAPORATION OF ENTRAPPED WATER

Wood contains pockets of entrapped water, or molecules chemically bonded in the molecular structure of the material. When the laser energy is absorbed by the material intense heating occurs which causes the chemical bonds to break and water and other compounds present in the material to evaporate. These volatilized products exert large internal pressures on the material, causing microfracture and ejecting out particles of matter.

2.2 HEATING OF ENTRAPPED GASES

Since wood is a porous material, it contains gaseous voids. The absorbed laser energy causes these gases to expand upon heating which in turn exert great internal pressures on the material. These forces can also cause the material to weaken by producing microcracks and by ejecting particulates of matter.

2.3 CHEMICAL REACTIONS

The laser energy, causing intense heating, can promote irreversible chemical reactions which result in the weakening or removal of the material. Combustion (i.e. burning) converts liquids and solids into volatile gases which readily escape from the heated zone. The combustion process consists of the following reactions:

$$2C + O_2 \longrightarrow 2CO \qquad (2.2)$$

$$2CO + O_2 \longrightarrow 2CO_2 \qquad (2.3)$$

$$C + O_2 \longrightarrow CO_2 \qquad (2.4)$$

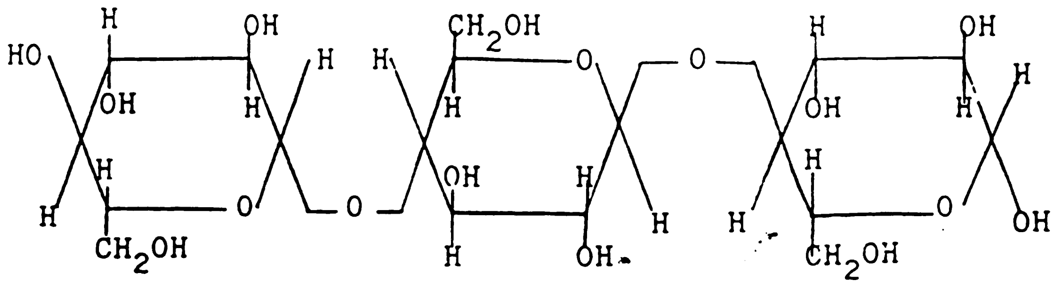
The chemical and physical processes that occur during the combustion reaction are very complex, because they depend not only on the type of the carbon compound reacting with oxygen but also on the conditions at which the reaction takes place such as the interaction time and the amount of energy available. Despite the complexity of the combustion process the above equations can represent the combustion process. Equations 2.2 represents the incomplete combustion of carbon, while equations 2.3 and 2.4 represent the complete combustion of carbon which is far slower than the incomplete reaction. The rates of these three reactions depend on several factors primarily on the amount of oxygen present.

The combustion of wood is better represented by the degradation of cellulose which is one of the three constituents of wood. Cellulose composes about one half of the wood, and lignin and hemicellulose make up the rest, depending on the tree species. As shown in figure 2.1, the structure of each component is different. Lignin has a complex and irregular form. Therefore, the consistent structure of model sample of cellulose is recommended to represent wood.

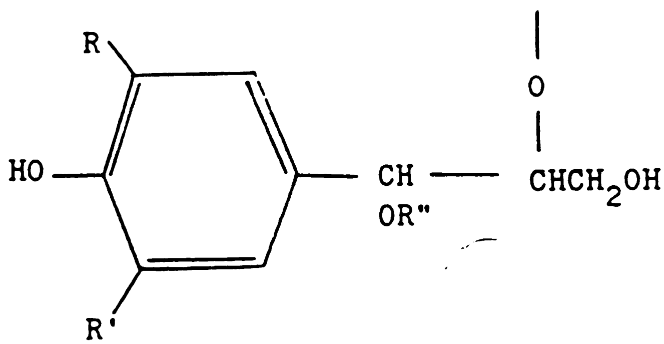
Pyrolysis of cellulose, upon heating, converts the solid matter into degradation products that can exist in the solid state (char), liquid state (condensible tar), and the gaseous state. The gaseous phase contains mostly carbon monoxide, carbon dioxide, and minor proportions of hydrogen, methane, ethane, and other light hydrocarbons (figure 2.2).

The relative concentration of combustion products as well as the cutting quality depends on several factors. One of the determining factors on the cutting process is the laser beam energy present at the interaction site. The laser beam spatial distribution and energy density depend on the transverse electromagnetic mode (TEM) structure of the laser beam and the spot size which in turn depend on the focusing conditions. The latter two beam characteristics depend on the design of the laser cavity and the delivery system.

= Cellulose =



= Lignin =



R, R' = H, OCH_3

R" = H or Ar or Carbohydrate

= Hemicellulose =

$(C_5H_8O_4)_n$ $(C_6H_{10}O_5)_2$

Figure 2.1 Structure of three major components of wood [14]

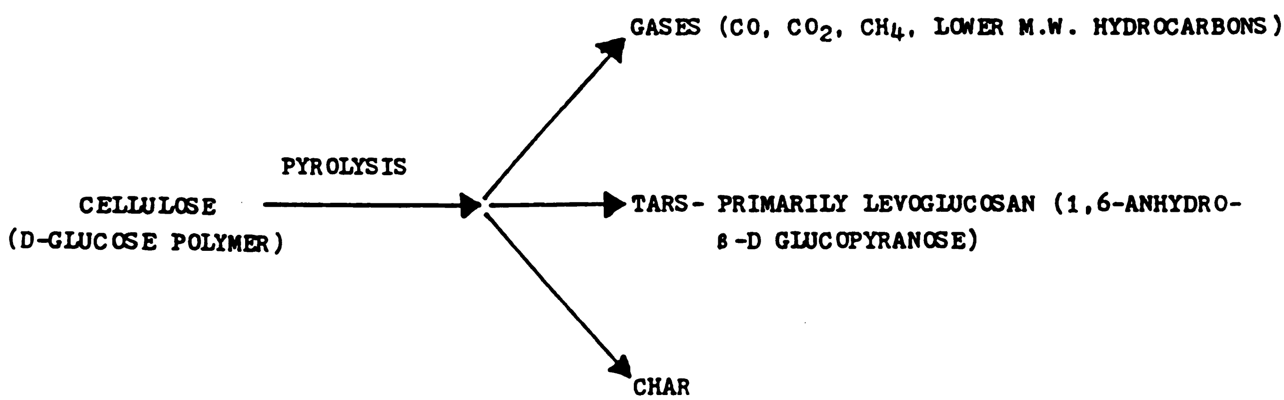


Figure 2.2 Three major products of wood pyrolysis [14]

2.4 SPATIAL DISTRIBUTION OF LASER BEAM

The transverse electromagnetic mode (TEM) of a laser determines the distribution of the beam energy in three dimensional space. It is the quality of the beam profile rather than the total power that determines ultimate processing performance. Most lasers used for cutting are designed to generate Gaussian or near-Gaussian distribution (figure B.1 in appendix B). With this type of beam it is possible to obtain a small focal point and generate the high energy needed for cutting. Additionally, the energy profile is the same about all axes, this characteristic is important where cutting performance must be independent of direction. Because the Gaussian energy distribution exhibits a sharp peak, the energy density at the center of the focused beam is significantly higher than the average energy density.

Another high symmetry low order mode is the TEM_{01*} mode which is characterized by a donut shape energy distribution (figure B.1 in appendix B). This mode has two energy peaks at symmetric positions from the center and is also suitable for cutting. Also with this type of mode the laser beam can be focused to a relatively small focal point, generating the high energy density needed for cutting. Both modes are stable at high and low operating powers.

Polarization is associated with the electrical and magnetic field components of laser light (figure 2.3).

The cutting quality is seriously affected by the polarization state of the laser. The depth of cut and the kerf vary with the direction of the electric field component of the laser beam. If the electric field component is parallel to the cut surface, deeper cuts with relatively narrow kerf are obtained. However, if the electric field component is orthogonal to the cut surface shallow cuts with wider kerf are obtained (figure 2.4). Thus, in contour cutting, optimum cutting speed and kerf can be achieved by using a laser beam which is circularly polarized, where the electric field component is always at an inclined angle with respect to the cut surface.

2.5 LENS FOCAL LENGTH

The laser beam coming out of the laser cavity has a diameter of about 2 to 3 cm. Even at the highest power levels, not enough energy is obtained to make deep cuts. Therefore, optical lenses are used to focus the laser beam to small spot size. In focused conditions energy densities of the order of several millions watts per square centimeter can be obtained. The CO_2 laser beam can be focused by using ZnSe, GaAs, or CdTe transmissive lenses. Figure 2.5 shows

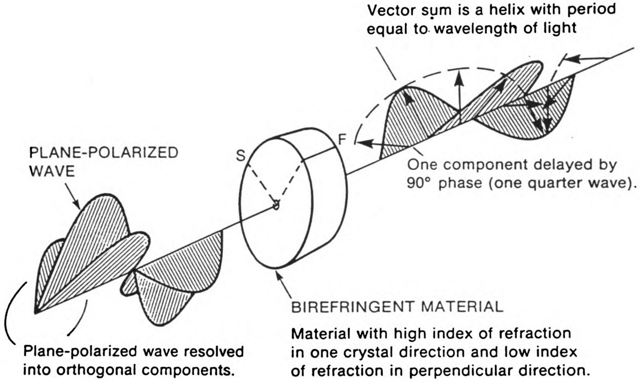


Figure 2.3 Plane polarized laser beam and circularly polarized laser beam [15]

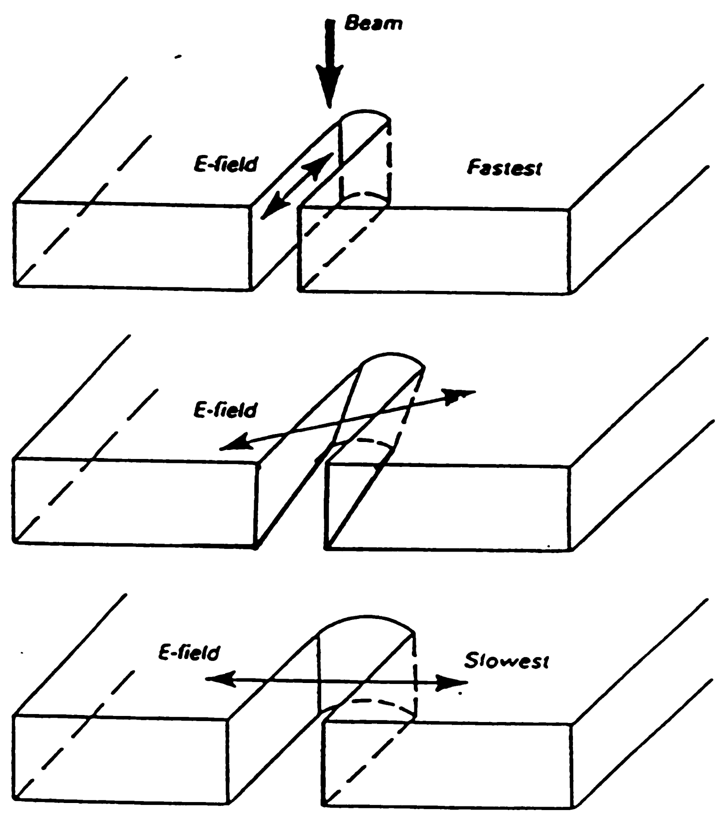


Figure 2.4 Effect of laser beam polarization on wood cutting [16]

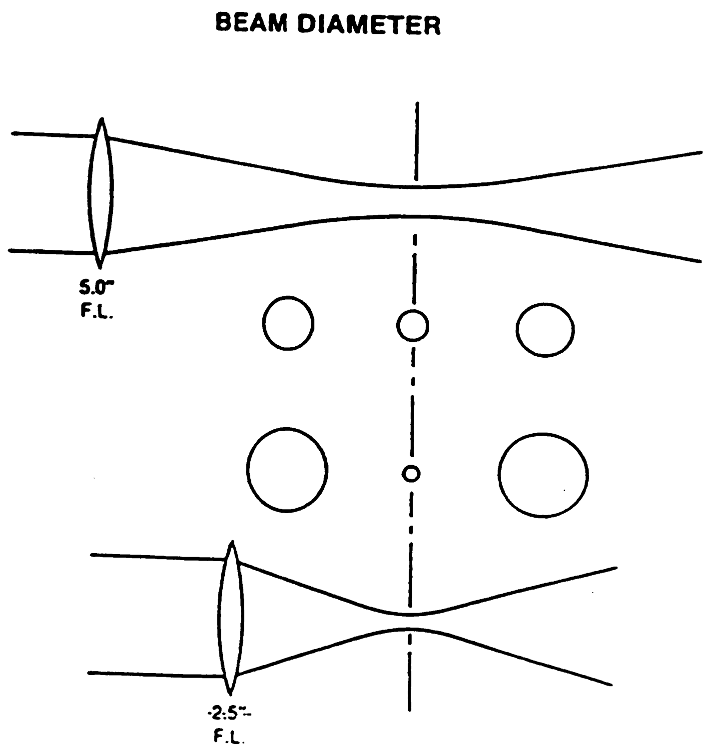


Figure 2.5 Beam diameters at different distances from the focal point [15]

the beam geometry over a range of distance from the lens. One can see that the spot size increases with the lens focal length, Thus, in order to obtain high energy density, lenses with small focal lengths are used. However, small focal length lens is not desired when cutting thick material because of the small focal depth of the lens. For the purpose of cutting 2.2 cm (7/8 inch) thick pieces of hardwood a 12.7 cm (5 inch) or a 25.4 cm (10 inch) focal length lenses can be used because they have a long depth of focus, which is essential to make straight cuts in thick pieces of hardwood.

CHAPTER 3

EXPERIMENTAL SETUP

A high energy carbon dioxide laser was used to make narrow cuts in various species of hardwoods. Five different types of 2.2 cm (7/8 inch) thick hardwoods namely Basswood, Soft Maple, Black Cherry, Black Walnut, and Hard Maple were cut under a wide range of laser and material parameters. Since the laser beam was stationary, relative motion to make cuts was provided by placing pieces of hardwood boards on a computer numerically controlled, X-Y table. The gases produced during laser cutting were removed both from the top and bottom of laser/wood interaction site. An overall view of the experimental setup is shown in figure 3.1. The experimental setup consisted of the following items:

(a) High Energy Carbon Dioxide Laser
(b) Computer Numerically Controlled X-Y Table
(c) Smoke Exhaust System
(d) Fully Computerized Gas Chromatograph

(a) High Energy Carbon Dioxide Laser:

A RF excited 3000 watt, Trumpf, carbon dioxide laser operating in continuous and pulse mode was used. The laser, having a TEM_{01*} mode, was equipped with a circular polarizer in order to obtain a uniform spatial energy distribution,

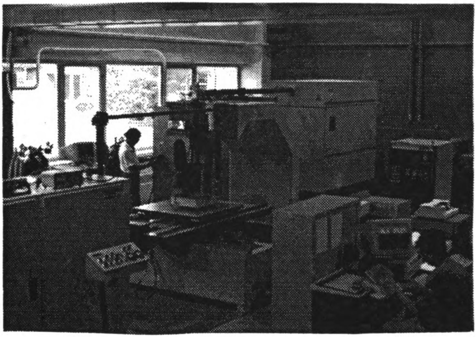


Figure 3.1 An overview of the experimental setup

thus resulting in similar cutting performances in all directions of the laser travel. The laser can be operated at different power levels ranging from 100 watt to 3000 watt. The laser delivery system was equipped with a transmissive and reflective laser beam focusing setup. A 25.4 cm (10 inches) focal length lens was used to focus the laser beam to a focused spot of about 0.05 cm. Some initial data was collected by using a 2500 watt BOC, CO_2 laser; a 12.7 cm (5 inch) lens was used to focus the beam. Throughout this text this data is indicated by @. Various gases such as air, nitrogen, and oxygen were used as a cover gas through a coaxial nozzle at a maximum pressure of 552 x 10^{-1} N/cm^2 (80 psi), (figure 3.2). Also an auxiliary gas setup consisting of a nozzle held at an angle of 45 degrees with respect to the workpiece was used to introduce oxygen into the kerf.

(b) Computer Numerically Controlled X-Y Table:

A computer numerically controlled, 127 cm x 127 cm (50 inch x 50 inch) travel length, X-Y table capable of providing a maximum linear speed of 25.4 cm/sec (600 ipm) was used to provide the relative motion of the workpiece. The linear resolution of the table is 0.0013 cm (0.005 inch). Necessary computer hardware and software were developed during the course of this research to transfer data to and from the CNC table to a personal computer. Hence

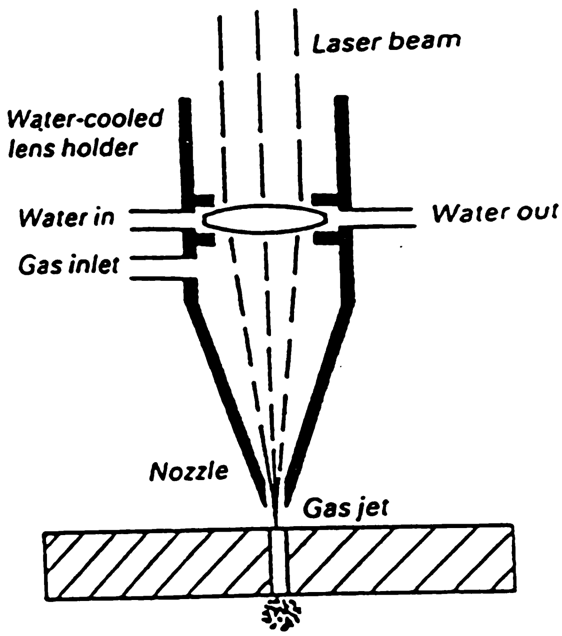


Figure 3.2 A schematic diagram of the Gas jet assembly used in laser cutting [16]

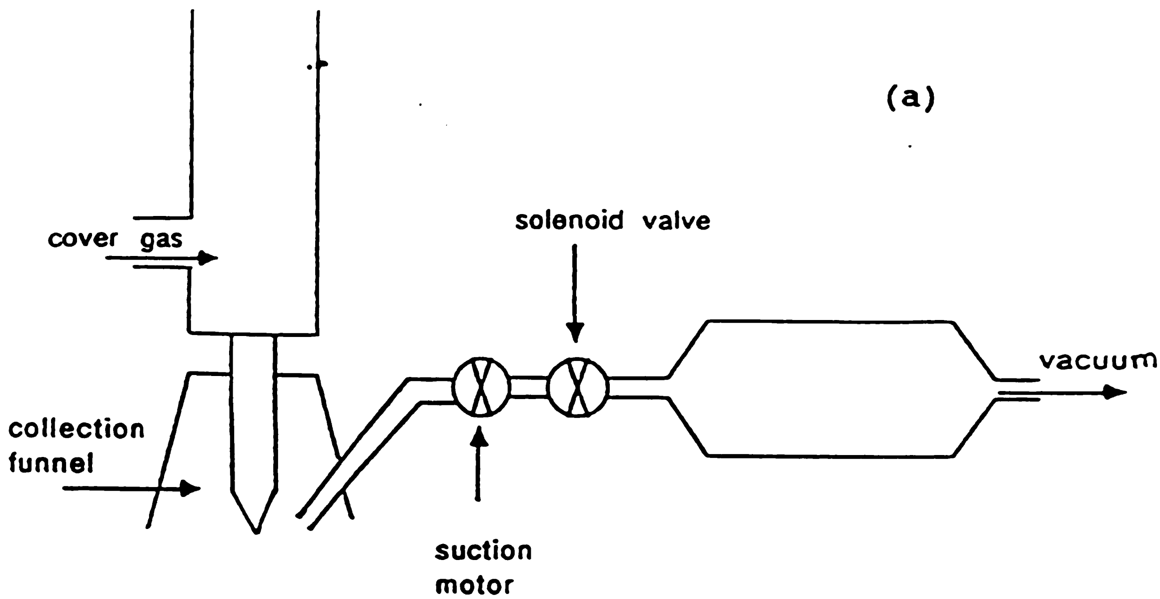
complicated shapes digitized and programmed on the personal computer can be cut easily.

(c) Smoke Exhaust System:

An exhaust system was used to remove the smoke, produced during the cutting process, both from the top and bottom of the laser machining site. Two high flow rate vacuum pumps were used to remove the smoke. A four inch diameter exhaust line was used to transfer the smoke away from the cutting site. The transferred smoke was released in a perchloric acid fume exhaust setup.

(d) Fully Computerized Gas Chromatograph:

A fully computerized, Perkin Elmer 8500, gas chromatograph was used to analyze the combustion products. A hot wire detector, a molecular sieve column, and a carbosieve column were used in the analysis of permanent gases such as nitrogen, oxygen, carbon monoxide and carbon dioxide. For the analysis of hydrocarbons a flame ionization detector and a carbowax column were used. The gas chromatograph was initially tested and calibrated by injecting gas samples of known composition. Then the gases produced during laser cutting of hardwoods were analyzed. The combustion gases were collected using the experimental setup given in figure 3.3. The apparatus shown in part (a) is used to collect combustion gases produced during the



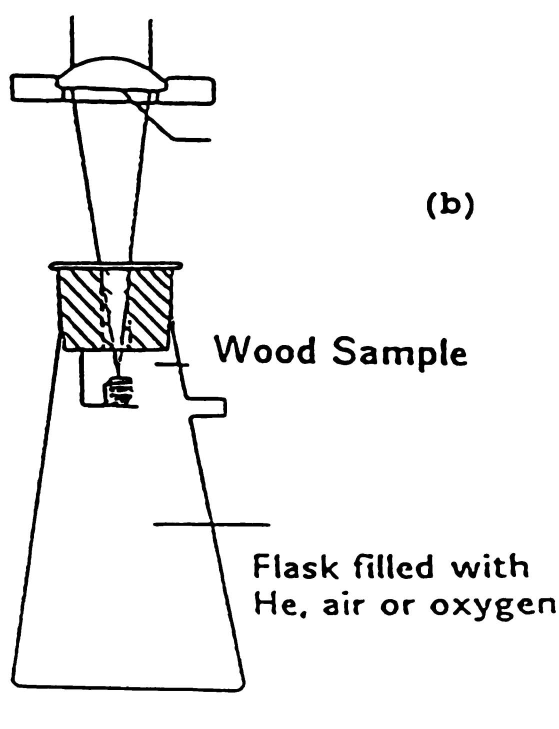


Figure 3.3 Smoke collection setup (a) during actual laser cutting and (b) under control conditions

actual laser cutting, the gases were collected in a reservoir which was initially evacuated. Figure 3.3 (b) shows the apparatus used to collect smoke under control condition. The smoke resulting from a three second pulse of 140 watt laser beam was collected in a flask filled with the cover gas used coaxially with the laser beam. Samples from the collected gases were taken and injected into the gas chromatograph by using hypodermic syringes.

The densities and volatile content of various types of hardwoods are given in table 3.1. Cuts were made in these woods under a wide range of operating conditions. Assessment of the quality of laser cuts was made by: (a) Visually examining the cut surface to determine the nature and amount of charring. (b) Measuring the width of cut at different locations of the cut region by using fine filler guages. (b) measuring the depth of cut by using triangular samples. Since the thickness of the sample increased gradually, the penetation depth is the maximum thickness at which the laser beam penetrated through the sample. Also, samples cut under the same conditions were examined to find the experimental error. The error was found not to exceed five percent. (c) Further surface analysis of the laser cut surface was done by electron microscopy. Samples observed under a scanning electron microscope were coated with gold to reduce the charging effect.

Table 3.1

Types of Hardwoods Used in the Study

Species	Density (g/cc)**	Volatile Content (%)*
Basswood	0.45	73.63
Soft Maple	0.54	-----
Black Cherry	0.56	66.15
Black Walnut	0.63	68.46
Hard Maple	0.70	74.15

* Temperature : 400 °c

  Test Time : 10 min

  Sample Weight : 1 - 0.2 g

** Moisture Content : 5-6%

CHAPTER 4

EXPERIMENTAL RESULTS

Since the Laser beam can be focused to a very small spot size, cuts with a narrow kerf can be obtained. Figure 4.1 shows cuts made by laser and by saw. It can be seen that the kerf width for cuts made by laser is about 0.043 cm which is about one eighth the kerf width of cuts made by conventional saw (0.37 cm). Further differences between laser cuts and saw cuts are manifested in the nature of the cut surface. Cuts made by laser are charred due to the nature of the laser wood interaction which is mainly a combustion process. Indeed scanning electron micrographs (figure 4.2) show that the laser cut surface is far smoother than the saw cut surface. Band and circular saws leave bundles of fibres protruding from the surface. However, on laser cut surfaces there is an insignificant amount of damage to wood structure, some carbon deposits are visible on cell walls and lumen cavities. Although, little melting occurs the cutting action is mainly a combustion process. The amount of melting depends on the different parameters involved in the process.

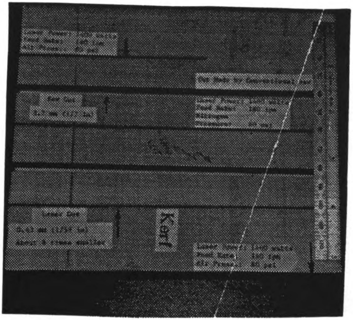
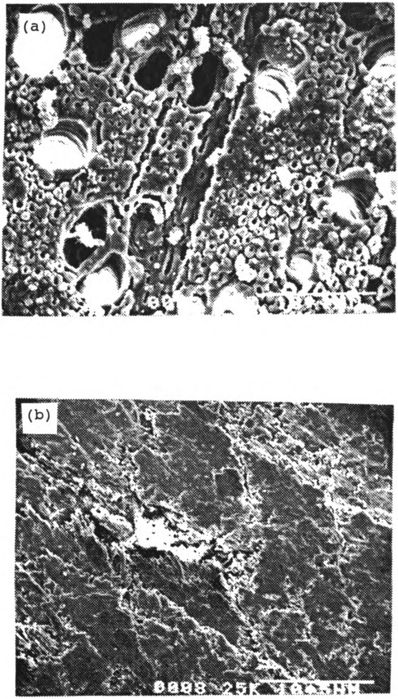


Figure 4.1 comparison of cuts made by laser and by saw @



*Fi*gure 4.2 SEM micrograph of (a) laser cut surface and (b) saw cut surface

4.1 EFFECT OF PROCESSING VARIABLES

4.1.1 EFFECT OF FOCAL POINT LOCATION

The location of the focal point with respect to the workpiece affects the cutting efficiency. Table 4.1 and figure 4.3 show that there is a critical distance inside the specimen where the focal point should be located in order to have maximum penetration and better energy distribution along the thickness of the specimen. This critical point is at or slightly above the half-thickness of the specimen. If the focal point is located above the workpiece, the energy density is diminished, the kerf width is increased, and the upper surface of the workpiece may be charred. If the focal point is located at the surface of the workpiece, maximum energy is obtained at the surface but diminishes as it penetrates into the workpiece. If instead the focal point is positioned at or slightly above the mid-depth of the workpiece, the average energy density is approximately uniform throughout the thickness. Thus, the kerf is smaller and more uniform, the cut surface has less char and is smoother, and deeper cuts are possible.

Table 4.1

Effect of the Location of the Focal Point on the Depth of Cut @

Laser Power:	1500 watt
Gas Pressure:	552 10^{-1} N/cm^2 (80 psi)
Cutting Speed:	10.16 cm/sec (240 ipm)
Lens Focal Length:	12.7 cm (5 inches)
Wood Thickness:	2.2 cm (7/8 inch).

Focal Point Location (inside the specimen, cm)	Depth of Cut (cm)
0.00	1.446
0.38	1.593
0.78	1.661
1.05	1.354
1.40	0.627

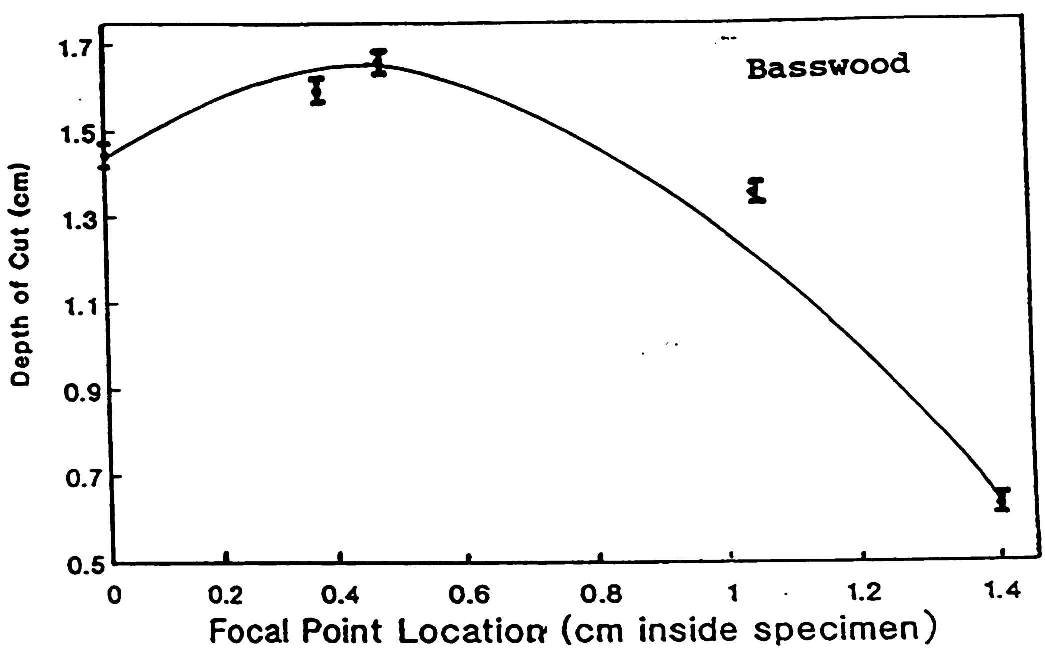


Figure 4.3 Effect of the focal point location on the depth of cut. Laser power: 1500 watt, Gas pressure: 552 x 10^{-1} N/cm^2 (80 psi), Feed rate: 10.16 cm/sec (240 ipm), Lens focal length: 12.7 cm (5 inches), and the Wood thickness: 2.2 cm (7/8 inch) @

4.1.2 EFFECT OF COVER GAS

As discussed earlier laser wood cutting is a gas assisted combustion process. The gas is needed to remove smoke and eject solid particles from the cut region, to regulate and control excessive burning, and to protect the focusing optics. The pressure and type of the gas used significantly affect the depth of penetration, the cutting speed, and the quality of the cut. Wood is usually cut using a jet of air coaxial with the laser beam. But when cutting particle and fiber boards or other wood composites containing adhesives, the selection of the gas and its pressure is very critical. Also as the gas flow rate increases, the cooling action of the gas jet increases. Thus at a significantly high rate of flow, power loss occurs and hence the cutting efficiency or the cutting speed is decreased for a given laser output power.

Figure 4.4 shows micrographs of laser cut surfaces at air pressures of 276×10^{-1} N/cm^2 (40 psi) and 552×10^{-1} N/cm^2 (80 psi). The laser cut surface at air pressure of 276×10^{-1} N/cm^2 (40 psi) shows excessive melting of the material, with carbon deposits present on the cell walls. However, at air pressure of 552×10^{-1} N/cm^2 (80 psi), the laser cut surface is very smooth with minimum melting. At

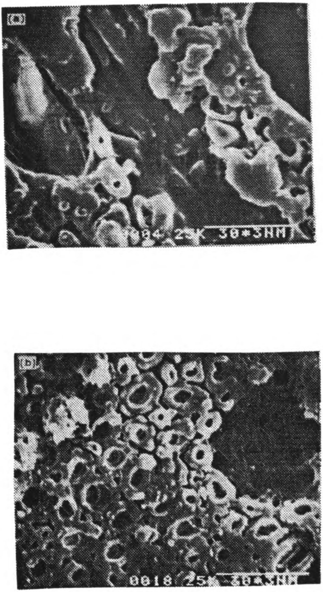


Figure 4.4 SEM micrograph of laser cut surface at (a) air pressure: 276×10^{-1} N/cm^2 and (b) air pressure: 552×10^{-1} N/cm^2, Laser power: 2500 watt, Feed rate: 10.16 cm/sec, Wood type: Basswood

low air pressure, excessive melting occurred because the air present was not enough to remove the heat caused by the laser energy and to cool the workpiece. Thus it is very important to have a cover gas at relatively high pressures. Higher air pressures not only reduce the melting of the material, but also reduce the amount of carbon monoxide produced. Figure 4.5 shows that carbon monoxide content decreases with increasing air pressure, this could be due to either the availability of oxygen, an important factor in the conversion of carbon monoxide to carbon dioxide or the dilution of combustion products at high air pressure. But one can not infinitely increase the air pressure to obtain better quality of cut because at significantly high cover gas pressures, power loss occurs and hence the cutting efficiency or the depth of cut is decreased for a given laser output power as shown in figure 4.6.

At a gas jet pressure of 414 10^{-1} N/cm^2 cuts were then made in basswood. Since, laser wood cutting is essentially a high temperature rapid combustion process, It was anticipated that selection of an oxygen rich cover gas such as air would augment the combustion process. Therefore, cuts were made in basswood at a fixed laser power and different feed rates by using two different cover gases, i.e. air and nitrogen. Experimental results are shown in table 4.2 which shows that cutting with air, as the assisting gas, gives

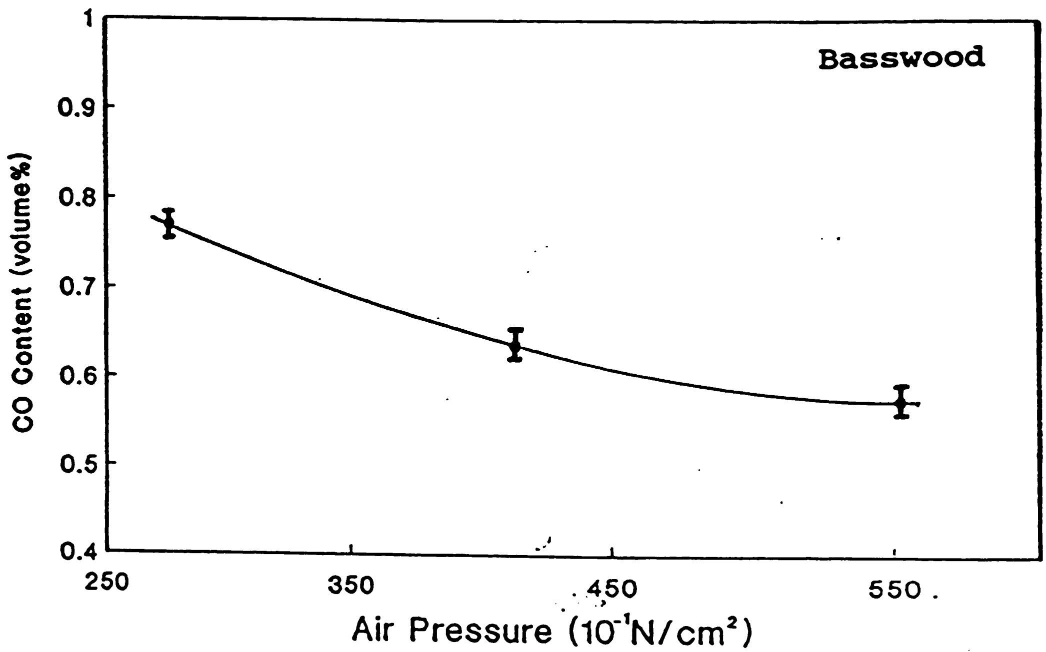


Figure 4.5 Effect of air pressure on CO content. Laser power: 800 watt, Feed rate: 6.35 cm/sec @

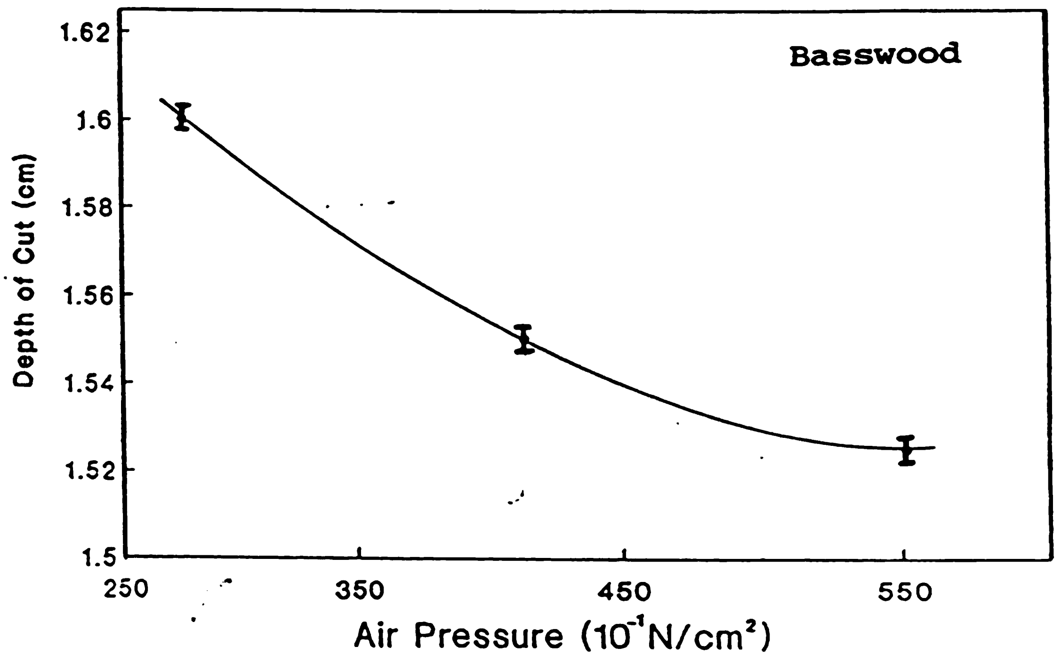


Figure 4.6 Effect of air pressure on the depth of cut. Laser power: 800 watt, Feed rate: 6.35 cm/sec @

Table 4.2

Effect of The Nature of The Coaxial Gas Jet.

Wood type: Basswood

Laser power: 1500 watt

Air/Nitrogen pressure: 552 x 10^{-1} N/cm^2 (80 psi) @

Feed Rate (cm/sec)	Depth of Cut (cm)	
	Air	Nitrogen
16.93	1.175	1.150
15.24	1.272	1.233
13.55	1.397	1.262
11.85	1.437	1.347
10.16	1.808	1.536
8.47	1.997	1.730
6.77	2.183	2.167

slightly better results than cutting with nitrogen. This is due to the fact that air contains oxygen which helps during the combustion process.

To verify this, experiments were performed under controlled conditions by using the setup shown in figure 3.3. Short laser pulses of 140 watt energy were used to ignite wood samples held in nitrogen and air respectively. Immediately after the experiments, samples were taken from the chamber and analyzed for permanent gases. Since the amount of carbon monoxide depends upon the extent of the combustion reaction, its volume percent in the smoke sample was used as an indicator to determine completion of the reaction. The results of the experiments are given in table 4.3. It can be seen that when using nitrogen as the cover gas, the combustion reaction was incomplete and a high volume percent of carbon monoxide was detected. However, in the case of air as the cover gas the combustion reaction was enhanced and relatively smaller carbon monoxide content was obtained.

Table 4.3

CO and CO_2 Volume Percent for Different Cover Gases Under Controlled Conditions.

Wood type: Basswood

Laser power: 140 watt

Pulse duration: 3 sec

ATMOSPHERE	CO VOLUME PERCENT	CO_2 VOLUME PERCENT
Nitrogen	18.9800	0.2130
Air	0.6050	7.3056
Oxygen	None	11.7093

4.1.3 EFFECT OF OXYGEN

to further investigate the role of oxygen in the combustion process pure oxygen at a low flow rate was introduced at the laser/wood interaction site through an auxiliary nozzle, held at an angle of forty five degrees with respect to the sample surface. The results show that the introduction of oxygen enhances the combustion process and improves the cutting performance (figure 4.7). Indeed deeper cuts with relatively cleaner surfaces and narrower kerfs were obtained. Besides an improvement in the cutting performance, the use of oxygen as cover gas led to a complete elimination of carbon monoxide from the laser burned smoke (table 4.3).

Because oxygen is rather an expensive and important to combustion, it is imperative to determine the optimum oxygen : nitrogen ratio in the cover gas that gives maximum cutting speed without affecting the nozzle or being hazardous to the operator. Experiments were also carried out with a mixture of air and oxygen as the cover gas. Initially oxygen was mixed with air at different pressures, and then cuts were made at constant feed rate and laser power. The smoke produced during this experiment was collected using the set up shown in figure 3.3. Gas chromatography results (figure 4.8) show that carbon monoxide content decreased with increase in oxygen pressure. This is because of the

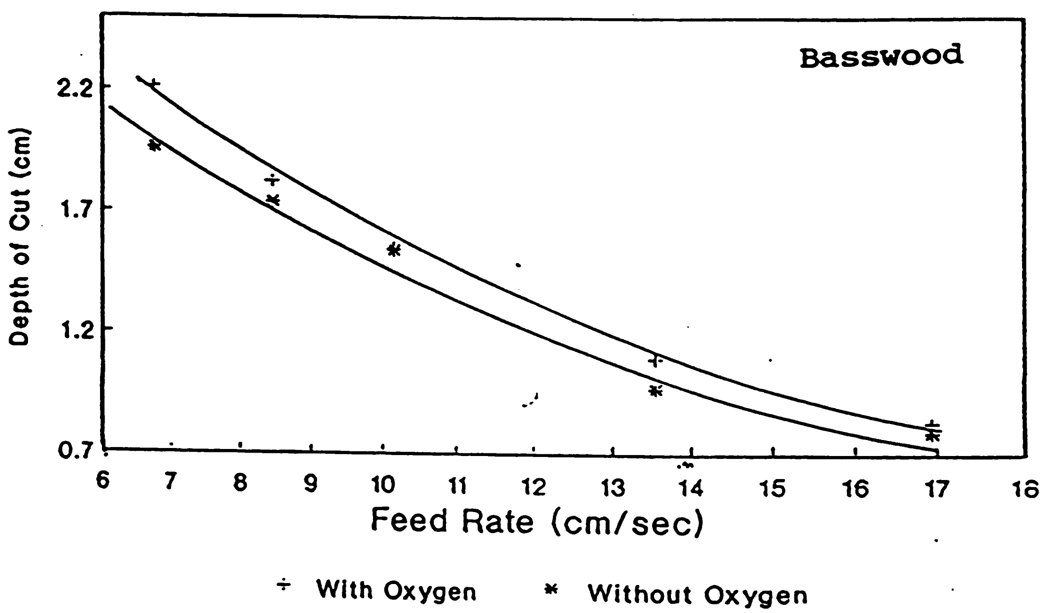


Figure 4.7 Effect of oxygen on the depth of cut. Laser power: 1550 watt, Air pressure: 276×10^{-1} N/cm^2 @

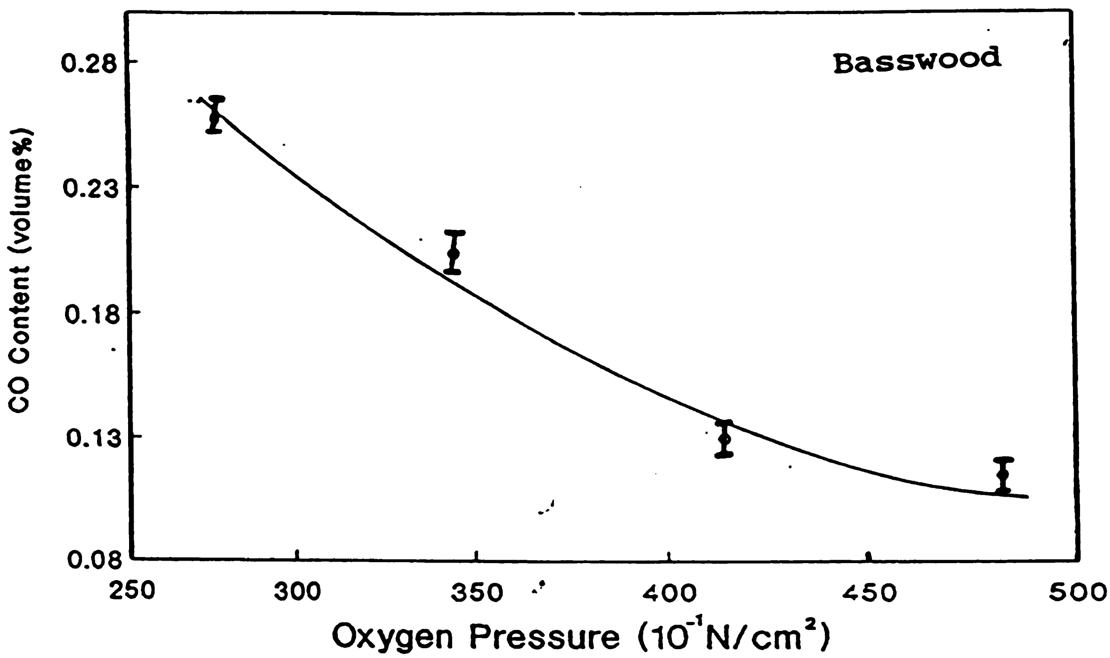


Figure 4.8 Effect of oxygen pressure on CO content. Laser power: 800 watt, Feed rate: 6.35 cm/sec, Air pressure: 276 x 10^{-1} N/cm2 @

positive role oxygen plays in the combustion reaction and in the conversion of carbon monoxide to carbon dioxide. This observation is in agreement with the data presented in table 4.3.

At high cover gas pressures an appreciable amount of the heat was lost by convection to the surroundings, less energy was therefore available at the incidence point. Hence, the depth of cut decreased with an increase in oxygen pressure (figure 4.9). In the next set of experiments, the oxygen pressure was kept constant and the oxygen flow rate was varied. Since oxygen is an important factor in any combustion reaction, the combustion reaction initiated by the laser was also enhanced with an increase in oxygen flow rate. A decrease in carbon monoxide content with an increase in oxygen flow rate can be seen in figure 4.10. It was also noted that the increase in oxygen flow not only reduces carbon monoxide content, which makes laser wood cutting more safe for the operator, but it also improves the cutting performance (figure 4.11). An increase in the depth of cut can be seen with an increase in oxygen flow rate. Electron microscopy of the wood surfaces cut at different oxygen flow rates also show (figure 4.12) that the melting is minimum at high oxygen flow rates. It can therefore be concluded that a high oxygen flow rate is very beneficial to the cutting process.

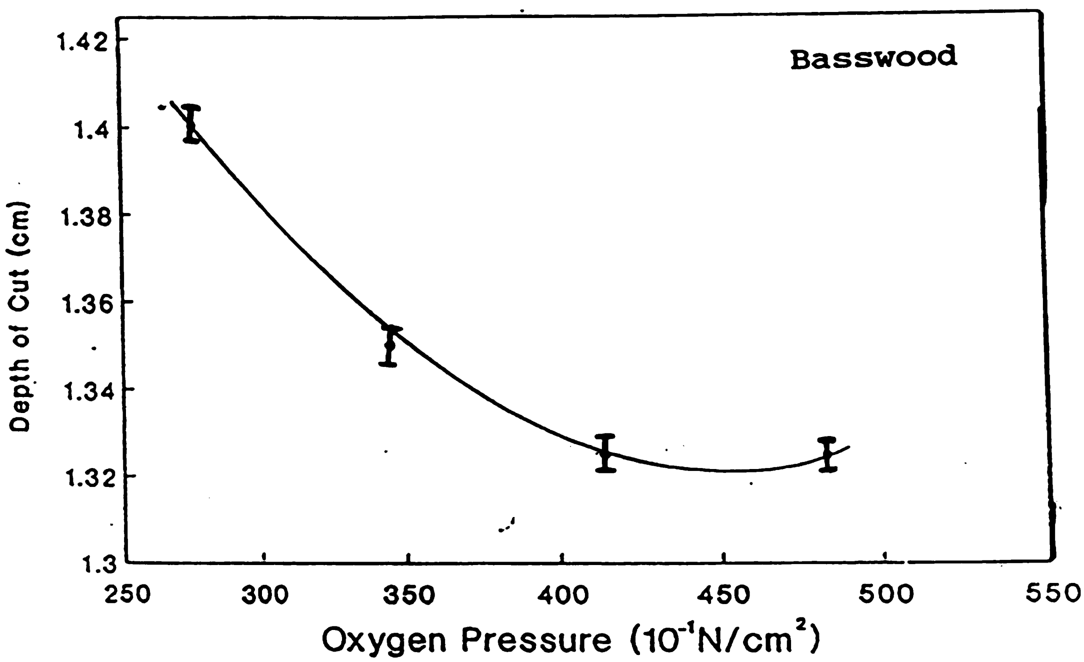


Figure 4.9 Effect of oxygen pressure on the depth of cut.
Laser power: 800 watt, Feed rate: 6.35 cm/sec,
Air pressure: 276 X 10^{-1} N/cm^2 @

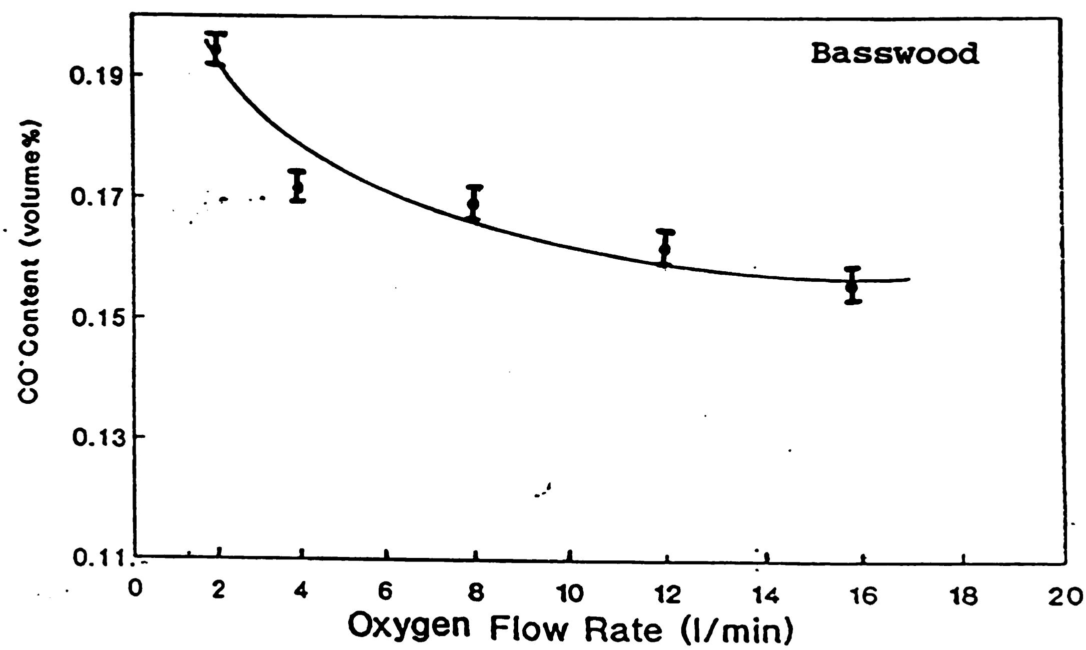


Figure 4.10 Effect of oxygen flow rate on CO content.
Laser power: 800 watt, Feed rate: 6.35 cm/sec,
Air pressure: 276×10^{-1} N/cm^2 @

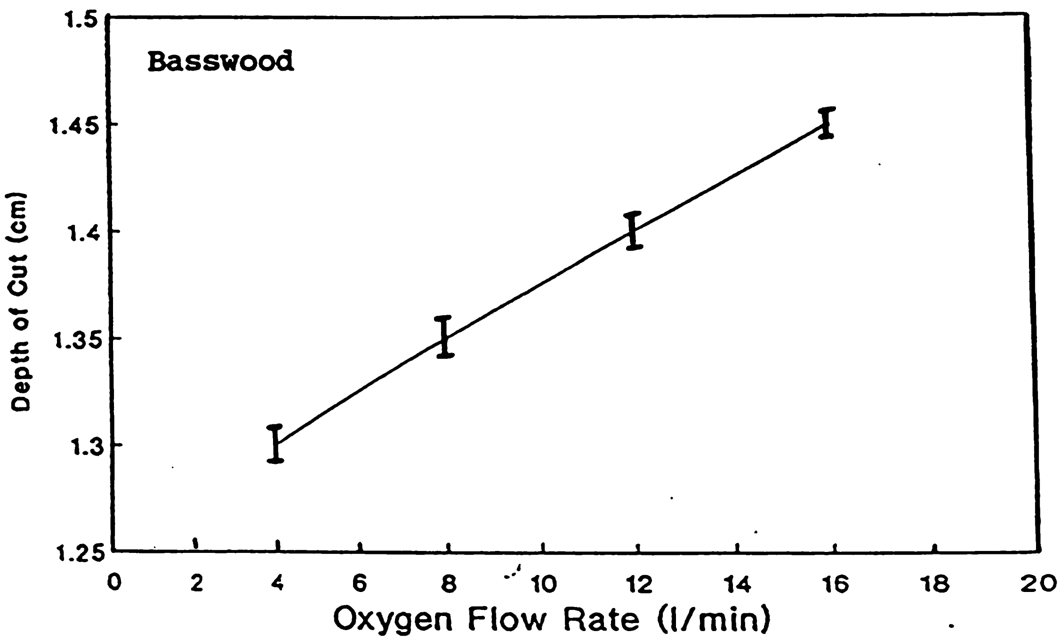


Figure 4.11 Effect of oxygen flow rate on the depth of cut
Laser power: 800 watt, Feed rate: 6.35 cm/sec @
Air pressure: 276 x 10^{-1} N/cm^2

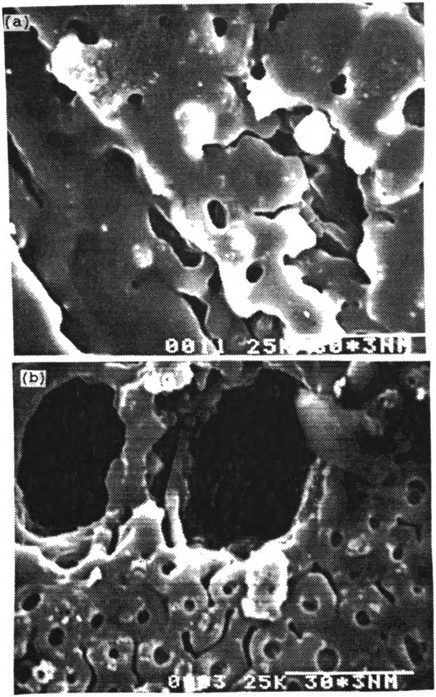


Figure 4.12 SEM micrograph of laser cut surface at
(a) oxygen flow rate: 4 l/min and
(b) oxygen flow rate: 16 l/min
Laser power: 1500 watt, Feed rate: 10.16 cm/sec, Wood type: Basswood

4.1.4 EFFECT OF LASER POWER

Cuts were made in all five types of hardwood at different power levels and keeping the pressure of the cover gas (Air) and the feed rate constant at 552×10^{-1} N/cm^2 (80 psi) and 16.93 cm/sec (400 ipm) respectively. The data show (figure 4.13) that the depth of cut increased with the laser power for all types of hardwoods used in the experiment. This is due to the fact that more energy is available at higher powers, thus more wood/mass can be removed. The depth of cut was linearly dependent on the laser power.

The quality of cut at different power levels was further investigated by studying the laser cut surfaces, coated with gold, by electron microscopy. Using low power laser beam lead to high carbon deposition on the cut surface (figure 4.14). Since the penetration depth was shallow the laser energy was confined to a very small region resulting in excessive melting of the material present in the laser beam/wood interaction zone. Inspite of using high pressure cover gas, some of the molten material was left behind leading to deposition of carbon compounds on the cut surface. At higher powers, the combustion reaction was enhanced and the material was evaporated and removed more efficiently. Thus, the cell walls appear clearly in the micrographs.

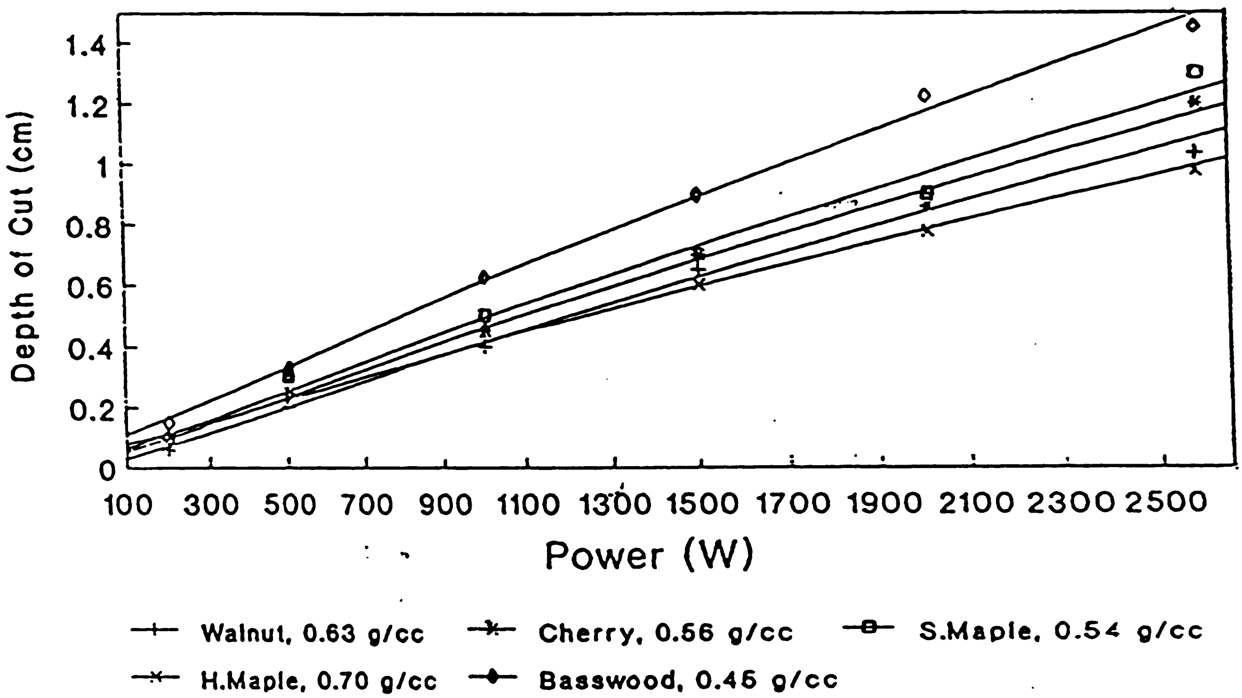


Figure 4.13 Effect of laser power on the depth of cut. Feed rate: 16.9 cm/sec (400 ipm) and Air pressure: 552×10^{-1} N/cm^2.

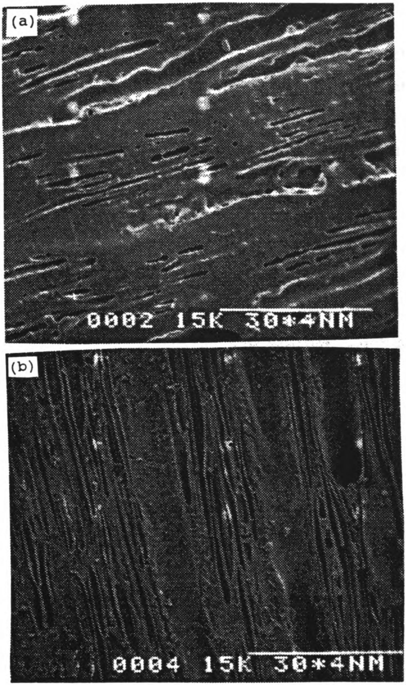


Figure 4.14 SEM micrograph of laser cut surface at (a) laser power: 500 watt and (b) laser power: 2400 watt, Feed rate: 16.93 cm/sec, Air pressure: 552×10^{-1} N/cm^2, Wood type: Basswood

4.1.5 EFFECT OF FEED RATE

The feed rate determines the amount of time the workpiece is exposed to the laser beam and hence the amount of energy that can be absorbed. Thus, with other laser cutting factors such as laser power, focusing conditions, and cover gas type and pressure held constant, an increase in the feed rate resulted in a decrease of the depth of cut for all types of wood used in this work (figure 4.15). At higher feed rates partial cuts were made. This could be due to either the loss of impinging laser energy by the combustion gases present inside the rapidly moving reaction front or to the lack of oxygen necessary to sustain the combustion process in the deeper region of the kerf.

Laser cut surfaces, made at different feed rates and keeping all other parameters constant, were further investigated by electron microscopy. Figure 4.16 shows that at lower feed rates, because the surface was exposed to the laser for a relatively long time the material contained in the kerf was completely evaporated and the cell walls were clearly seen in the micrograph. But at relatively higher feed rates the cut surface was exposed to the laser energy for a very short time, thus only partial evaporation occurred resulting in the melting and deposition of carbon compounds on the cell walls which appear totally covered by the resolidified matter.

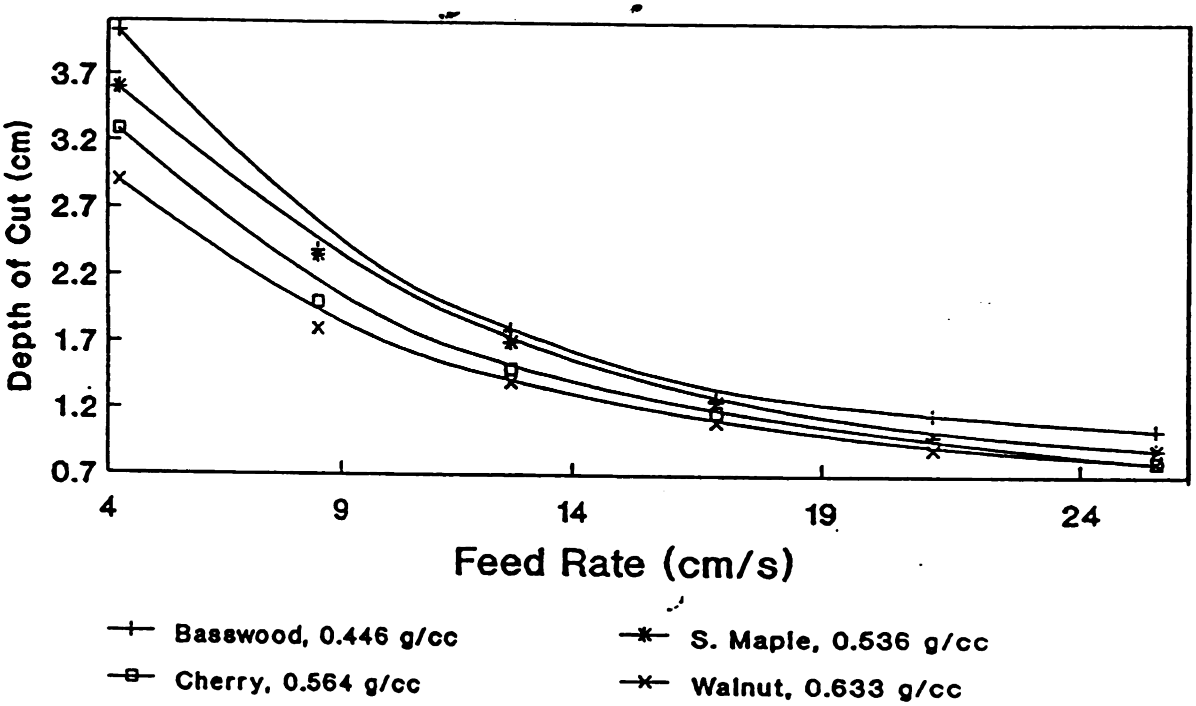


Figure 4.15 Effect of the feed rate on the depth of cut. Laser power: 2580 watt, Air pressure: 552 x 10^{-1} N/cm^2

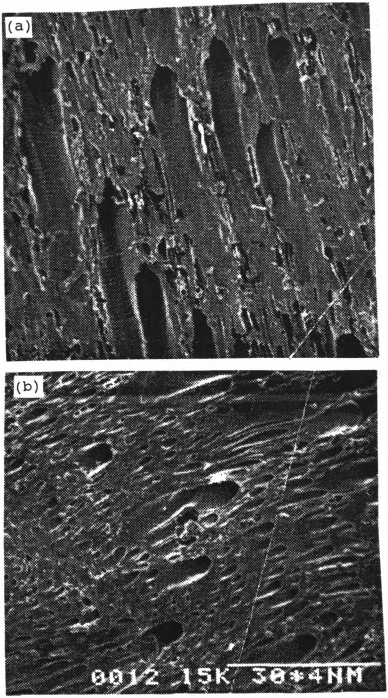


Figure 4.16 SEM micrograph of laser cut surface at (a) feed rate: 4.23 cm/sec and (b) feed rate: 25.4 cm/sec, Laser power: 1500 watt, Air pressure: 552 x 10^{-1} N/cm^2, Wood type: Basswood

The data presented in figure 4.15 only shows an experimental trend between the depth of cut and feed rate. It can be seen that the depth of cut is not a linear function of feed rate. However, equation 2.1 presented earlier predicts a linear relationship between depth of cut and inverse feed rate for a fixed laser power and constant evaporization energy and kerf width. Therefore, the data presented in figure 4.15 are replotted by taking the inverse of the feed rate (figure 4.17). It can be seen, as predicted from equation 2.1, that the experimental data also show a linear trend.

The threshold values for cutting 2.2 cm (7/8 inch) thick hardwoods at a laser power of 2550 watts and a cover gas pressure of 552 x 10^{-1} N/cm^2 (80 psi) are given in table 4.4. These threshold values can be improved by optimizing other processing parameters such as the focusing conditions and the gas type and flow.

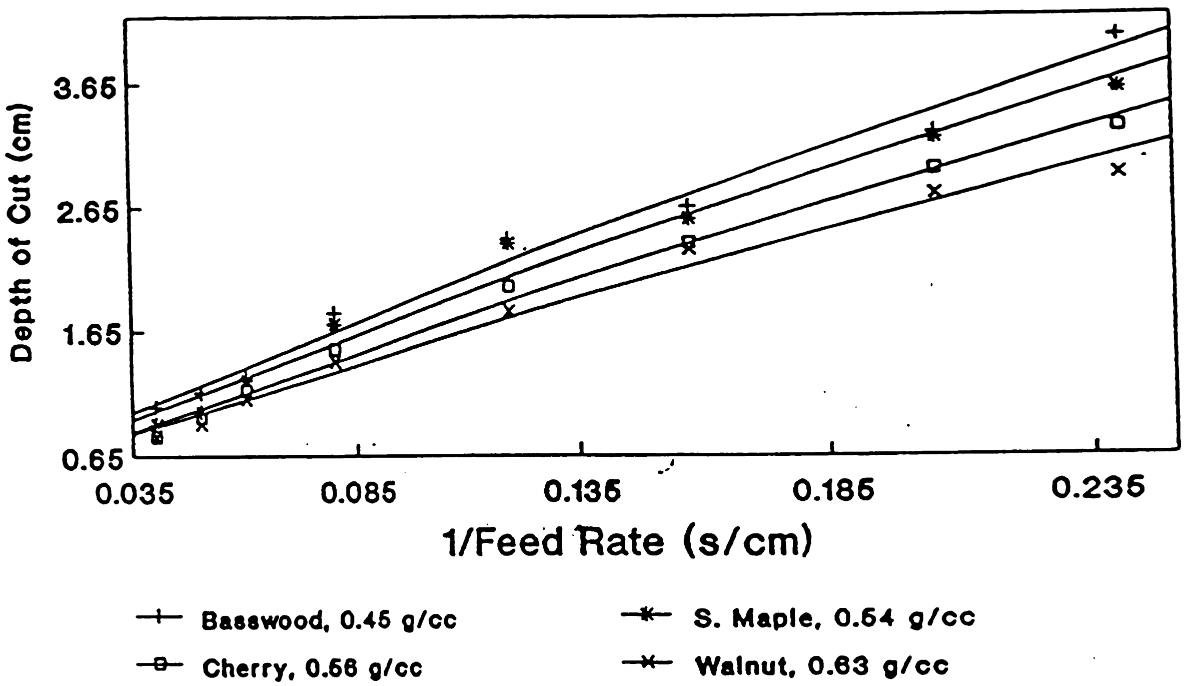


Figure 4.17 Depth of cut versus inverse feed rate. Laser power: 2580 watt, Air pressure: 552 x 10^{-1} N/cm^2

Table 4.4

Threshold Values for Cutting Different Types of Wood

Laser power: 2550 watt

Air pressure: 552×10^{-1} N/cm^2 (80 psi)

Species	Cutting Speed
Basswood	12.70 cm/sec (300 ipm)
Black Cherry	0.93 cm/sec (220 ipm)
Black Walnut	0.85 cm/sec (200 ipm)

4.2 EFFECT OF MATERIAL PROPERTIES

The phenomenon of material (wood)/laser light interaction is rather complex. In general, laser light wood interaction consists of the absorption of laser light by the wood, the absorbed light energy transforms into heat which is transmitted into the workpiece. The distribution and rate of heat transfer within the workpiece, and the rate of combustion and vaporization in the zone of radiation are related to two optical properties of wood: absorptivity and transmissivity. These two properties in turn depend on the moisture content, chemical composition, and density of wood.

4.2.1 EFFECT OF MATERIAL DENSITY

The depth of cut decreased as the density of the material increased (figure 4.18). This can be explained as due to the fact that denser the material the larger the amount of matter that occupies the same volume. Hence, more energy is needed to remove this larger amount of matter. Furthermore, the thermal conductivity of wood, though very small as compared to metals, increases with density (17), and as thermal conductivity of wood increases, the absorbed laser energy spreads into a relatively larger volume of matter resulting in reduction of the energy concentrated at the point of incidence. Thus, holding the material and

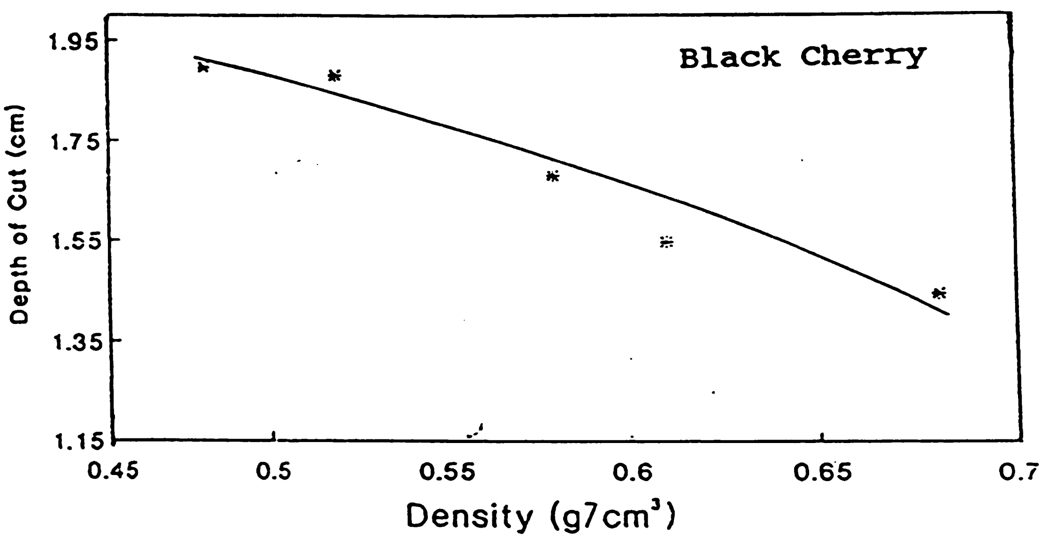


Figure 4.18 Effect of density on the depth of cut. Laser power: 2500 watt, Air Pressure: 552 x 10^{-1} N/cm^2

and the processing variables constant, an increase in the material density will result in a decrease in the depth of cut. Also, an increase in the kerf width was observed at high wood densities.

4.2.2 EFFECT OF MOISTURE CONTENT

The moisture content has negative effect on the depth of cut as shown in table 4.5. This can be explained by the difference between the absorption coefficients of water and wood for the laser light. For light of 10.6 micron wave length, the absorption coefficient of water is less than that of wood. Thus, the overall absorption coefficient for the wet wood sample is less than that of the dry wood sample. Also, a portion of the laser energy is used up in the form of enthalpy of vaporization of water and in the subsequent super heating of steam. Furthermore, the thermal conductivity of wood increases with increase in moisture content resulting in less energy concentration at the point of incidence. Therefore, more power is required to cut wet wood than is required to cut dry wood.

In figure 4.19, it can be interpreted that at lower cutting speed, higher moisture content seems to be beneficial to the cutting process. This could be due to the

Table 4.5

Effect of the Moisture Content on the Depth of Cut. @

Laser power: 1550 watt

Air pressure: 552 x 10^{-1} N/cm^2 (80 psi).

Wood type: Basswood

Feed rate (cm/sec)	Depth of Cut (cm)	
	dry wood*	wet wood
16.93	1.080	0.955
15.24	1.305	1.173
13.55	1.457	1.234
11.85	1.517	1.675
10.16	1.675	1.826
8.47	1.733	1.845
6.77	2.193	2.033

* wood was left in water for 24 hours then dried for 24 hours

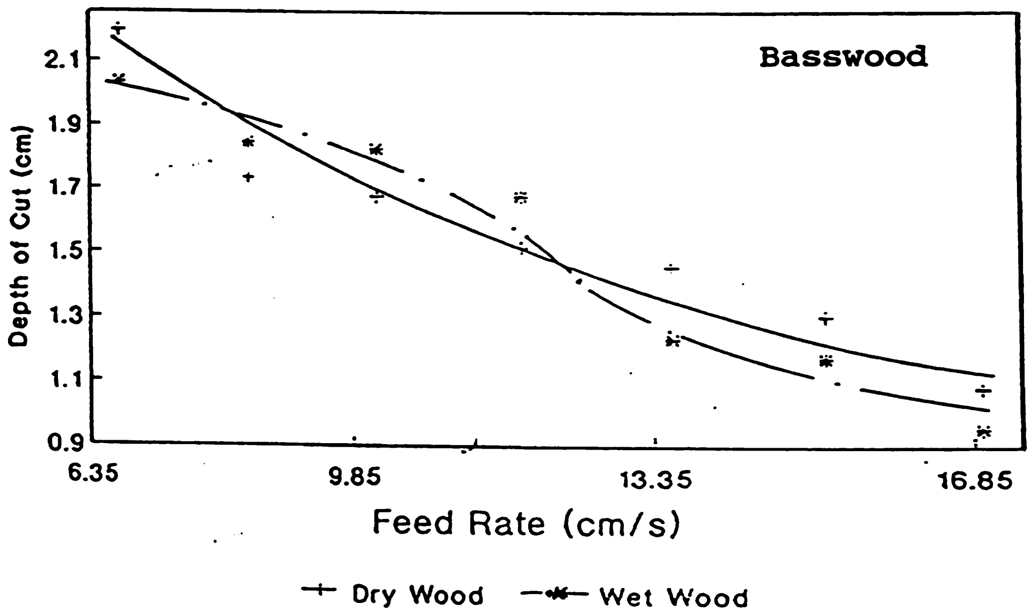


Figure 4.19 Effect of the moisture content on the depth of cut. Laser power: 1550 watt, Air pressure: 552 x 10^{-1} N/cm^2 @

release of evaporated water. At slow cutting speeds the workpiece is exposed to the laser beam for a longer time and hence the energy absorbed is large. Some of this energy is used to evaporate the moisture content present in the wood. Evaporated moisture exerts great internal pressure upon the material, producing microfracture and ejecting out particles of matter. Also, it is possible that at low feed rates the evaporating moisture helps in the cutting performance by forming an optically converging lens which results in a better and sharper focused beam inside the kerf. Further study is needed to prove either hypothesis.

4.2.3 EFFECT OF CUTTING DIRECTION

Part of the laser beam energy absorbed by the wood is lost by conduction of heat to the bulk material. Since the thermal conductivity of wood along the grain is significantly greater than that across the grain (17), less conduction losses result from a heat source moving in the direction of the grain than from a heat source moving across the grain. Furthermore, local density along the grain is smaller than that across the grain. Hence, deeper cuts were obtained when cutting along the grain (figure 4.20)

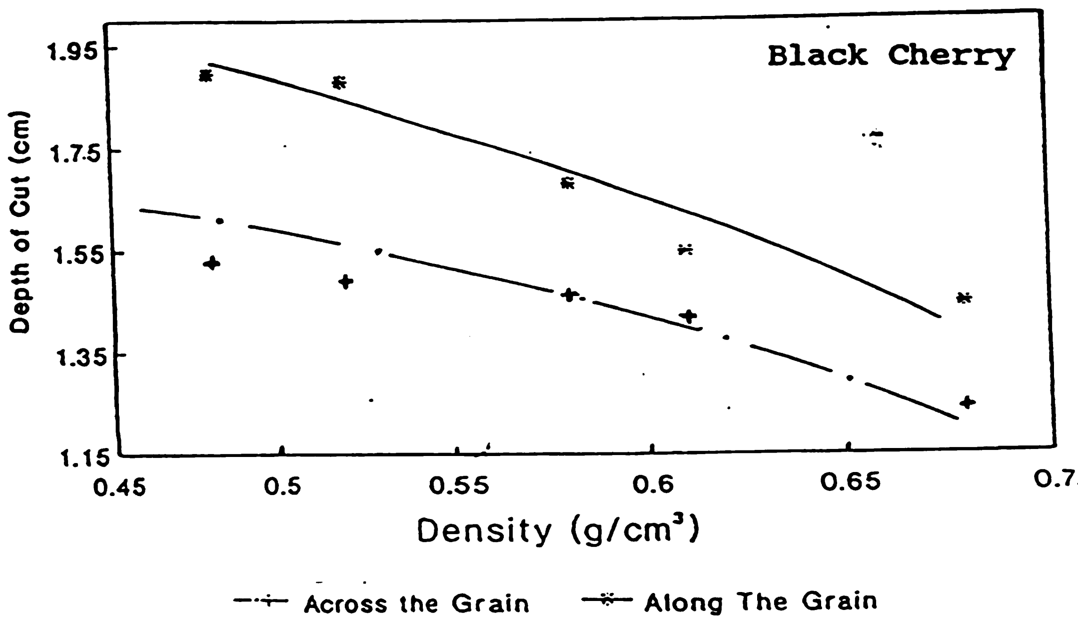


Figure 4.20 Effect of the grain orientation on the depth of cut. Laser power: 2500 watt, Air Pressure: 552 x 10^{-1} N/cm^2

4.3 ANALYSIS OF HYDROCARBONS

Limited experiments were performed under controlled conditions to determine the presence of various hydrocarbons produced during laser cutting of hardwoods. Several cover gases were used to fill a flask containing small samples of hardwoods. A 140 watt, three second pulse was triggered to ignite the wood samples. At present only benzene and toluene peaks were identified, benzene and toluene were present in small amounts (figure 4.21). Furthermore, it is expected that the use of a more reactive gas such as oxygen will reduce the amount of benzene and toluene formed during the cutting process. Indeed K. Mukherjee et. al (18) found that when a more reactive gas such as oxygen is used for laser machining of epoxy based composites, the benzene and toluene level dropped below OSHA limit, i.e. 0.01 volume % and 0.2 volume % respectively. It is also, important to mention that all these experiments were conducted under controlled conditions. In actual laser cutting conditions, due to a constant supply of cover gas, the combustion products will be more diluted.

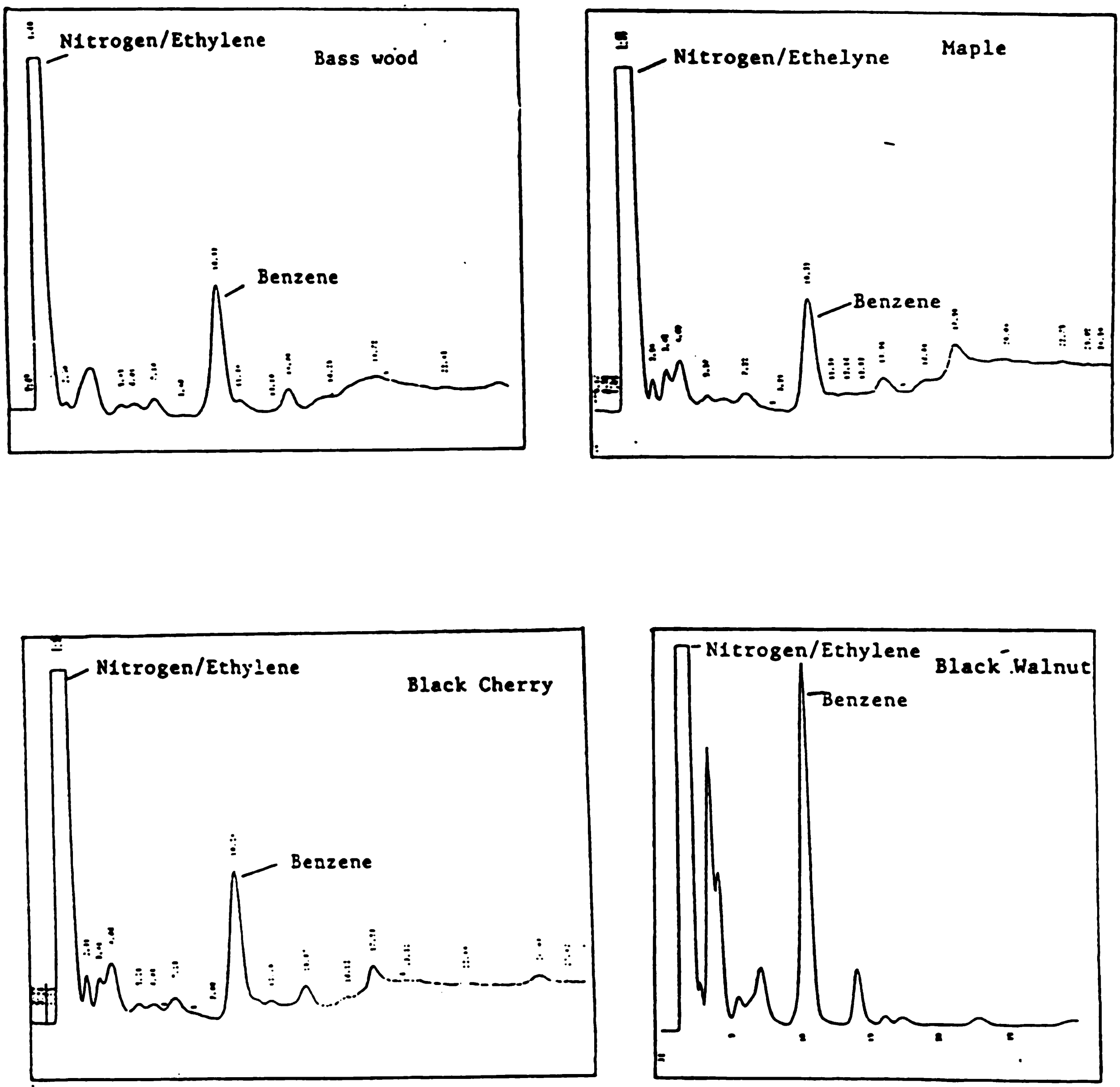


Figure 4.21 The gas chromatogram for hydrocarbons produced during laser cutting of hardwoods

CHAPTER 5

CONCLUSIONS

In this research, the feasibility of using the laser as a tool to cut hardwoods was investigated. A 3000 watt carbon dioxide laser was used to make high speed cuts in different species of one inch thick hardwoods under a wide range of process and materials parameters. The relationship between various laser processing parameters, wood properties, and the quality of cut was established. Furthermore, to determine the environmental and operator safety of laser wood cutting, analysis of the smoke produced during cutting was also investigated. Following are the major conclusions of this research:

1. Clean cuts with narrow kerf can be made at high speeds in different types of hardwoods by using a high power carbon dioxide laser.

2. The laser cut surface seems to be different from the saw cut surface and its nature changes with the pressure and flow rate of the coaxial and auxiliary cover gas.

3. The depth of cut is directly proportional to the laser power and inversely proportional to the feed rate, spot size, and wood density.

4. The use of a reactive gas such as oxygen improves the cutting performance.

5. A small amount of carbon monoxide was produced during laser cutting of hardwoods, the CO content decreased with increase in cover gas pressure and flow rate.

RECOMMENDATIONS

In the future, the analysis of hydrocarbons will be completed. Also, since some of the combustion products might have small lifetime, an on line analysis of the plasma and smoke formed during the cutting process by using a multichannel optical analyzer will be performed. Data collected will be used toward the development of a theoretical model.

APPENDICES

APPENDIX A

AN OVERVIEW OF THE CO_2 LASER

The CO_2 laser is the most widely used gas laser, The conventional CW CO_2 laser is nothing more than a water cooled tube with mirrors in both ends through which the laser gas mixture is circulated and electrically excited (figure A.1). There are two methods for exciting a CO_2 laser. The first method applies the discharge energy directly to the continuously flowing CO_2:N_2:He mixture. In order to achieve the highest output power from this method, a ratio 0.8:1:7 of the gases must be used. The output power increases steadily with the flow rate of the gas. This is due to the enhanced removal rate of the dissociation products such as CO and O_2, and the direct cooling of the discharge. The second method consists of separate inlets for the N_2 and CO_2 gases. In this situation, only the N_2 is excited by the discharge. The N_2 molecules will later transfer the energy to the CO_2 molecules as they collide with them downstream. In either case, the discharge current will determine the rate at which the CO_2 molecules in the laser tube are pumped to a higher energy level by direct electron excitation or by collision with the excited N_2 molecules.

The basic CO_2 laser process involves exciting of the lasing medium to a higher energy or vibrational level to cause a population inversion. The electrical discharge

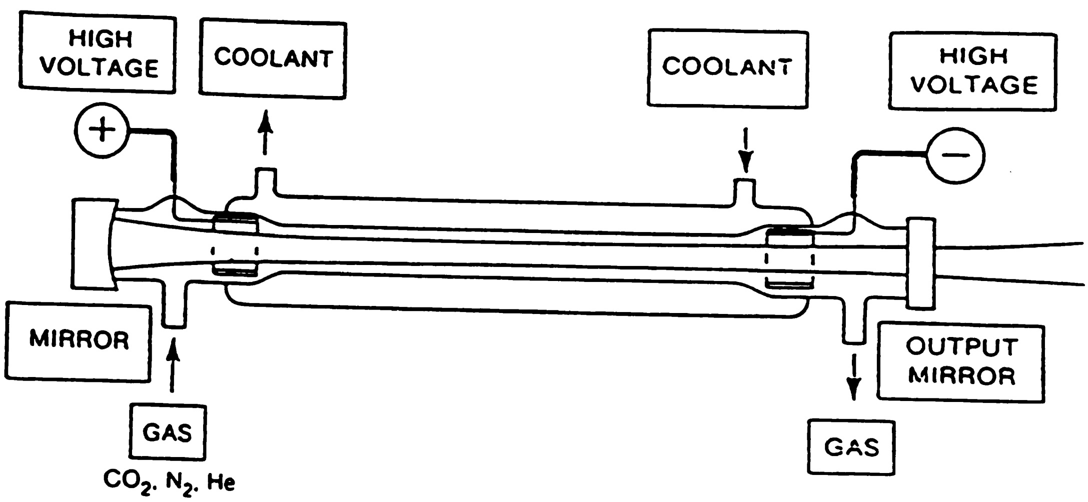


Figure A.1 Schematic diagram of conventional CO_2 laser [15] excites the N_2 molecules in order to establish a population in energy level 1, (or vibrational level v = 1). This energy is dissipated by means of a resonant energy transfer to a second level 2, (vibrational 00^01), which is the upper laser level of CO_2. This is accomplished through super elastic collisions with ground state CO_2 molecules, causing them to be excited into the higher level. Soon this level will have an excess of CO_2 molecules compared to the lower energy levels. This is the required population inversion. The decay from level 2 to a lower energy state 3 (vibrational 10^00), results in lasing at 10.6 um. If the CO_2 molecules fall instead to an even lower energy level 3', (vibrational 02^00), a 9.6 um laser energy is produced. After lasing the CO_2 molecules must be allowed to return to their ground state. If this is not accomplished, a built up at level 3 or 3' will eliminate the possibility of the population inversi-on. The helium in the discharge helps to quiet the excitat-ion of the CO_2 molecules through collisions, allowing them to return to their ground state (figure A.2). The excitation and de-excitation rates are controlled by radiative or non radiative decay rates, which are intrinsic properties of the laser ion and the hot material.

The resulting laser radiation, which can be continuou-sly produced, is highly monochromatic and exhibits high spatial coherence and high temporal coherence correlation. The spatial coherence results in high radiance from the

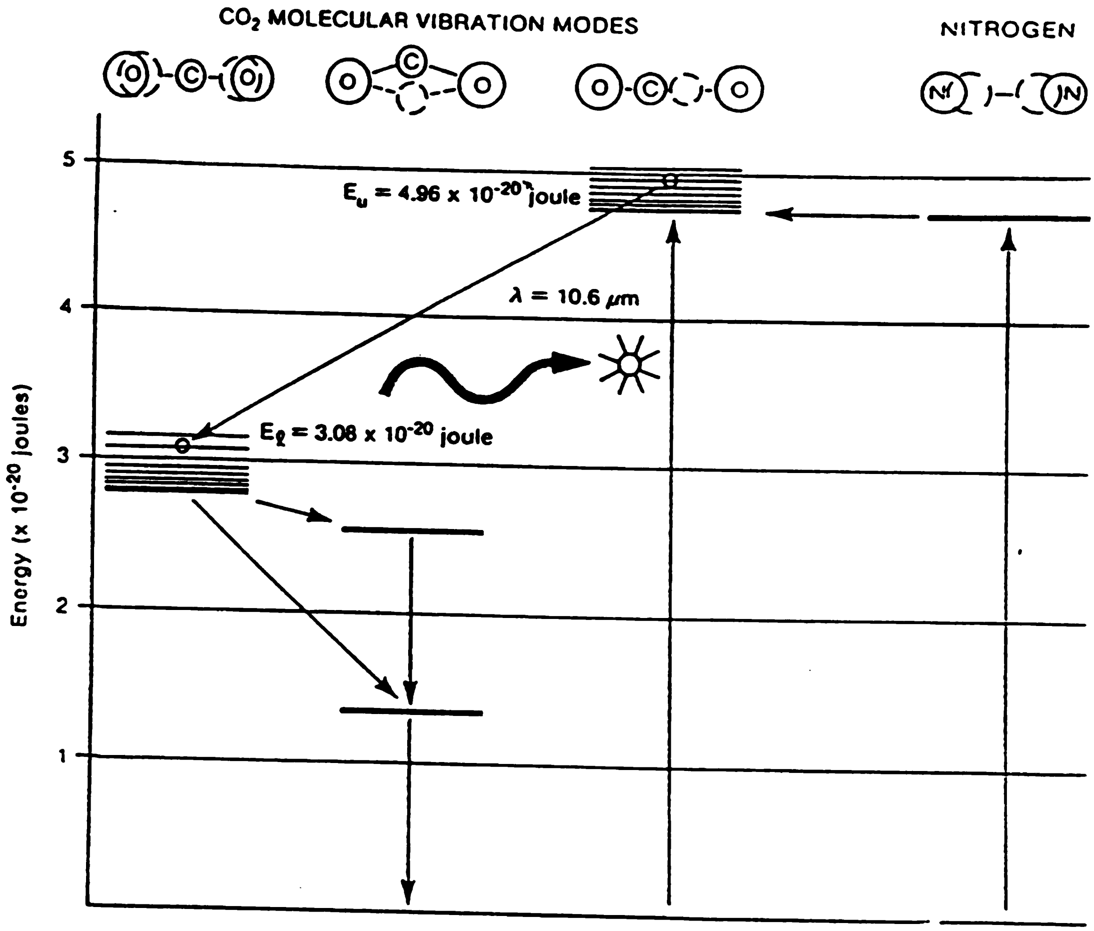


Figure A.2 Energy level diagram for the CO_2 and N_2 molecules [15] laser sources. Once produced, the laser energy is allowed to leave the discharge section of the tube through the partia-lly transmitting mirror as a coherent beam. The other end of the tube is covered by a totally reflecting mirror which helps directing the laser energy to the opposite end of the tube.

APPENDIX B

SPATIAL PROFILE OF A LASER BEAM

The spatial profile of a laser beam is determined by the geometry of the laser cavity. The shape of the laser cavity in a direction transverse to the optical axis defines the boundary conditions for the wave equation which determines the configurations of the electromagnetic field that will be allowed in the cavity. When this cross section is symmetrical, as in cylindrically or rectangularly shaped resonator, the spatial profile of the permitted transverse electromagnetic modes is dictated from the theory of the wave guides.

Particular modes are labeled TEM_{mn} where m and n are the number of nodes in two orthogonal directions. Both cylindrical and rectangular geometries have the TEM_{00} (Gaussian) mode as the transverse mode of highest symmetry. Other higher modes are labeled TEM_{01}, TEM_{11}, TEM_{12} and so on (figure B.1). In order to inhibit operations on high order modes the diameter of the laser cavity is reduced until operation on TEM_{00} or the fundamental mode is produced. The critical diameter of the resonant laser cavity for initiation of the TEM_{00} mode is a function of the cavity length.

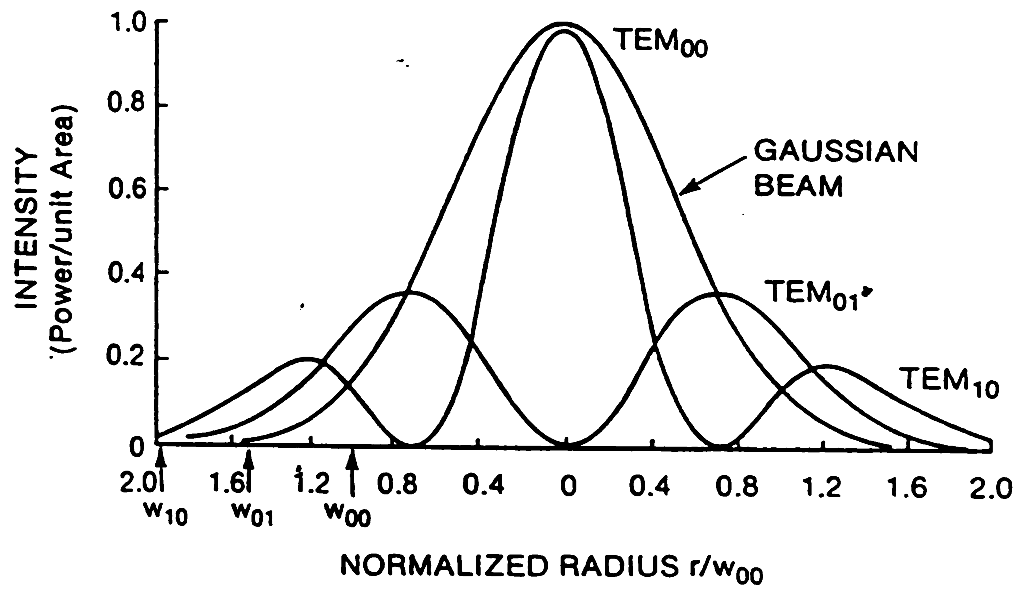


Figure B.1 Spatial distribution of the laser energy for different modes [15]

Operation on the fundamental mode provides true diffraction and limited beam divergence. Operation on high order modes are accompanied by instabilities in laser output as oscillation shifts from one transverse mode to another with similar gain.

APPENDIX C

PHYSICAL PROPERTIES OF WOOD

Physical properties of wood play an important role in determining the quality of the cut. Properties of most interest are moisture content, density, thermal conductivity, and specific heat.

Moisture Content

Moisture content of wood is defined as the weight of water in wood expressed as a fraction, usually as a percentage, of the oven dried wood. Weight, shrinkage, strength, and other properties depend on the moisture content of wood.
Many methods are used to calculate the moisture content of wood. The most widely used method is the direct measurement method, in which the weight of the sample is measured, then the sample is dried in an oven and reweighed. The percent moisture content is the difference in weight divided by the original weight multiplied by one hundred.

Density

The total density of wood depends on the density of the basic wood structure, the moisture content, and the minerals and extractable substances such as tar and other organic compounds. Since the moisture content makes up part of the weight of woods, the density must reflect this fact, hence the density is usually given on a moisture content condition.

Specific Heat

The specific heat of wood depends on the temperature and the moisture content of the wood. The specific heat of dry wood is relatively insensitive to the species of wood and is approximately related to temperature T, in ^{o}F by:

$$\text{Specific heat} = 0.25 + 0.0006\ T$$

When wood contains water the specific heat increases because the specific heat of water is larger than that of dry wood. The apparent specific heat of moist wood is larger than That would be expected from a simple sum of the separates effects of wood and water. This increase is due to thermal energy absorbed by the wood/water bonds.

$$\text{Specific heat} = (M+c_0)/(1+M) + A$$

where 'M' is the fractional moisture content of the wood, 'c_0' the specific heat of dry wood, and 'A' is the additional specific heat due to the wood/water bound energy. 'A' increases with increasing temperature.

Thermal Conductivity

The thermal conductivity of woods is a small fraction of that of metals and it is several times larger than that of insulating materials. The thermal conductivity of wood is affected by density, moisture content, grain direction and structural irregularities. It is nearly the same in the radial and tangential direction with respect to the growth rings but is 2.0 to 2.8 times greater parallel to the grains than in either radial or tangential directions. It is related to wood density and moisture content by:

$$k = S\ (1.39 + 0.028\ M) + 0.165 \qquad \text{for } M<40\%$$

$$k = S\ (1.39 + 0.038\ M) + 0.165 \qquad \text{for } M>40\%$$

where k is the thermal conductivity in British thermal unit per inch per hour per square foot per degree Fahrenheit, 'S' is specific gravity, and M is the moisture content.

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