OPTIMIZATION OF PROCESS PARAMETERS ON FIBER LASER CUTTING OF CERAMICS

A thesis submitted towards partial fulfillment of the requirements for the degree of

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In
Laser Technology
By

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Examination Roll No. : M4LST22014 University Registration No. : 154569 of 2020-2021

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Chapter - 1

Introduction

1) INTRODUCTION

1.1) Introduction to laser cutting

Lasers are most widely used devices used in science and technology with applications ranging from laboratories and research and development projects to manufacturing and industrial consumer products. All of these use the unique properties and characteristics of laser.

In laser cutting, we use different parameters such as laser power, gas pressure, scanning speed and frequency of laser. Laser power is taken into consideration to understand the behavior of cutting at different powers. The gas pressure is observed to know the impact on the cutting quality at certain pressure range. The scanning speed is the speed at which the laser cutting machine operates over the work piece. And frequency is the no.of pulses incident over the work piece per second.

In this process of laser cutting the material is ablated using thermal energy. This process is much efficient in machining of complex and intrinsic part of the work pieces. Lasers are super useful for makers when it comes to cutting and etching of materials.

Laser cutter is a type of CNC machining, CNC stands for computer numeric control . To simply say, a laser cutter is a prototyping and manufacturing tool that uses a laser beam to cut their materials to create patterns and design with a laser. With a laser cutter we can fabricate parts and engrave designs on a variety of materials like metals, glass and even some plastics.

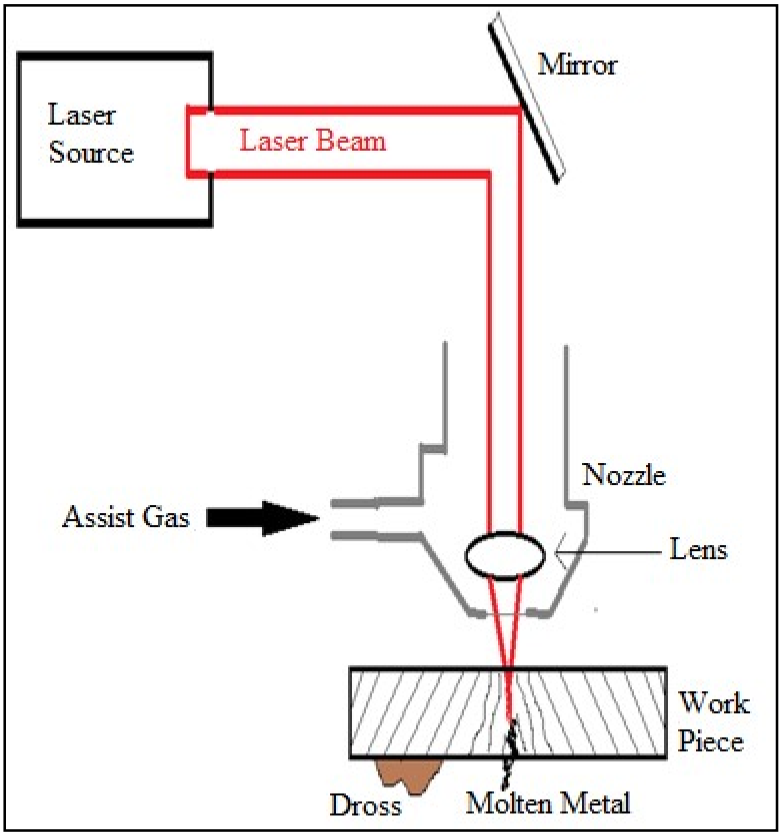

Fig 1) Schematic of Laser Cutting process

There are three types of laser cutter available in the current market and they are CO_2 laser, fiber laser, and Van-date laser. The differences between them are as under:

CO_2 laser utilizes carbon dioxide mixtures which are stimulated by electricity, they are known for their high efficiency and beam quality. This is why they are the most widely used laser. These lasers are best used for machining of plastics, and non-metallic materials wood, acrylic, glass and even leather.

Fiber lasers belong to the solid state laser group i.e. the laser beam is generated by a process involving specially designed glass fiber. They have 100 times higher intensity than CO_2 lasers, yet they emit same average power. They can engrave on materials such as metals, coated metals and plastics.

Finally we have, Van-date lasers, which uses crystals to generate the beam, since they have same wavelength as fiber, Van-date lasers are suited for metals and plastics. However, unlike fiber lasers, the Van-date lasers offer shorter life and are highly expensive.

Among these CO_2 Laser cutting is the most powerful cutting and it is widely used in industrial domain. Over the years the laser cutting methods has been developed to attain industry goals and to reach the required objective. Lasers have a wide range of applications in bar code readers, compact discs, computer printers, color copiers, laser shows, 3D holography, and position and motion control.

The laser is basically made to incident through lens, from the lens the laser light is further focused onto the work piece. There is no requirement of tool as it is a non-contact machining operation. Hence tool making expenditure is excluded,thus this has saved millions for the manufacturing industries.

1.2) Working principle of laser cutting

Laser cutting is a two dimensional operational process done by comparative motion between laser source and surface of the job. A continuous and high intensity laser is emitted from the laser source, which is reflected by the mirror onto the job. A converging lens is used to focus the laser light.

By ablation process the material removal occurs from the surface of the work piece material due to sudden surge in temperature. The focused power of the laser melts the material at the focal zone and thus material removal occurs. The assist gas used at certain pressure, enhance the cutting operation by washing out molten metal and doesn't allow any atmospheric influence during the cutting operation. During the cutting operation, these inert gases chemically respond to the job.

The quality of cutting by laser depends upon the optical properties of the job rather its mechanical properties. The cutting is maintained by equilibrium of energy between thermal conduction and radiant energy of job and laser respectively.

In the fiber laser machine which we have used has a solenoid regulator to assist the gas pressure during each puff. The gas is reserved at a cylinder at approximately 150 bar, and from cylinder it is further released at approx 50 bar at the outlet 1. From outlet 1 again we control it and release it at maximum 12 bar pressure to the machine component. At the machine component we have a solenoidal regulator that regulates the gas pressure during each puff.

1.3) Types of laser cutting

1.3.1) Fusion cutting

In this cutting the laser is focused on the work piece and an assist gas at certain pressure is used to wash out the molten metal during cutting operation. The assist gas enhances the cutting process, and the operation of cutting involves ablation of work piece material. In this cutting type, comparatively less energy is needed to ablate material. One of the drawbacks of fusion cutting is that it undergoes dross formations and other surface roughness.

1.3.2) Photochemical cutting

This process is also known as photochemical milling . This process uses photoresist method. It is a step wise process in which each step has important aspect. It delivers low cost tooling, prototype to production compatibility, burr free components, and identification marks at no extra cost. The first thing that should be happen for a part to be chemically etched is that there to be artwork generated. Drawings are taken from computer generated data and photo plotted onto film creating areas on the film that are either black or clear. It needs photo tool that can be created from a DXF or DWG file. In industrial point of view generally copper alloys, stainless steel, aluminium alloys or nickel alloys are used . Material is cut into sheets and then metal is cleaned to remove oils and greases. Once the material is cleaned it is then coated with photosensitive resistant that is sensitive to light. After the metal is coated it then it goes into the exposure unit where between two pieces of film that is created from file, where it is exposed on the top and bottom by UV light. When the light goes through the film where the resist becomes hard and polymerizes where the resist is shaded are soft. After exposure the sheet goes to the development process where the soft resists are washed away and the hard resists remains. This process is also called as cold ablation because it requires very less amount of heat during machining process.

1.3.3) Sublimation cutting

As we know that sublimation means the transition of a metal from solid phase to gaseous phase , in this type of sublimation cutting the intensity of laser power is kept high with high pulse frequency and the inert gas pressure in also kept high so as to wash away the vapor formed after the interaction between the laser action and the surface of the job. We can obtain high surface finish and narrow kerf width with minimum deviation from the actual desired kerf width.

1.4) Different cutting methods

Cutting is a fundamental operation in industrial applications where different types of materials are cut such as polymers , metals, ceramics, and plastics. This is a process of removing or opening a physical part of a component and separate it into two different parts. The type of cutting required for a certain material depends upon the mechanical and optical properties of material such as brittleness ,ductility, thermal conductivity , hardness, malleability , elasticity etc.

1.4.1) Traditional machining

In traditional machining macroscopic chips are formed and surface roughness is compromised. The quality of cut is also compromised. The tool is harder than the work piece material and thus the chip formation is irregular in shapes. The removal of material is due to the cutting forces thus this comes under the mechanical energy domain. But traditional machining is economical.

Traditional Cutting methods are:

1)Diamond Cutting

2)Mechanical Mounting

3)Abrasive wheel cutting

4)Wire Saw Cutting etc

1.4.2) Non traditional machining

This types of machining are widely used due to their high precision and surface finish. Unlike traditional machining process using tools, the non-traditional machining process uses chemical, thermal, mechanical , electrical processes or combination of all of them . This types of machining processes uses no physical tool and microscopic chip formation use to be there. Some of the best examples of non-traditional machining are as under:

1)Laser Beam Machining

2)Electro Discharge Machining

3)Electrochemical Machining

4)Wire electrical discharge machining.

1.4.3) Hybrid method of cutting

Both traditional and non-traditional cutting methods are having their limitations in terms of precision, accuracy , surface finish, efficiency , cut quality etc. Hybrid machining techniques involves the combination of both traditional and non-traditional machining techniques and their tools and energy functions. These includes both advantages of traditional and non-traditional cutting methods, to create a new method that is more effective and well organized than other cutting methods. Some examples of hybrid cutting methods are:

1) Electrochemical discharge assisted wire machining
2) Hybrid laser assisted water jet machining , etc

1.5) Laser source used for cutting

There are variety of laser sources however only CO2 and Nd:YAG lasers are widely used. The high power fiber lasers can be utilized for the requirement of high peak value in varied applications. However, the Nd:YAG lasers produce larger peak pulse powers.

1.5.1) Nd:YAG Laser

This type of laser is the most widely used laser. This is a solid state laser in which the active medium is the impurity of the host material. Here neodymium ion(Nd+3) is used as the dopant, or impurity is directly and deliberately added. The 1064 nm wavelength of the laser is dictated by Nd^{+3} ions. The substance or the host for lasing is in the shape of a cylinder with length 150 mm and diameter 10 mm. The inner and outer surface of the cylinder is flattened maintaining high tolerances, and then coated with silver to have a reflective surface over there, having an optical finish. The crystal is excited by an krypton atom. The development of high power laser is obtained by xenon lamp. By integrating numerous separately pumped laser rods in a single resonator, this was possible. Thus efficiency of pumping and extraction both are improved. Oscillator amplifier systems can be a better alternative for single multirod oscillators. Nd:YAG lasers cane be operated on three different modes such as Q-Switched mode, Pulsed mode and Continuous output mode. These types of lasers have peak power as 100kW and its average power ranges between 0.35 to 4.5kW. It has an advantage of sending laser radiation over optical fibers.

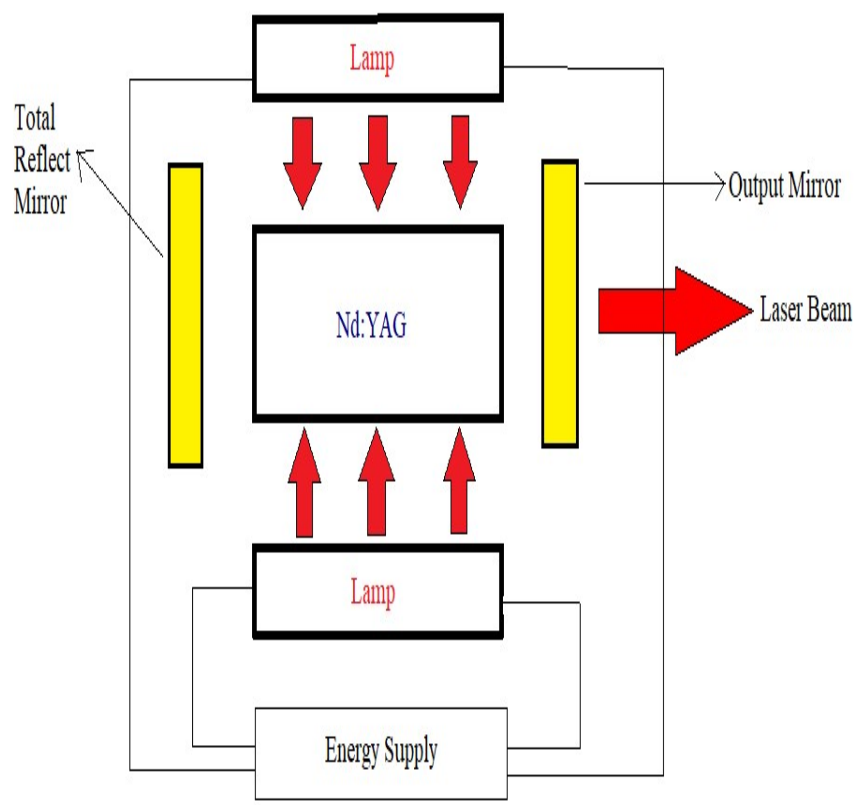

Fig 1.5.1) Schematic of Nd: YAG Laser

1.5.2) CO_2 Laser

This type of laser is widely used in industrial processing and it is more efficient than Nd:YAG laser. It has better light quality as compared to Nd:YAG lasers. Gas mixtures of oxygen and nitrogen are mostly used in such types of lasers. An electric glow discharge is used for combining He with CO_2. CO_2 lasers can produce an output power of 3-10 kW. The transverse flow and rapid axial flow CO_2 lasers are mostly used in industrial zones. It has low operating cost , can scale high power operations and has excellent electrical efficiency. The gas heating can be adjusted by continually circulating gas blend via optical cavity.

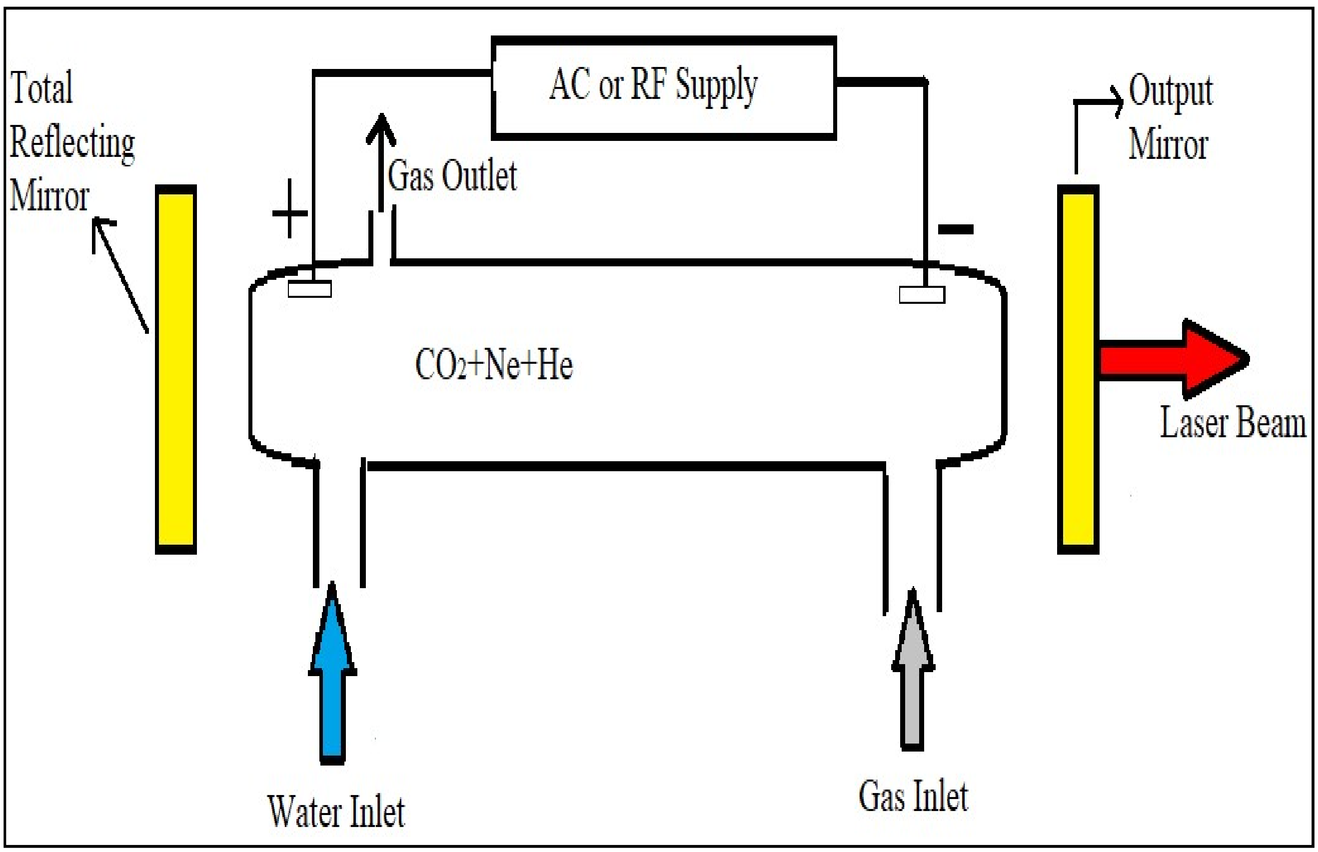

Fig 1.5.2) Schematic of CO2 Laser

1.5.3) Fiber Laser

The core of the laser is the fiber medium in the fiber laser. Here it is doped with an earth element. The most common type of fiber laser is single mode optical fiber laser. The pumped beam travels inside the fiber along the core or along the cladding around the core of the fiber. Fiber laser is a good substitute of CO_2 laser.

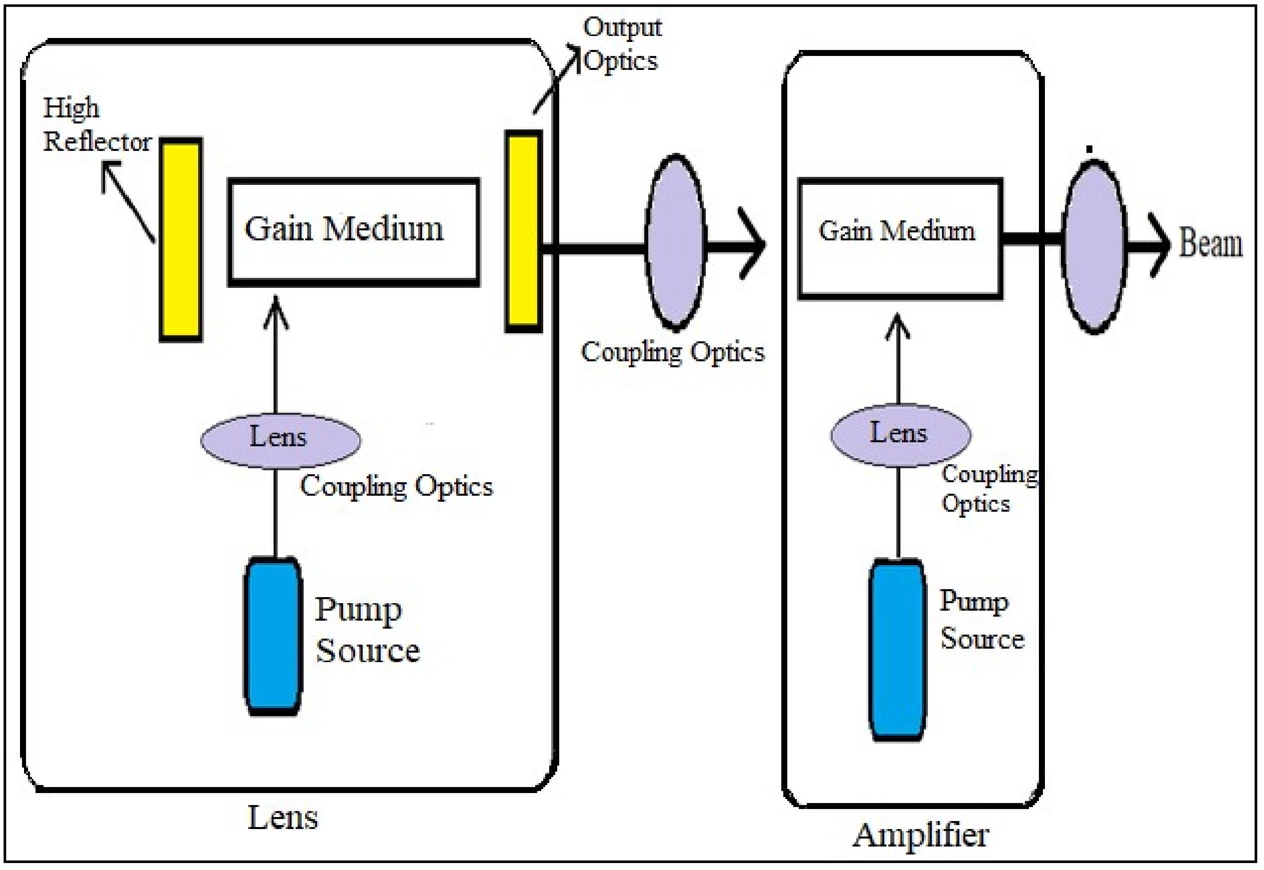

Fig 1.5.3) Schematic Diagram of Fiber Laser Cutting Machine

1.6) Mechanism of material removing during laser cutting

The part of material gets vaporized after the high intensity laser is incident on the particular spot, that melts that area and thus material removal occurs. The fundamental idea behind material removal is that there need to be a generation of high temperature heat flux over the particular spot on the surface of the material, where there is localized laser light. A suitable laser source is required to generate the laser of certain wavelength. From the lasing medium, a laser beam is incident with small diameter. A lens which is a converging element is used to direct or focus the laser beam onto to the surface of the job material. Due to such convergence there is a significant concentration of laser light on the particular spot of the material. The optical energy is transformed into heat energy source and therefore vaporization, boiling, ablation, or phase explosion, liable on the heat source and substrate material.

Vaporization

It is a process of transformation of solid/liquid phase of material into gaseous phase. When the laser light strikes the spot on the surface of the material, it first transforms the solid phase of the material on that spot into liquidus form. Then after further action of the laser light the liquidus part of the material is then transformed into vapor state. Under the operation of inert gas used as an assist gas, the liquidus form of the material is washed away. The generated steam generates steam or back pressure, pushing the steam away from the target, exerting strength on the molten substrate and expel it from the side.

Ablation

There are two ways to by which ablation process can be achieved. First is by producing a high energy quantum which will obtain us a power source. Thereby every molecule can be split into atoms of the material and be removed when the energy is more than the threshold energy of the atoms of the job material.

The other method is to incident a high power laser beam over the surface of the work piece which enable the focused spot to get vaporized and thus the material removal occurs or achieved on that particular spot.

Femto-second and Excimer lasers are the most widely used laser sources. The advantage of such method is that then machined surface of the material develops very less HAZ. We can get a good surface finish and the micro machining is possible by such methods.

Boiling

Boiling requires a comparatively long pulse period and contains the nucleation of foreign vapor bubbles that can form on the external surface of the liquid; in most liquids; or at the boundary between the liquid and surrounding solids.

Boiling occurs at the absorption depth ($1/\alpha$, where the absorption coefficient is α). The surface temperature is fixed, as is the vaporization temperature, which corresponds to the surface pressure.

Boiling is a process where the material either gets evaporated or melts away from the parent body during material removal process. It is almost like the vaporization process but the only difference is that in the case of solids, the boiling process transforms the solid into gaseous state only after transforming into liquid state.

Phase Explosion

For this process to achieve the laser fluence must be strong enough and the pulse duration must be rapid so that the temperature of the material surface reach at least 90% of the critical thermodynamic temperature. The substance quickly transitions from a superheated liquid to a vapor or liquid droplet combination, resulting in uniform bubble nucleation. The occurrence rate increases near the critical temperature and hence homogeneous nucleation is possible to achieve. This can be called as explosive boiling.

1.7) Laser Cutting Parameters

Due to advantages in high speed cutting the laser cutting mechanism is highly appreciated in industries and for scientific research area. There many specific parameters in which a particular cutting operation is undergone. These parameters are needed to be specified for certain cutting categories depending upon the type of job material we are going for cutting operation. To improve cutting with minimum manufacturing cost, labor cost, productivity with time saving factor, we are required to configure out the best set of parameters. The optimal parameters are needed to be set in order to ensure good cutting quality , productivity, and reducing manufacturing cost in fully automated manufacturing process. The main parameters that affect the laser cutting processes are:

Beam power

Beam power and depth of cut are directly proportional to each other. One of the most significant parameter of laser cutting mechanism. Extreme laser fluence on the kerf width may cause dross formation and also affects the surface finish. Due to high power fluence plasma plume may occur along with vapor formation when the laser fluence strikes the molten metal. Due to high power laser ,there is a chance of formation of spatter, HAZ and recast layer formation.

Wavelength

The electromagnetic force is converted into heat energy inside the workpiece to achieve the required cut. The wavelength factor does depend upon the absorptivity of the material . The stability of the process is maintained or achieved by initially using a beam of shorter wavelength. At shorter wavelength we can get Fresnel absorptivity. This is because the coefficient of absorption in the plasma does not vary much with the squared value of the wavelength. So the impact of plasma absorption on the cutting is minimal. Longer wavelength are not advisable for highly reflective surfaces.

1.7.1) Beam characteristics

Significant beam characteristics of laser cutting operations are as under:

- **Beam Mode**

  It determines the amount of beam intensity spread across the beam zone. The mode describes the ability of the beam to remain focus and can be compared to the keenness of a cutting tool. The fundamental or Gaussian distributed TEM_{00} mode is preferred for cutting due to the least possible focal dimensions thus highest power density for a given power of a laser beam.

  The multi-order & higher order beams has bigger focal sport and thus has very less density at the focal point and the output is very low for the identical laser power because the focal point is widely spread out.

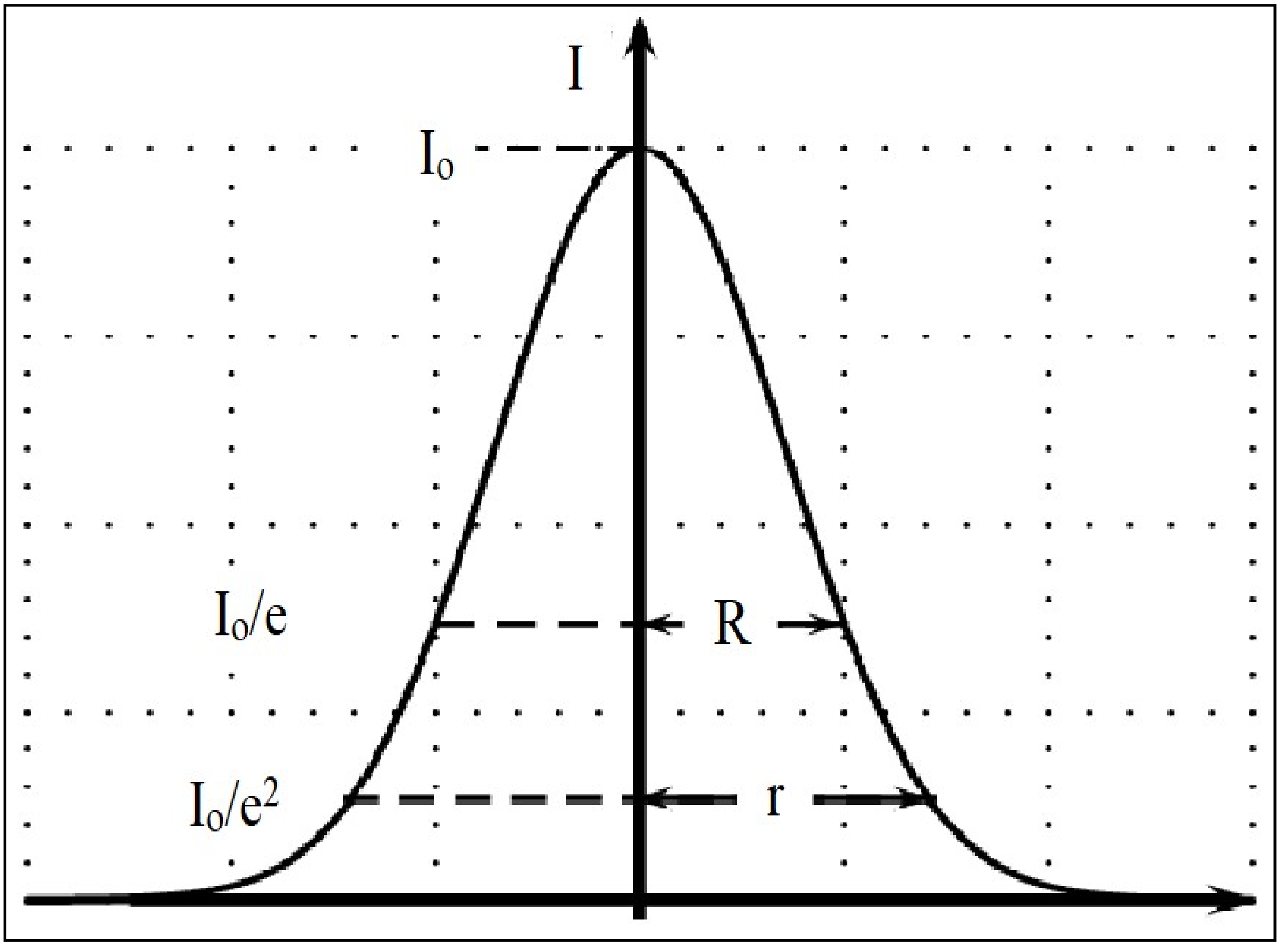

Fig 1.7.1 a) Gaussian distribution mode

- **Polarization and Beam Angle**

Absorption depends upon the polarization and angle of incidence. If the beam is polarized circularly, than we can obtain higher cutting rates. A beam that is plane-polarized and the angle of incidence is between 80-90^0 seems to have much better efficiency of absorption. The cut may have fine kerf with sharp & straight edges whenever beam is polarizing on cutting route. The absorption energy is decreased when the plane polarization is oriented away from the line of cutting, this results in undesired cut, larger kerf width, reduction in scanning speed and irregularities along the edges.

- **Beam Form**

Laser cutting uses both pulsed and CW beams, with continuous beams are quite frequent. The surface roughness gets affected pulse duty cycle, the pulse duty increases as the surface roughness decreases. The pulse duty cycle is ratio between pulse on time to the total time of pulse. Figure below describes pattern of beam forms of continuous and pulsed wave respectively as under:

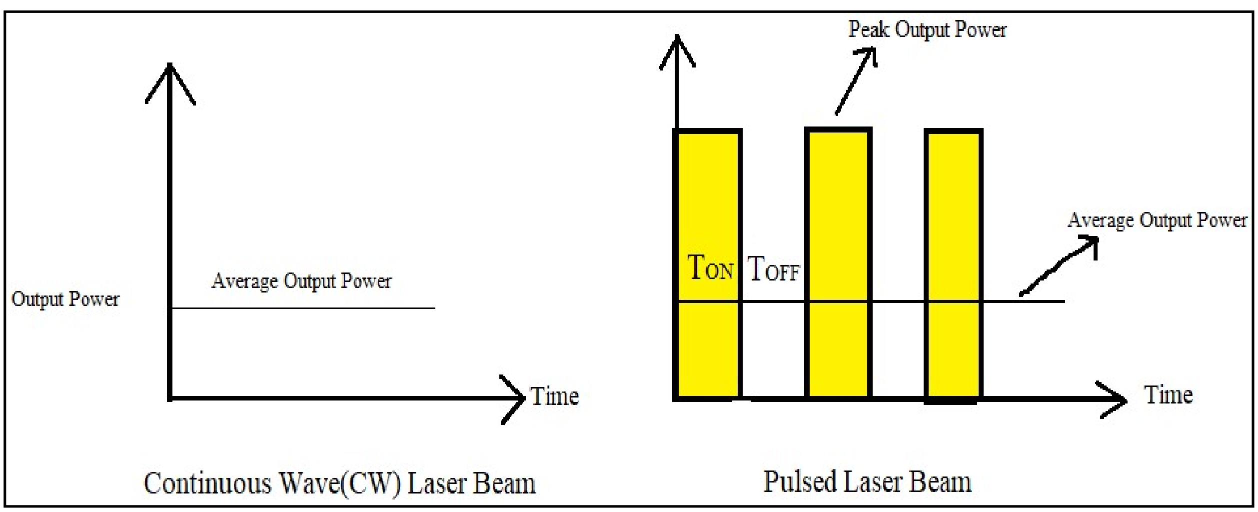

Fig 1.7.1 b) Continuous and Pulsed wave laser beam

- **Beam Stability**

The beam must remain steady and stable during the course of laser cutting operation to ensure maximum output from the laser power, also beam stability ensures mode of machining and focusing ability of the beam. A stable beam is always desired to ensure high product quality and better product output. The stability of beam depends upon the design of the optical resonator and the system of beam delivery.

1.7.2)Traverse speed

With the increase in width of the job, the highest speed achievable for a given laser power gets decreased**.** Traverse speed affects quality of surface & kerf width which vary in accordance to the type of material. In case of ceramics, surface quality gets enhanced by slow traverse speed. Extreme burning of the cut edge occurs when there is slow cutting; it does reduce edge quality and increase the breadth of HAZ. A material's cutting speed is inversely proportional to its width. While crossing sharp turns, the speed must be slower, which necessitates a drop in beam strength to avoid burning.

1.7.3)Assist gas and its pressure

The functions of assist gas are:

a) Ejection of molten material

b) Enhanced the cutting process through exothermic reaction

c) Protects the lens from back spatter.

The assist gas acts over the spot of cutting with a certain pressure regulated by the operator. The assist gas prevents solidification of molten metal along the cut area and by its pressurized force it washes down the molten metal. The assist gas also ensures that there is no atmospheric interference in the cutting operation. The importance of assist gas in directly proportional to the width of the job material.

1.7.4)Focal position

The divergence of the focal point plays a major role in cutting operation by laser. When the focal position is at the surface of the material or when it is just below the surface than best cutting output is obtained i.e least kerf width is obtained. It is always desirable that the focal point be maintained at one third of the width so get the best results.

1.8) Characteristics of laser cut samples

The quality of cut can only be ensured if there is a specified programmed parameters. The specified parameters are the factors that affects the kerf width, dross formation, surface finish and taper angle.

Kerf

The kerf is the slot molded during through-thickness cutting. In optimized laser cutting, the kerf width is defined as the width of the cut at the bottom, and it is usually significantly bigger than the concentrated beam diameter. Usually the bottom kerf width is smaller than the top kerf width; hence there is a formation of taper. The width of the gas jet determines the width of cut in laser cutting processes assisted by an assist gas.

Heat Affected Zone (HAZ)

Heat affected zone increases as the laser power incident per unit length increases and as the width of the job increases. The width of HAZ is vital while cutting in accordance with the vicinity of the thermal components. Hence, we've encountered some cases where maximum limit of HAZ is set for the output of the incident beam or the thickness of the plate, or the minimum limit is set for the cutting speed.

Recast Layer

It is the layer formed by the molten metal when it cools down. It forms burrs beneath the bottom kerf width . The burrs formed below can develop as an extended droplets. Such slags can be removed during processing by having high pressurized jet of gas or by filer.

Surface Roughness and Surface Finish

The condition of surface post cutting operation is characterized by the burrs and dross formation and the change in color over the surface of the job.

Surface finish is the microscopic observation of any surface. Good surface finish helps to increase the quality of the machine & also in dynamic condition of machine components. Good surface finish helps to increase the efficiency, reduces the friction & reduces the power consumption & also reduces the noise.

Good surface finish helps to make efficient lubrication. As per engineering design, both good and bad surface finish are the requirements. In a microscopic view of any metal, impurities present in any work piece is viewed. On two dimensional plane representing flow and lay together, gives continuous peaks and valleys over the sampling length is called surface texture.

Surface texture is the qualitative representation of the metal surface. Over the sampling length surface texture is divided into two types of deviations i.e waviness and roughness. Waviness or primary texture is the large wavelength deviations over the sampling length & this is because of machine vibrations or errors in guide. Waviness can be eliminated by improving the quality of finishing. In traditional methods of removing surface roughness, it was done by filing using a filer.

Roughness or secondary texture is the small wavelength deviations over sampling length and this is because of tool vibrations. Roughness is difficult to eliminate from the point of consideration. Due to roughness the orientation of lay marks are omni- directional , and every symbol of lay helps to identify the method of machining performed on job material.

Taper Angle

When working on high power laser it can reduce the possibility of creation of taper angle. Taper angle is caused whenever there is a difference between the upper width and lower width. This is caused due to the convergence of the lens focusing the laser light.

1.9) Material considerations

Laser cutting is a technique which depends upon many factors of the properties of work piece material, such properties are reflectivity, thermal conductivity, absorptiveness, heat of response, melting point, boiling point etc.

Metals

Metals are very good conductor of electricity and heat. Some metals has high reflectivity than absorptiveness. In such case it is difficult to operate laser cutting on such materials as work piece. Due to this, a black coating is done over the surface of the material for increasing its absorptiveness. Metals such as steel, titanium and its alloys , aluminum and its alloys, copper and its alloys, etc. are usually machined by laser beam machining. One of the major drawback in metals are the HAZ formation during laser cutting and dross formation during through cut, which initiates irregular surface texture. The surface finishing becomes difficult whenever dross formation occurs.

Composites

Composites are made up of various materials, hence the cutting parameters are decided by considering only one individual material component in the mixture. This can cause disruption in cutting due to the interference of other materials. When the fundamental material property is alike, it is easier to cut the material. Extreme caution is required while machining composites to contain harmful gases.

Ceramics

Ceramics are inorganic, crystalline, nonmetallic, hard , amorphous, thermally stable at high temperatures, less dense than metals, brittle, more elastic than metallic conductors, and has a high melting point, including excellent electrical and thermal insulation. Ceramics can be covalently linked. The excessive temperature gradients that occur during laser machining creates cracking due to thermal stress generation.

Polymers

There is a possibility of tearing down of polymer chains due to action high power laser beam. To have a polymer we just need a molecule that can bond with another identical molecule at two points. Polycarbonate and polyester are easy to cut while polyimide, PVC , phenolic etc leaves a section of disintegrated material along cut edge.

1.10) Application of laser cutting

Laser is a versatile tool in the field of manufacturing. Laser cutting emphasis on smooth cutting and tight finish along with cut. It can be guided by computer. For reflective metals , fiber laser cutting is much effective. Lasers are also used in engraving and marking market. Many metal insignias, signs are produced through marking. Due to the technology of laser cutting of silicon, the technology has increased in capacity and shrinks in size. Laser cutting is extremely precise and this is why it is possible to cut extremely smaller pieces of silicon. Our world and the IT industry runs on silicon, Microchips, circuits, semi-conductors are all manufactured by laser cutting technology. Laser cutting finds its applications in solar energy domain too.

In the medical industry, laser cutting performs a vast role. Laser cutting is preferred in such domain is because it has the ability to cut with extreme precision and tight dimensional tolerances. It has the ability to design replica with accuracy and precision.

Many medical devices has their origin from laser cutting. Cardiovascular, orthopedic devices and components for surgical implants are all having laser cutting origin of technology. Laser cutting can fabricate such devices with speed and without compromising accuracy.

1.11) Measuring equipments and machine details

Fiber laser cutting machine

The MEHTA Fiber laser cutting machine is being utilized for all cutting related experiments. It produces continuous Q-switched beam of laser. The primary cabinet is house of the CNC-controlled Laser Source as well as a workstation. The laser is controlled by a console affixed to the side walls of the main cabinet. At the back of the machine, there is chiller unit which is utilized for cooling purposes. The assist gas is supplied from a gas cylinder attached to the main cabinet. The laser beam output & the assist gas output are coaxial. A voltage regulator is present, which ensures that the machine receives a constant voltage input. There is a stabilizer that functions to provide optimum voltage required for machine operation. It is a Q-switched laser source which consists of a clipping mechanism to hold and maintain the work piece at the required position during the cutting operation. Thus the main components of the fiber laser cutting machine are the laser, computer controlled operator, console, voltage stabilizer, clipping equipment, supporting console, assist gas and chiller unit.

Before switching ON the laser machine, the chiller unit and voltage stabilizer is switched ON. Then the gas cylinder is made to release gas at a particular gas pressure (not more than 10 bar), this is followed up by starting the laser monitor and machine along with. The laser machine is made to puff in order to remove the excess amount of gases. Then parameters are set up by Cypcut software, and the frame is adjusted with the help of the software. Then the shutter is closed and the laser machining of the material is initiated.

The laser machine consists of the following sub-systems:

a) Console monitor for laser

b) Fiber laser system

c) Chiller unit of the laser

d) Voltage stabilizer of the laser

e) Assist gas cylinder

f) Clipping unit of the equipment

Fig1.11 a) Fiber Laser Cutting Machine

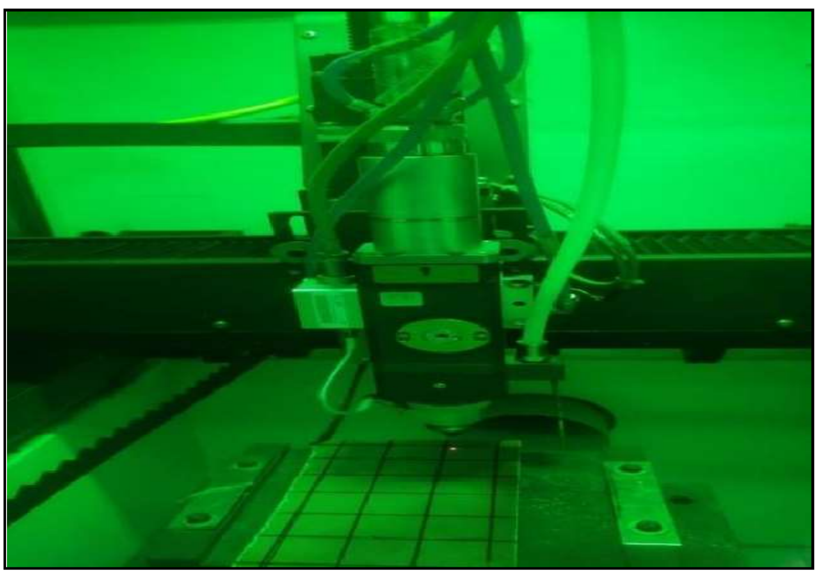

Fig 1.11 b) Fiber Laser Cutting System

Fig 1.11 c) Console Monitor For the Laser

Table 1.11 Specifications of Fiber Laser Cutting Machine

Sl.No	Parameter	Value
1.	Max. Output Power	500 W
2.	Switching and Mode of Operation	Q switched continuous operation
3.	Assist Gas	Nitrogen
4.	Nozzle Distance Range	10 cm to 25 cm
5.	Wavelength	1064 nm
6.	Laser Spot Diameter	50 micro m at focus

Fig 1.11 d) Chiller Unit

Fig 1.11e) Assist Gas Cylinder containing Nitrogen

Fig 1.11 f) Voltage Stabilizer

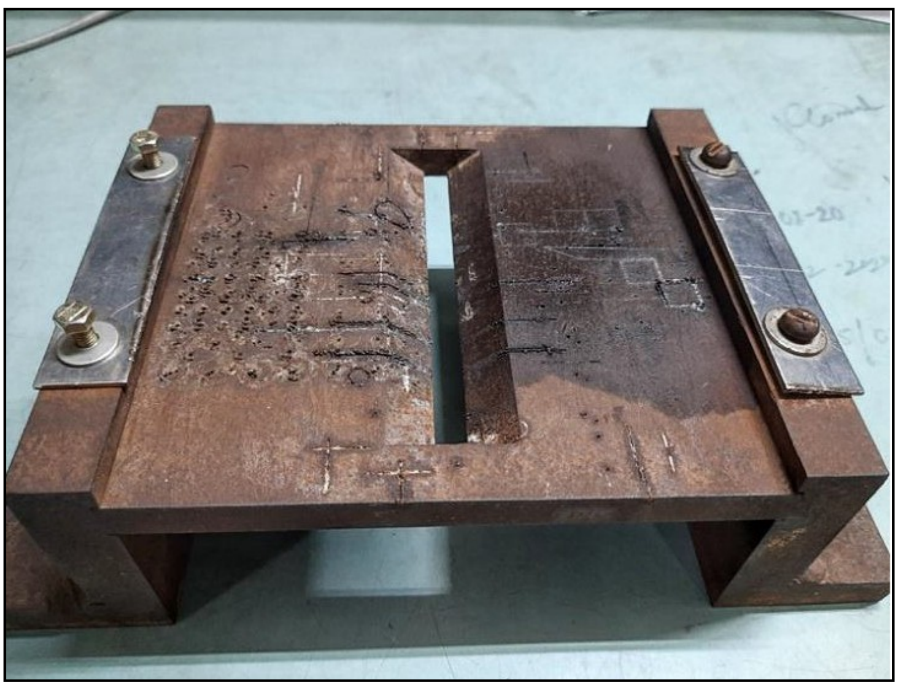

Fig 1.11 g) Clipping Equipment

Cypcut Laser Machine Software

This software has been designed to plane laser cutting. The prominent functions include graphics, cutting process control, parameters settings, custom cutting process editing, path planning simulation and layout designing. The figure below consist of the drawing interface where the design layout has been set up . Along with that we have the highlighted grid where the machine breadth is signified. Above the interface from top to bottom are Title Bar, Menu Bar and Tool Bar. There is "Quick Bar"

At the left of the title bar which is used for simultaneous creating, opening and saving a file? At the left of the interface we have "Drawing Tool Bar" which provides the basic drawing functions. At the extreme right of the drawing area ,there is "Process Toolbar" which functions in order to vary and set the process parameters.

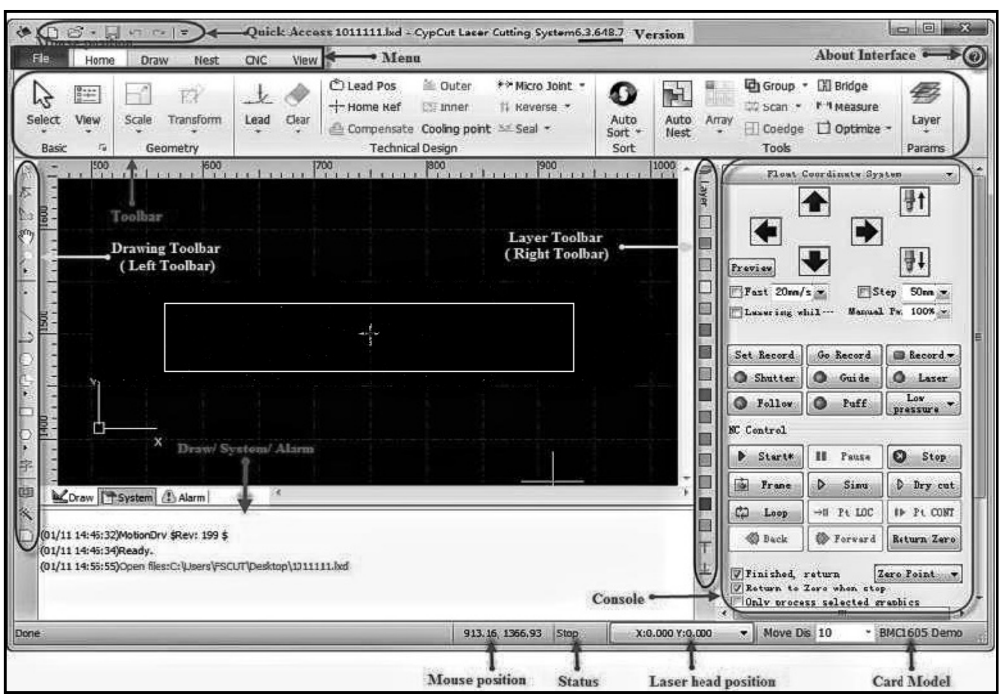

Fig 1.11 h) Cycpcut Laser Cutting Screen Display

Optical Microscope

The optical microscope belongs to ZEISS STEMI 508 . it is used to minutely record the output response. Data is collected from ScopeImage 9.0 software installed in laptop. It has two lenses which can be operated together where no image is formed on the screen i.e. only for précised viewing operation , and the other technique is by using only one lens where an image is formed on the screen i.e. for precise viewing and accurate measurement.

After the machining of the work piece their characteristics including surface roughness, HAZ formation, dross formation, kerf gap, etc can be observed and examined by the microscope. It is required to adjust the focusing power and zooming factor to examine the machined part. The microscope is first connected to the power supply and then it is switched ON. Subsequently after switching ON the optical lights are incident automatically on the positioned place where the work piece is going to be placed later on.

The optical lights can also be adjusted by human hand. There are two sets of focusing arrangement. The 1st one is adjusted in keeping in mind to get a better view of the product at the optimal focusing value and simultaneously the focusing value is adjusted with the value in software. The 2nd one is used for clarity and it is basically used to adjust the microscope head.

Fig 1.11 i): Optical Microscope

One most important thing that we have to keep in mind to ensure the particular zooming factor while measuring or working on the microscope. It is important because it will help us to avoid any kind of human error during measuring. To maintain the standard of experiment and work it is important to view at constant zooming factor.

1.12)Advantages & disadvantages of laser cutting

a) Advantages are

- Narrow kerf width, which results in less waste,
- Cutting rates are fast,
- Precision and accuracy are well maintained,
- It's a non contact technique ,so there is no tool piece required,
- Both soft and hard materials can be machined such as paper, diamond etc,
- And, it has low noise and high flexibility.

b) Disadvantages

- Highly shiny and reflective materials are difficult to cut.
- Set up cost is high.
- High maintenance cost.
- Skilled operator is required.
- It has to be machined at certain safe range.
- Polymer materials release lethal gases that are harmful for human beings.
- Chances of developing burrs and dross at the cutting edge.
- Assist gas is required for preventing atmospheric interference.

Chapter – 2

Literature Survey

2.1) Literature review

Dr. Paramasivan Kalvettukaran et al [1] studied about the behavior of stainless steel, they describes the simulation of laser processing of stainless steel of grade AISI 304 sheet metal. In this they described about determining limiting values of process parameters such that the material temperature remains below or just above the maximum temperature specified, by depending upon certain desired requirement. COMSOL MULTIPHYSICS was used in this study. The design matrix layout was based upon central composite design (CCD) and four parameters were studied with five levels. After the output of simulation, by relating the sheet thickness & laser process parameters, a regression equation has been developed to find out the maximum temperature.

Arif M. Varsi et al [2] observed that machining of PMMA which is having the capacity of maximum absorptivity of laser radiation incident on it. It is used for manufacturing cavities of spherical and rectangular shapes. The significant parameters to achieve depth of cut are no. of passes, scanning speed, & laser power. This paper talks about algorithm modification & establishing relation between no. of passes & depth of cut, along with prediction of depth of cut & comparing the theoretical results with experimental outcomes. Here they also established a possible no. of passes that would be required to gain a desired depth of cut.

I Esmail et al [3], studied about the improvement of V shaped cut on the alumina ceramics. A relation has been established between kerf profile and depth of cut. Here their developed approach defines the kerf profile as a function of depth of cut for all the V shaped cut profiles. When the wobble pitch was above 30µm, the surface roughness increased significantly. When the amplitude of wobble was small and their frequency was low, they produce smaller kerf taper and deeper cut. At frequency of 100Hz the ceramics significantly melts and what we have observed that the heat effected zone was larger. Hence, 100Hz was considered as threshold frequency.

Elyas Haddadi et al [4], has stated that increasing the laser power & velocity can minimize the heat affected zone, also a covering gas is required to control the HAZ. The cutting velocity is the most significant factor deciding the angle of cut & ration between top kerf width & bottom kerf width. The optimized outcomes for better cut quality came from laser power 60 (W) & cutting velocity 14 mm/sec. One of the disadvantage of using covering gas is that it helps in limiting the HAZ, however it doesn’t reduce the dross height, in fact the dross height reduces only when the experiment is done without covering gas. Here a CO_2 Laser has been used for cutting of polystyrene sheets of 3 mm thickness. So, according to our study the lesser the thickness of work piece is, the lower the taper angle will be during laser cutting of ceramics.

Mojtaba Karami Moghadam et al [5], has observed the 3.2 mm polycarbonate sheet is subjected to laser cutting operation, where the operational processes were optimized to improve the cut thereby minimize the kerf. The equipment used here is a low powered continuous CO_2 laser. They found that by decreasing laser power from 50 to 20w and increasing scanning speed from 4 to 20 mm/sec , the HAZ is minimized. To reduce the kerf, the cutting speed was maintained at 20 mm/sec and focal length was kept at -3. The gas pressure assumed was 3 bar for the polycarbonate material.

Girish Dutt Gautamet al [6], studied about teaching learning based optimization technique which was used for machining of 1.25mm Kevlar-29 fiber reinforced polymer composite sheet. The operator used was pulsed Nd:YAG laser. The input parameters were lump current, pulse width, pulse frequency, air pressure and cutting speed. The analysis demonstrates that cutting speed has 52% contribution on deviation of top kerf whereas lamp current has 47% contribution on deviation of bottom kerf.

Pankaj Khatak et al [7] has studied about different applications of CO_2 laser cutting of process to thermoplastic polymers, metal sheet cutting, polypropylene (PP), polycarbonate (PC) in diverse thicknesses varieties. This review studied on theoretic and experimental studies on laser cutting to end the enactment process. They studies about meting out parameters such as scanning speed, pulse frequency, gas pressure etc. Also the aim of the study was to make the product profitable by using FEA, quality management and software nesting.

T. Muangpoolet al [8], stated that in 21^{st} century, laser cutting technology became more popular. It gained a significant role, especially in the domain of industrial production. The advantages has improved speed and precision for productions. This helps in ensuring the end-products to be impressive and less expensive. Hence this has increased the number of the Thailand based industries to accept this technology into their line of production. Laser cutting provides the advantage of cutting the material with higher speed, less heat, less vibration, less gas production, smaller cutting area and less twisted production, as compared to other technology .But the problem is that the technology is expensive & very less in its usage. A decrease in tax in such technologies can only attract industries to adhere to laser cutting operations.

John D. Kechagias et al [9], told about feed forward and back propagation neural network (FFBP-NN) for prediction of characteristics of kerf from three different distances i.e top, middle and bottom & kerf angle during cutting of 4 mm PMMA (polymethyl methacrylate) thin plates by laser. Stand-off distance (SoD: 7, 8 & 9 mm), cutting speed (CS: 8, 13 & 18 mm/sec) and laser power (LP: 82.5, 90 & 97.5 W) were the parameters for low powered CO2 laser cutting. A three factorial array was used & 27 cuts performed. The top width, middle width & bottom width & kerf angle were analyzed by ANOM & ANOVA & plots of interactions. According to the ANOM plots, values of parameters which optimize the kerf Angle resulting in values close to 0^0 are the 7 mm stand-off distance, 8 mm/s Cutting Speed and 97.5 W laser power.

Ray Tahir Mushtaq et al [10] says that CO_2 is used in variety of cutting applications of polymers like thermo-setting plastics & thermo-plastics. The variety of polymeric materials are used in household & commercial products in industries. They are widely available in the market so they are used excessively. The obstacle while cutting of such materials are formation of dross, kerf angle, roughness of surface, striations formation & formation of heat affected zone. The cut quality is analysed by optimizing gas pressure, cutting speed, laser power, pulse frequency ,nozzle pipe, nozzle diameter, & standoff distance.

Suresh. R et al [11] told that drilling of GFRP composite and Borosilicate glass. The characteristics of drilling were MRR & taper angle of the hole. Standoff distance, abrasive particle size, time taken & pressure are the four characteristics that were studied. The most important parameter is recognized and their influence on taper angle and MRR is studied. It is formulated that MRR and taper angle is mostly affected by standoff distance and abrasive particle size.

Meltem Altin Karatas et al [12] has observed that Fiber Reinforced Polymers do not exhibit plastic deformation because they are heterogeneous and anisotropic. They have vast range of applications in space and aviation technology, maritime, sports industry, and automotive industries. Carbon Fiber Reinforced Polymer and Glass Fiber Reinforced Polymer has excellent strength and low specific weight properties , thus they are widely used and they are replacing other conventional FRP materials. Because of their good manufacturability in different combinations, high fatigue, toughness, high temperature bearable capacity, and oxidation resistance qualities, they are identified as the best choice in engineering manufacturing. The machining of heterogeneous and anisotropic materials, failure mechanisms were reported for the machining of materials like GFRP and CFRP, by bpth traditional and non-traditional machining and the results were obtained from artificial neural networks models, variance analysis ,FIS, Harmony Search Algorithm , genetic algorithm, Taguchi's Optimization method.
D. Arola et al [13] studied about Kerf quality and kerf characteristics of Gr/Ep laminate were studied for abrasive water jet machining. The analyses shows that the kerf characteristics of kerf depends upon three major macro regions along the cutting depth. The rough cutting, smooth cutting and initial damage, all depends upon operational conditions. Analysis of variance and design of experiments were used to study the kerf characteristics. The MRR on operation on Gr/Ep do not change over jet penetration.

Daivik Kothwala1 et al [14] has researched on how the laser cutting is the most sophisticated type of cutting and it finds its used for cutting of AISI 2205. It has been observed that kerf characteristics are also changing with the profile of cut. This paper deals with optimization of different process parameters for the improvement of cut quality and kerf characteristics while cutting of AISI 2205. The process input were the nozzle diameter, gas power, scanning speed and thickness of the work piece. Taguchi method has been used for straight and circular profiles. They used Nd:YAG laser for the operation.

Milos Madic et al [15] in their research, the study has been carried out to establish a relation between gas pressure, scanning speed, material properties and kerf characteristics. A CO_2 laser has been used for the machining of AISI 304 stainless steel. To establish the relation, an ANN trained with gradient descent with momentum algorithm was used. Taguchi's L_{27} method was used for this particular aim. Statistically, the ANN model was used to study the influence of laser cutting on the kerf characteristics at different plots like 3D & 2D plots.

U Ashok Kumar et al [16] observed input parameters like jet pressure, abrasive flow rate, traverse speed and stand-off distance, the GFRP has been machined to study its kerf characteristics. Taguchi L_9 array bhas been used to study the characteristics of ker width and kerf angle.

R.D.S.G. Campilho et al [17] observed that CFRP are highly used in appliances with high responsibilities and this also poses a requirement of their handling after damages. Efficient repair methods can be used to restore the strength of the structure. The availability of repairing equipments is important for the cost reduction and reduction of time for testing purposes. This paper studies on tensile characteristics of 3D adhesively-bonded scarf repairs in CFRP structures, using a ductile adhesive. The Finite Element analysis is done on ABAQUS. On two geometric parameters, parametric studies was performed.

L.M. Wee et al [18], studied that due to reduction of line of width and line space of Si devices, the absence of debris on the laser micromachining area's periphery is critical. The article discusses about study of different volatile liquids that will reduce the formation of debris and spatters during femto-second laser drilling of Silicon. It was noted that water with lower atomic presence of carbon and lower boiling point was absolutely effective for reducing formation of debris while femto-second laser drilling operation of Silicon. Shock waves and plasma confinement in liquids were reasons behind reduction of debris formation. A more volatile liquid will be able to reduce the taper angle created in the hole.

Pratik P. Shukla et al [19]did a comparative study has been done on fiber and Nd:YAG laser during treatment of surface of engineering ceramic i.e Si_3N_4 , to find out the influence and contribution of laser beam brightness. Here the fiber and Nd:YAG with identical parameters were used. Considering modification in dimensional size and the irradiated microstructure of the engineering ceramics, the effects of laser beam was studied. It is found that despite using two different lasers with identical parameters, there has been a change in dimensional size and microstructure of the engineering ceramic. This variation & change occurred due to the difference between the two laser-beam-light of fiber laser and Nd:YAG laser. When compared, the fiber laser produce more power per unit area in Steradians, than Nd:YAG laser. Bright laser beam is cost effective as it uses low power to do required machining of Si_3N_4 ,whereas a laser with lesser beam brightness needs more power to do the same required machining. Therefore, it is recommended to use high brightness laser beam for economic advantage.

Xinyuan Zhao et al [20] studied the single edge V notched beam method based on the laser notching approach can reduce the limitations of time consuming and errors in traditional toughness measurments method. Taking oxides like ZrO_2 ,Al_2O_3 , Silica Carbides (SiC) ,Borides (ZrB_2), and nitride (Si_3N_4) based ceramics as the working objects. This research studies the effect of notch tip sharpness, relative notch depth (a/W), relative notch angle.

H. and Yazdani Sarvestani et al [21], their research was on ceramic materials are inherently brittle, thus poses significant drawbacks while machining. Due to such drawbacks ,we face obstacles in fabrication of intrinsic parts .Also, by using mechanical methods ,it becomes difficult to obtain a good quality of cut, since the mechanical methods creates micro-cracks along the interface of cut. In this wobbling method is developed for high precision, defect free & deep laser cutting. The parameters considered were linear speed, focal point , and wobble amplitude to control the depth of cut and optimize the cut quality in terms of surface cleanness , kerf angle, kerf width , during avoiding of crack formation. Maximum MRR achieved was 10 mm^3/min.

M. Genest et al [22], has found out that to enhance the strength and toughness of brittle materials, a robust design strategy is required which can be provided by architectured materials. The brittle ceramics can be transformed into impact resistant structures by architecture materials. They also provide tunable stiffness, strength and toughness. X-ray radiography , X-ray penetrant , infrared thermography , NDE (non destructive evaluation) techniques ,3D/ Stereo laser scanning microscopes were used to get accessed the architecture structures. This was done before evaluating multi scale damage post individual impact. by stacking laser-cut hexagonal tiles (differing the cut depths) and interlayers of commercial monomer Surlyn, the multi-layered ceramics were created.

S. Y. Martowibowo et al [23], observed that for producing dies, fixtures, and jigs ,the best machining method is Wire EDM process. The work pieces having taper and oblique, van be easily cut by EDM process. The objective in this research paper was to optimize the process parameters in wire EDM process cutting. The input parameters that has been taken into consideration were capacitor, off-time , on-time , no-load voltage, and servo voltage for machining of carbon steel AS_SAB 760. The analysis of variance, Taguchi design of experiments , signal to noise ratio were employed to study the influence of process parameters by adopting L_{18} Taguchi orthogonal array for conducting experiment by electrode of brass wire having a diameter if 0.2mm. In order to achieve minimum surface roughness and maximum MRR ,the six controllable factors that is the parameters of each at three levels were applied to find out the best optimized combination of levels and factors. It was found that the surface roughness (SR) and material removal rate (MRR) was significantly influenced by taper angle and on-time.

F Quintero et al [24] , observed that efficiency in material removal has a critical influence on laser cutting process. But , they are difficult to analyze and study because the parameters that govern the laser cutting processes are complicated to measure and observe experimentally. This is why development of theoretical models are required to analyze the complicated influencing parameters. The assumption made here is that the ceramic material could be melted by the laser irradiation. So, three ejection mechanisms were investigated and they are: evaporation of liquid, ejection of molten material due to pressure of recoiling generated from evaporation from cutting front .

Shengqi Wu et al [25], investigated on minimizing taper angles. Here three GDI(Gasoline Direct Injection) fuels were investigated to analyze the taper angle of nozzle for characteristics of spray. All the injectors were having identical diameter, however the only change made was the taper angle. The pressure maintained was 197.385 atm and the temperature maintained was 25^0 C. When the taper angle of the nozzle was increased, there was a space between nozzle wall and internal flow, which brought air interference into the picture. The consequence to this is that radial flow at the nozzle increased. This was advantageous for atomization and breakup of spray. The larger the nozzle taper angle, the broader & shorter the global spray, which increased the probability of plume interaction. Also the larger nozzle taper angle resulted in larger plume angle, wider fuel plume. Moreover, smaller fuel drops were observed. An additional degree of freedom can be possessed by adjusting nozzle taper angle while trying optimization of spray characteristics of injector to improve atomization , reduction of emission and engine combustion.

C Wandera et al [26], observed that different parameters like cutting speed, focal position and focal length were tested to reach to the maximum possible cut quality of kerf width. The optimization also helped in removal of melt through the cut to prevent formation of dross. By reducing scanning speed from maximum possible speed, using larger length of focal lens for laser beam focus, & having focal position at the bottom of width of work piece surface, would help us to gain better cutting edge quality ,enhanced kerf width ,and high melt removal.

K. Abdel Ghany et al [27], studied that stainless steel has high melting point and its oxides formed has low viscosity. Hence it is required to do laser cutting by high laser power and high gas pressure. Stainless steel is thus difficult to cut by methods of oxy-fuel. In this paper, the optimum cut is achieved by laser power of 210 W , frequency 200-250 Hz, scanning speed 1 to 1.5 m/min, Focus position -0.5mm to -1mm, nitrogen pressure was kept 9-11 bar and oxygen pressure was kept 2-4 bar. It has been found that the kerf width & surface roughness decreases by increasing the scanning speed and frequency, whereas, surface roughness and kerf width increases whenever gas pressure and laser power has been increased. Using high gas pressure is quite not economical.

TLBO is a teaching–learning process-inspired algorithm proposed by Rao et al. (2011, 2012) based on the influence of a teacher on the output of learners in a class. The algorithm mimics the teaching–learning ability of the teacher and learners in a classroom. The teacher and learners are the two vital components of the algorithm. The algorithm describes two basic modes of the learning: (1) through teacher (known as the teacher phase) and (2) interacting with the other learners (known as the learner phase). The output in the TLBO algorithm is considered in terms of the results or grades of the learners, which depend on the quality of the teacher. A high-quality teacher is usually considered a highly learned person who trains learners so that they can achieve better results in terms of their marks or grades. Moreover, learners also learn through interaction among themselves, which also helps to improve their results.

2.2) Motivation of the research

The motivation of the research came from the idea of optimizing the cost of industries working in the field of laser applications and laser machining. Ceramics are one of the multipurpose materials with high thermal and electrical resistance, good chemical stability, high corrosion resistance, & hardness.

Ceramics are used for electrical insulation, a high thermal application where super alloys are failed to resist heat. Ceramics are used in electronics industries as dielectric and insulators, application of heat shields for the space shuttle, heat exchanger and electronics substrate for microwave instruments, piezoelectric ceramics have wide applications in microelectronic mechanical systems (MEMS), ultrasonic measurements, strain gauge. Also, ceramics are used as mechanical tools and dies, fuel systems in space vehicles, automobile engines, defense weapon systems, biological and nuclear industries.

Cutting of ceramics is a bit challenging using conventional machining techniques such as Abrasive wheel cutting, Diamond saw cutting, etc. due to their brittleness and hardness nature. Conventional techniques take more time, are noisy, and are less efficient compare to non-conventional techniques such as laser machining. A laser is a photonic device, where we manipulate the photons using the electric signal. The laser acts as a heating point source just equivalent to machine tools in conventional techniques.

The laser machining technique is eco-friendly, less noisy, very fast, and precise. In this present work ceramic tiles are used as a work piece. Conventional techniques currently used for cutting ceramic tiles are very noisy, polluted, and less efficient in cutting speed than laser cutting.

We can easily control the response parameters such as kerf width, glass formation width, heat affected zone (HAZ), and taper angle from process parameters such as laser power, frequency, scanning speed, and gas pressure. We simply optimize the process parameters for optimizing responses for the desired response concerning minimal laser power, maximizing scanning speed, increasing productivity, and less machining time.

2.3) Objective of present research

From review of past researches we have found that numerous research papers and articles were published for minimizing the kerf width during laser cutting of different material and its components. Most of the researchers focused on different type of cutting to achieve their goal with different conditional parameters. In our present work we have used the parameters so as to minimize the cost for cutting. For a 100 meter long job length, we have calculated the cost required behind cutting operations.

As per as the above mentioned requirements are concerned, our objective of the present work is as below:

- Laser Cutting is a very cost effective operation so, our 1st objective was observe the characteristics of expense during operation.
- A range of values of parameters has been decided and framed to determine the top kerf length, our 2nd objective was to see if the top kerf width can be minimized or not to positively impact the overall taper angle.
- Our 3rd objective was to find the particular set of parameters which would give us a minimum top kerf width.

- Our 4th objective was to get the particular set of parametric values which would provide us minimum cost for identical job length.
- Our 5th objective was to find out the combination of overall parameters which would provide us best possible desired top kerf width along with best possible minimized cost.

Chapter - 3

Research and Methodologies Adopted

3.1) Brief details about the operation

The laser cutting was done on a ceramic plate of 7mm thickness by a laser cutting machine of maximum 500 watt laser power capacity with the help of a laser beam of 50 micro meter diameter and the assist gas taken was nitrogen to avoid atmospheric interference. A constant distance between the nozzle and the surface of the ceramic place was used. At first, a random no. of trials was done to exactly know the process parameters and the upper and lower limits. The table below shows the process parameters and their specifications that were chosen for the experimental purpose:

Table 3.1 Process parameters and their limits

Parameters	Notations	Unit	Lower Limit	Upper Limit
Laser Power	p	Watt	370	440
Scanning Speed	v	mm/sec	1.6	4.4
Gas Pressure	g	bar	7.2	12.8
Frequency	f	Hz	230	720

The range of parameters regulates the output response. The experiments were designed and optimized by using RSM methodology. The RSM look up into a good relationship approximation between input parameters and output responses. The DOE can meet the needs of issue solving and product/process design optimization projects in a cost-effective manner using the RSM technique. This method reduces the time taken to make a decision regarding experiment. Experiments can be used to enhance product/project designs, explore the influence of many parameters in the output response. To validate this technique we use ANOVA model here.

3.2) RSM Methodology

Response Surface Methodology**,** RSM (also known as Response Surface Modeling**)** is a technique to optimize the response(s) when two or more quantitative factors are involved. The dependent variables are known as responses, and the independent variables or factors are primarily known as the predictor variables in response surface methodology.

While *p-value*s are used for a particular point such as to test the hypothesis of "whether the 70-degree Fahrenheit is the most comfortable temperature or not," the response surface is useful in determining a range of temperatures for the same comfort level. As maintaining the temperature exactly at a 70-degree could be very expensive, maintaining the temperatures within a range are often desired for a cost-effective solution.

Moreover, keeping very cool in summer or very hot in winter would be very wasteful. Response Surface Methodology, RSM, is very useful to optimize variables/factors more practically as compared to just the statistical significance test for a particular point.

While the response surface is visually appealing and provides a quick meaningful overview of the relationship, a contour plot is easier to understand with respect to the optimized values for the independent variables, for which the same level of comfort (response or dependent variable) can be achieved.

3.3) ANOVA Analysis

When we have more than two sample sets, we need ANOVA to compare them. It was developed by Ronald Fisher. There are some assumptions in ANOVA and they are:

- Each samples must be random.
- The samples taken from any population must be normally distributed.
- The variance of population must be equal.
- Each sample must be independent from each other.

ANOVA is a statistical test for determining dissimilarities in the group means when there is one dependent variable and one or more independent variable. Basically we are interested to find out the differences between the population means.

Types of ANOVA

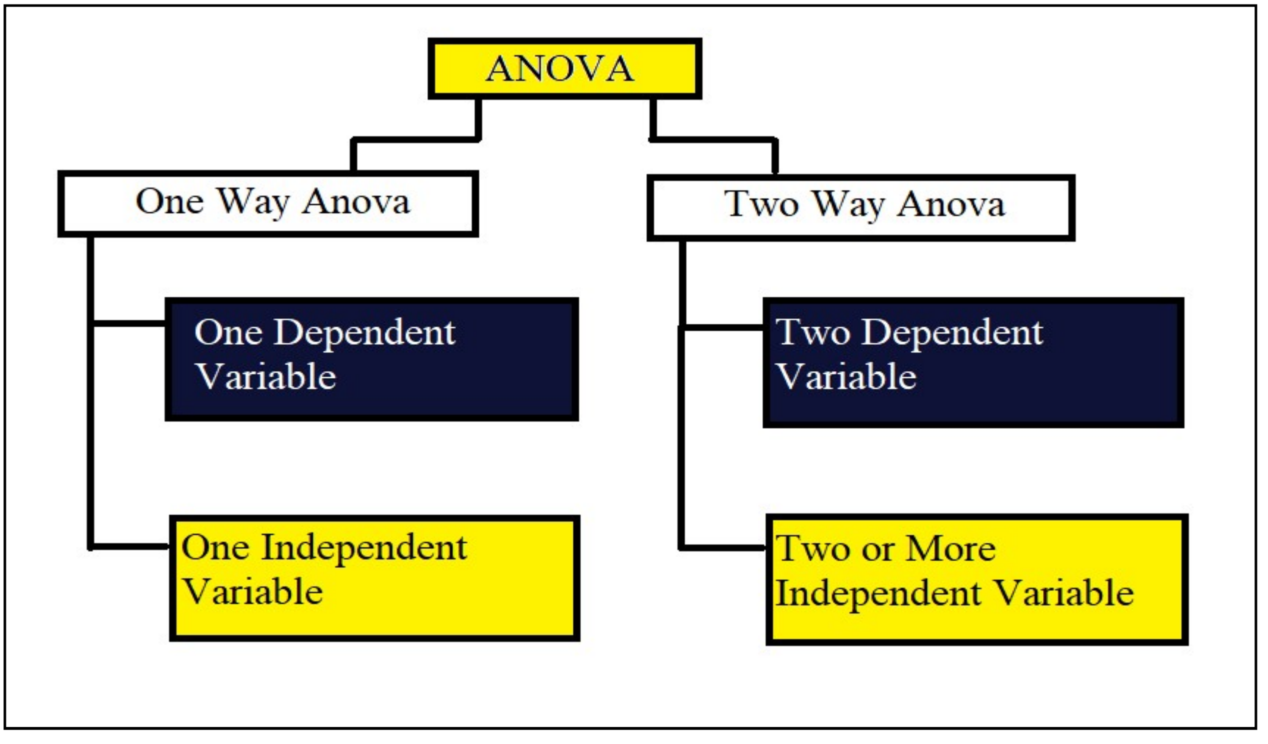

Fig 3.3) Types of ANOVA

Real world example where ANOVA is widely used are as suppose as a marketing manager of any product based company , if we want to know if three different types of marketing /advertisements effects the average sales differently or not. So the best possible way to do that is by applying each type of advertisements in 20 different stores for a definite period of time and configure out the total sales for the same period of time. Now to observe the statistical mean differences in the sales with respect to three types of advertisements, we can apply one way ANOVA. There we should consider advertisement as the factor and sales as the response variable.

Null Hypothesis

It determines that there is no relation between two or more samples or there is no relation between the measured phenomena.

Alternative Hypothesis

It says that whenever a new thing is happening , a new theory or latest theory is developed instead of an old theory.

P-Value

The P-value is the probability value that finds out the observed value or the extreme value when the null hypothesis of the data set question is true.

Alpha Value

It determines whether a test statistic is important or not.

3.4) Regression Analysis

Regression sets up a relation between unknown values with known variables, so that one can predict the unknown parameters with the known value. In regression one variable is considered as independent and the other variable is considered as dependent. With regression possible values of dependent variables can be determined from independent variables through a definite relationship.

Regression analysis helps us to cross check whether the experiment done by us is logically correct or not. Through regression equation we can develop required graphs to determine the surface plots and contour plots to know where the optimum output response is actually occurring. The surface plots also gives us an idea of safe zone of working, or the parametric working range where it is destined to achieve our goal or desired results as an output response. Prior to regression analysis it is important to analyze the ANOVA table and check the F-value and p-value to understand the quality of experiment or work.

The regression equation helps us to find the output response at any point of set of respective parameters. We can even compare the experimental output response and theoretical output response, and find the percentage of error to cross check our validity of experiment.

Regression analysis is more versatile and has wide applicability. Linear regression and Neural networks are both models that you can use to make predictions given some inputs. Regression analysis allows you to understand the strength of relationships between variables. Using statistical measurements like R-squared / adjusted R-squared, regression analysis can tell us how much of the total variability in the data is explained by our model. Regression analysis tells you what predictors in a model are statistically significant and which are not. In simpler terms, if you give a regression model 50 features, which can find out which features are good predictors for the target variable and which aren't.

Regression analysis can give a confidence interval for each regression coefficient that it estimates. Not only can you estimate a single coefficient for each feature, but you can also get a range of coefficients with a level of confidence (e.g. 99% confidence) that the coefficient is in. The point is that there are a bunch of statistical techniques within regression analysis that allow you to answer many more questions. Regression Analysis is less of a black box and is easier to communicate. Two important factors that I always consider when choosing a model are how simple it and how interpretable it is. A simpler model means it's easier to communicate how the model itself works and how to interpret the results of a model. For example, it's likely that most business users will understand the sum of least squares (i.e. line of best fit) much faster than back propagation. This is important because businesses are interested in how the underlying logic in a model works — nothing is worse in a business than uncertainty — and a black box is a great synonym for that. Ultimately, it's important to understand how the numbers from a model are derived and how they can be interpreted.

Learning Regression Analysis will give us a better understanding of statistical inference overall. Regression analysis helps in learning building simple and multiple regression models, conducting residual analysis and applying transformations like Box-Cox, calculating confidence intervals for regression coefficients and residuals ,determining the statistical significance of models and regression coefficients through hypothesis testing ,evaluating models using R squared, MSPE, MAE, MAPE, PM,, identifying multi-collinearity with variance inflation factor (VIF) ,comparing different regression models using the partial F-test.

3.5) Teaching learning optimization technique

Optimization	Meta-heuristic Techniques
Decision Variables	gene, marks, positions, subjects
Solutions	Chromosomes, child , learner, parent, paricle, bee , population member,moth, flame
Set of Solutions	water body, swarm, flames, population, moths
Objective Function Value	Fitness, energy, nectar amount
Iteration	Cycles , generation

TLBO- Teaching Learning Based Optimization technique is the latest proposed optimization technique. We have taken TLB as meta-heuristic technique to learn. Because we have found that TLB is much easier to understand as well as it does not have complexity with respect to the tuning of the algorithmic parameters. Unlike other algorithms there are only two parameters over here. Most meta-heuristic techniques generate randomly a single solution or a set of solutions right. So, when we say solutions; it's nothing but the value of the decision variables.

So, if u have a problem with five decision variables then we have a vector of five values within the bounds of the problem. Once we generate the solution, the decision variables are sent to the optimization problem. And fitness function is evaluated , which is only communication between the meta-heurestic techniques and optimization problem. For every solution we will get a fitness function value. The fitness function is sent back to the algorithm. The algorithm sends the decision variable and the problem send back the fitness function. Based on the information; the fitness and the current set of variables which were sent to the optimization problem, the algorithm uses intelligent operator to come up with new set of decision variables which is again sent to the problem and the fitness function value is received from the problem. This communication goes on till we complete specified termination criteria.

So let us assume that we have three variable problem as X = [x_1 x_2 x_3]. Let x_1 , x_2 and x_3 be assigned 5, 2, 3 as integers respectively. Let us assume that our objective of optimization problem is to minimize this function: $f= x_1^2 - 8x_1x_2 + x_3$

Now if we calculate for X= [5 2 3], the value of function "f" comes out to be 52. That value is sent back to the meta-heuristic techniques. So, this is the only communication that is happening between the meta-heuristic technique and the optimization problem broadly if we see.

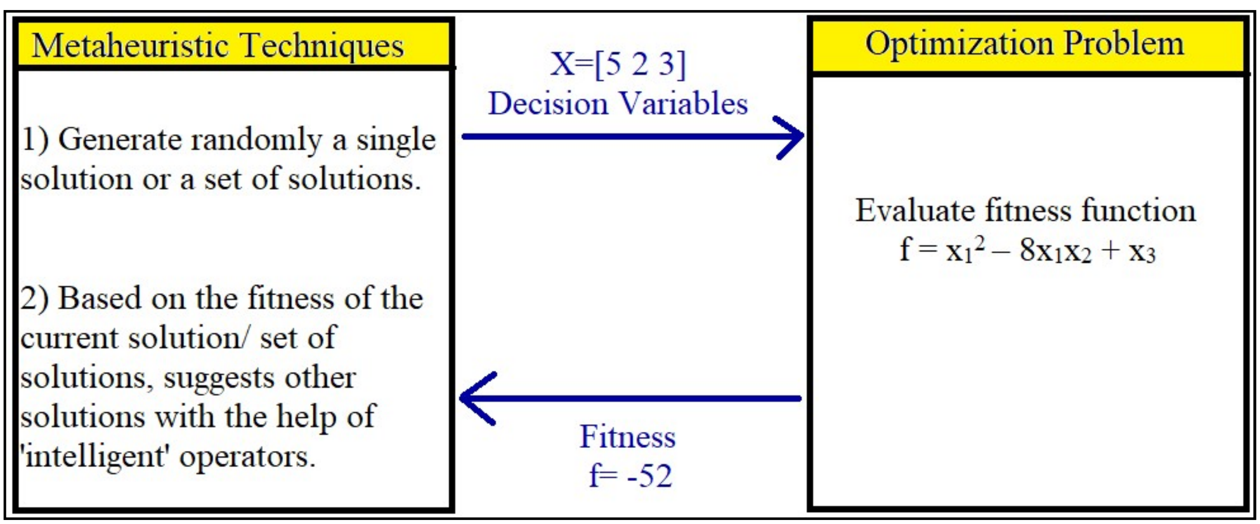

Fig 3.5 a) A schematic diagram of meta-heuristic technique

In order to understand how we can use TLBO we need to understand the nature as the technique is nature inspired. Nature is made to solve problems, if we look at the physical design of natural creatures like beak, fins, wings of birds etc they give us inspirations to solve many of the problems, they give idea of designing and many of our actual engineering design are actually based on nature's physical structures.

Then comes the behavior of nature, if we look at the ants, the birds etc, the way they behave are all social natural behavior, TLBO depends upon social natural behavior. That means every individual will learn and the one that has leant the maximum knowledge will become the teacher. The teacher will act as learner and keep on learning, and this process keep on revolving.

In TLBO, we have an objective function where we need to maximize or minimize the function as per requirement. Than search space or feasible solution is required, this is applicable to only problems where we have a pre idea about the solution. So here thus our approach is to find the best solution. Than we have optimization methods, where TLBO is fast while other traditional methods are not feasible as their running time is too high. So that's why we use TLBO. Design parameters are specified by design variables.

Need For TLBO

An efficient optimization algorithm called teaching–learning-based optimization (TLBO) is proposed in this article to solve continuous unconstrained and constrained optimization problems. The proposed method is based on the effect of the influence of a teacher on the output of learners in a class. The basic philosophy of the method is explained in detail. The algorithm is tested on 25 different unconstrained benchmark functions and 35 constrained benchmark functions with different characteristics. For the constrained benchmark functions, TLBO is tested with different constraint handling techniques such as superiority of feasible solutions, self-adaptive penalty, ϵ-constraint, stochastic ranking and ensemble of constraints. The performance of the TLBO algorithm is compared with that of other optimization algorithms and the results show the better performance of the proposed algorithm.

All other traditional methods are probabilistic and they require some common controlling parameters like size of population, no. of generation etc. Along with that, they also require some algorithmic parameters like when we talk about Genetic Algorithm they need mutation probability, selection operator etc. Similarly when we talk about particle swarm optimization, it requires information about inertia, weight etc.

Similarly in ABC algorithm it needs onlooker bees, employed bees, scout bees and limits. And the most difficult task is the proper tuning of all these algorithmic parameters, because it affects the performance of algorithm.

If the tuning is not proper than there is a chance of un-local solution outcome that may be trapped in the local optima. There could be also a chance of increase in computation.

This algorithm consists of two phases:

1) Teacher Phase

All the students learn from teacher and gain knowledge.

2) Learner Phase:

Students share knowledge among themselves by interacting with each other.

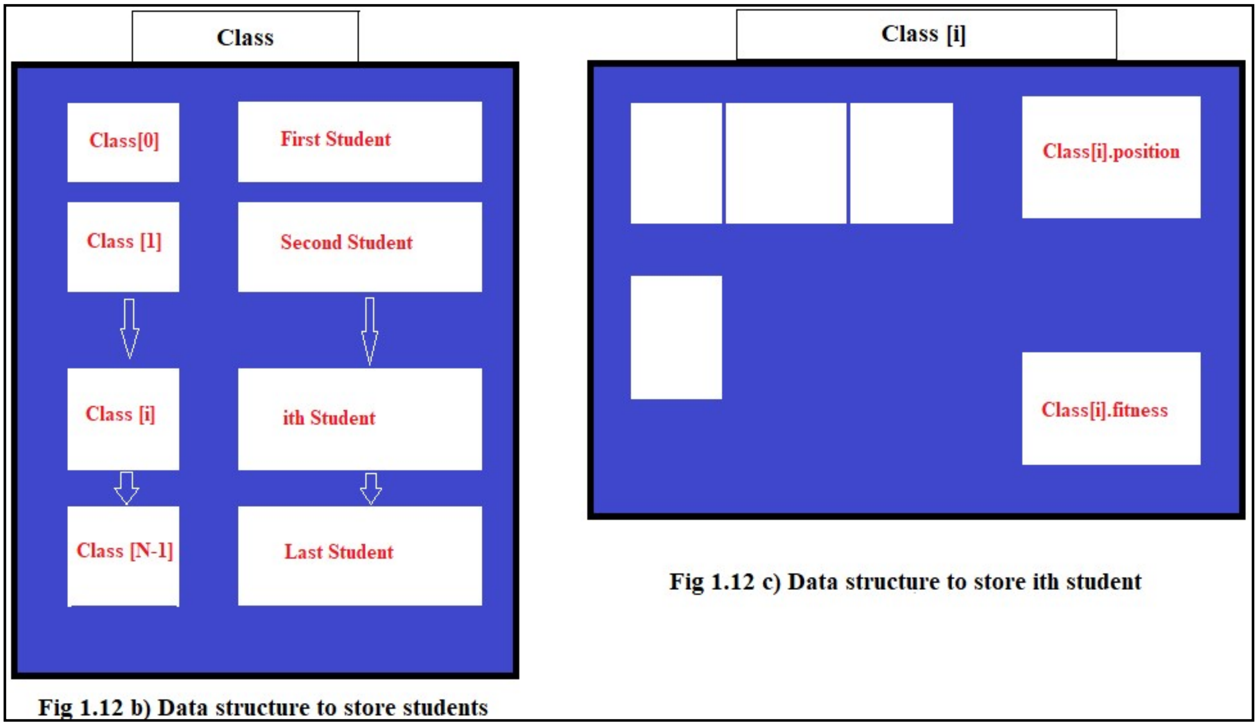

Fig 3.5 b) Data Structure

In a classroom, the teacher works hard to make the students educated with proper knowledge. Then learners interact with themselves to further modify and improve their gained knowledge. Then the students share the knowledge between themselves by interacting with each other.

In the past decades, meta-heuristic algorithms are widely applied in various research fields and practical scenarios, which are favored by researchers because of their simplicity, efficiency, low computational cost, and extraordinary performance. Different from exact algorithms, meta-heuristic algorithms are a type of optimization technology that seeks approximate optimal solutions of the problem under limited time and resource constraints. Nowadays, with the development of emerging technologies such as the internet and artificial intelligence, large-scale optimization tasks with features such as non-differentiable, non-differentiable, or discontinuities are increasing rapidly. This allows meta-heuristic algorithms to play an increasingly important role. In meta-heuristics, exploration and exploitation abilities are two crucial characteristics, which together affect the search performance of the algorithm.

Constrained and unconstrained optimization problems are generally associated with many difficulties such as multi-modality, dimensionality and differentiability. Traditional optimization techniques generally fail to solve such problems, especially with nonlinear objective functions. To overcome these difficulties, there is a need to develop more powerful optimization techniques and research is continuing to find effective optimization techniques. Some of the well-known population-based optimization techniques developed during the past three decades are: genetic algorithm (GA) (Holland 1975), artificial immune algorithm (AIA) (Farmer et al. 1986), ant colony optimization (ACO) (Dorigo 1992), particle swarm optimization (PSO) (Kennedy and Eberhart 1995), differential evolution (DE) (Storn and Price 1997), harmony search (HS) (Geem et al. 2001), bacteria foraging optimization (BFO) (Passino 2002), shuffled frog leaping (SFL) (Euusuff and Lansey 2003), artificial bee colony (ABC) (Karaboga 2005), biogeography-based optimization (BBO) (Simon 2008), gravitational search algorithm (GSA) (Rashedi et al. 2009) and grenade explosion method (GEM) (Ahrari and Atai 2010). These algorithms have been applied to many engineering optimization problems and have proved effective in solving specific kinds of problem.

Proper selection of the parameters is essential for the searching of the optimum solution by the above-mentioned optimization algorithms. A change in the algorithm parameters influences the effectiveness of the algorithm. In addition to the population size as a controlling parameter, the existing optimization algorithms have their specific controlling parameters. The most commonly used evolutionary optimization technique is GA. However, GA provides a near optimal solution for a complex problem with a large number of variables and constraints. This is mainly due to the difficulty in determining the optimum controlling parameters such as crossover rate and mutation rate. The same is the case with PSO, which uses inertia weight, and social and cognitive parameters. Similarly, ABC requires optimum controlling parameters of the number of bees (employed, scout and onlookers) and limit. HS requires harmony memory consideration rate, pitch adjusting rate and the number of improvisations. SFLA requires the number of memeplexes and iteration per memeplex. ACO requires exponent parameters, pheromone evaporation rate and reward factor. Sometimes, the difficulty in the selection of parameters increases with modifications and hybridization. Therefore, efforts must be continued to develop an optimization technique that is free from the algorithm-specific parameters, i.e. no algorithm parameters are required for the working of the algorithm. This aspect is considered in the present work. An optimization method, teaching–learning-based optimization (TLBO), is proposed in this article to obtain global solutions for continuous nonlinear functions with less computational effort. The TLBO method works on the philosophy of teaching and learning. The algorithm mimics the teaching–learning ability of the teacher and learners in a classroom. The teacher and learners are the two vital components of the algorithm. The algorithm describes two basic modes of the learning: (1) through teacher (known as the teacher phase) and (2) interacting with the other learners (known as the learner phase). The output in the TLBO algorithm is considered in terms of the results or grades of the learners, which depend on the quality of the teacher. A high-quality teacher is usually considered a highly learned person who trains learners so that they can achieve better results in terms of their marks or grades. Moreover, learners also learn through interaction among themselves, which also helps to improve their results.

TLBO is a population-based method. In this optimization algorithm, a group of learners, n, is considered as a population and different subjects offered to the learners are considered as different design variables, m, of the optimization problem. A learner's result is analogous to the ‘fitness’ value of the optimization problem. The best solution in the entire population is considered as the teacher. The design variables are actually the parameters involved in the objective function of the given optimization problem and the best solution is the best value of the objective function.

3.6) Design of experiment

The design of experiments (DOE, DOX, or experimental design) is the design of any task that aims to describe and explain the variation of information under conditions that are hypothesized to reflect the variation. The term is generally associated with experiments in which the design introduces conditions that directly affect the variation, but may also refer to the design of quasi-experiments, in which natural conditions that influence the variation are selected for observation.

In its simplest form, an experiment aims at predicting the outcome by introducing a change of the preconditions, which is represented by one or more independent variables, also referred to as "input variables" or "predictor variables." The change in one or more independent variables is generally hypothesized to result in a change in one or more dependent variables, also referred to as "output variables" or "response variables." The experimental design may also identify control variables that must be held constant to prevent external factors from affecting the results. Experimental design involves not only the selection of suitable independent, dependent, and control variables, but planning the delivery of the experiment under statistically optimal conditions given the constraints of available resources. There are multiple approaches for determining the set of design points (unique combinations of the settings of the independent variables) to be used in the experiment.

Main concerns in experimental design include the establishment of validity, reliability, and replicability. For example, these concerns can be partially addressed by carefully choosing the independent variable, reducing the risk of measurement error, and ensuring that the documentation of the method is sufficiently detailed. Related concerns include achieving appropriate levels of statistical power and sensitivity. A methodology for designing experiments was proposed by Ronald Fisher , in his innovative books: The Arrangement of Field Experiments (1926) and The Design of Experiments (1935). Much of his pioneering work dealt with agricultural applications of statistical methods. As a mundane example, he described how to test the lady testing tea hypothesis, that a certain lady could distinguish by flavor alone whether the milk or the tea was first placed in the cup. These methods have been broadly adapted in biological, psychological, and agricultural research.

Comparison

In some fields of study it is not possible to have independent measurements to a traceable metrology standard. Comparisons between treatments are much more valuable and are usually preferable, and often compared against a scientific control or traditional treatment that acts as baseline.

Randomization

Random assignment is the process of assigning individuals at random to groups or to different groups in an experiment, so that each individual of the population has the same chance of becoming a participant in the study. The random assignment of individuals to groups (or conditions within a group) distinguishes a rigorous, "true" experiment from an observational study or "quasi-experiment". There is an extensive body of mathematical theory that explores the consequences of making the allocation of units to treatments by means of some random mechanism (such as tables of random numbers, or the use of randomization devices such as playing cards or dice). Assigning units to treatments at random tends to mitigate confounding, which makes effects due to factors other than the treatment to appear to result from the treatment.

The risks associated with random allocation (such as having a serious imbalance in a key characteristic between a treatment group and a control group) are calculable and hence can be managed down to an acceptable level by using enough experimental units. However, if the population is divided into several subpopulations that somehow differ, and the research requires each subpopulation to be equal in size, stratified sampling can be used. In that way, the units in each subpopulation are randomized, but not the whole sample. The results of an experiment can be generalized reliably from the experimental units to a larger statistical population of units only if the experimental units are a random sample from the larger population; the probable error of such an extrapolation depends on the sample size, among other things.

Statistical replication

Measurements are usually subject to variation and measurement uncertainty; thus they are repeated and full experiments are replicated to help identify the sources of variation, to better estimate the true effects of treatments, to further strengthen the experiment's reliability and validity, and to add to the existing knowledge of the topic. However, certain conditions must be met before the replication of the experiment is commenced: the original research question has been published in a peer-reviewed journal or widely cited, the researcher is independent of the original experiment, the researcher must first try to replicate the original findings using the original data, and the write-up should state that the study conducted is a replication study that tried to follow the original study as strictly as possible.

Blocking

Blocking is the non-random arrangement of experimental units into groups (blocks) consisting of units that are similar to one another. Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the estimation of the source of variation under study.

Orthogonality concerns the forms of comparison (contrasts) that can be legitimately and efficiently carried out. Contrasts can be represented by vectors and sets of orthogonal contrasts are uncorrelated and independently distributed if the data are normal. Because of this independence, each orthogonal treatment provides different information to the others. If there are T treatments and T – 1 orthogonal contrast, all the information that can be captured from the experiment is obtainable from the set of contrasts.

Factorial experiments

Use of factorial experiments instead of the one-factor-at-a-time method. These are efficient at evaluating the effects and possible interactions of several factors (independent variables). Analysis of experiment design is built on the foundation of the analysis of variance, a collection of models that partition the observed variance into components, according to what factors the experiment must estimate or test.

Chapter - 4

Data Analysis & Discussions

4.1) Design of Experiment

Table 4.1 Design of Experiment

Sl. No.	Laser power p (W)	Scanning speed v (mm/s)	Gas pressure g (bar)	Frequency f (Hz)
1	440	3	10	475
2	405	3	12.8	475
3	430	2	8	650
4	380	2	12	300
5	430	2	8	300
6	430	2	12	650
7	405	3	10	720
8	430	4	12	300
9	380	2	8	300
10	380	2	12	650
11	405	1.6	10	475
12	380	4	8	300
13	380	4	12	300
14	370	3	10	475
15	380	4	8	650
16	405	3	10	475
17	405	3	10	475
18	405	3	7.2	475
19	405	3	10	230
20	405	3	10	475

21	405	3	10	475
22	430	4	8	650
23	380	2	8	650
24	405	4.4	10	475
25	405	3	10	475
26	380	4	12	650
27	430	4	12	650
28	430	2	12	300
29	430	4	8	300
30	405	3	10	475

The design of experiment is nothing but a blue print before the actual setup of experiment is initiated. The frequency, laser power, scanning speed, and gas pressure were used as factors to analyze how they influence the kerf widths, glass formations, and economic barriers. The table 4.1 above shows the prime design of experiments we've chosen to analyze.

Design of experiment is needed to minimize failure cost during any experimental procedure. Moreover, it is important to select the right combination of parameters to work on it in order to exclude the unnecessary working set of operations. This is very important in industries to minimize the time consumed for work and to reduce the handling of load of human resources in order to maintain sequential order of each and every operation.

4.2) Analysis of variance for top kerf width

Table 4.2 a) ANOVA table for top kerf width

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	4644.54	331.753	28.83	0.000
p	1	342.34	342.341	29.75	0.000
v	1	96.99	96.986	8.43	0.011
g	1	203.43	203.432	17.68	0.001
f	1	1.80	1.800	0.16	0.698
p^2	1	406.86	406.858	35.36	0.000
v^2	1	120.85	120.854	10.50	0.005
g^2	1	147.38	147.379	12.81	0.003
f^2	1	1.20	1.196	0.10	0.752
p×v	1	42.47	42.468	3.69	0.074
p×g	1	67.79	67.786	5.89	0.028
p×f	1	6.04	6.041	0.52	0.480
v×g	1	61.55	61.548	5.35	0.035
v×f	1	1.55	1.552	0.13	0.719
g×f	1	1.14	1.136	0.10	0.758
Error	15	172.60	11.507		
Lack-of-Fit	10	165.47	16.547	11.61	0.007
Pure Error	5	7.13	1.426		
Total	29	4817.14			

Table 4.2 b) Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.39215	96.42%	93.07%	82.15%

The R^2 value is 96.42%, which implies that the model is acceptable. The ANOVA table helps us to know the most significant parameters that influence the experiments. The p- value (<.0001) signifies the important process parameters and combination of process parameters, which mostly affects the response. The ANOVA table 4.2 a) implies that laser power is always significant as a process parameter for response to top kerf width. Scanning speed, gas pressure and frequency also affect the top kerf width significantly but not to the extent as what the laser power does.

The ANOVA provides us the F-values and p-values which gives us an idea about the series of significant parameters during the trials and experiments. ANOVA is used when the no. of samples are more than two. The t-test is done when there are only two samples. Now we need to understand the basic difference between the population and sample.

The regression equation for top kerf width is as follows:

$$\textbf{Kerf Width}=1551-(8.08\times p)-(46.7\times v)+(38.12\times g)+(0.0358\times f)+(0.01075\times p^2)+(3.66\times v^2)-(1.011\times g^2)+(0.000012\times f^2)+(0.0652\times p\times v)-(0.0412\times p\times g)-(0.000140\times p\times f)-(0.981\times v\times g)-(0.00178\times v\times f)-(0.00076\times g\times f)$$

Based on the parametric data available with us, we have performed kerf width optimization by Response Surface Methodology and we have found that the minimized kerf width that resulted is 54.7283 µm. The kerf width that has been obtained is against the following parametric values as below:

Table 4.2 c) Parametric values for optimum kerf width obtained

Power (W)	Scanning Speed (mm/sec)	Gas Pressure (bar)	Frequency (Hz)
391.574	4.4	12.8	720

After obtaining the results we have furnished the surface plot and contour plots for the kerf width to understand the variation of kerf width with respect to the parametric values. The following contour plots obtained for kerf width response with respect to different parametric sets as below:

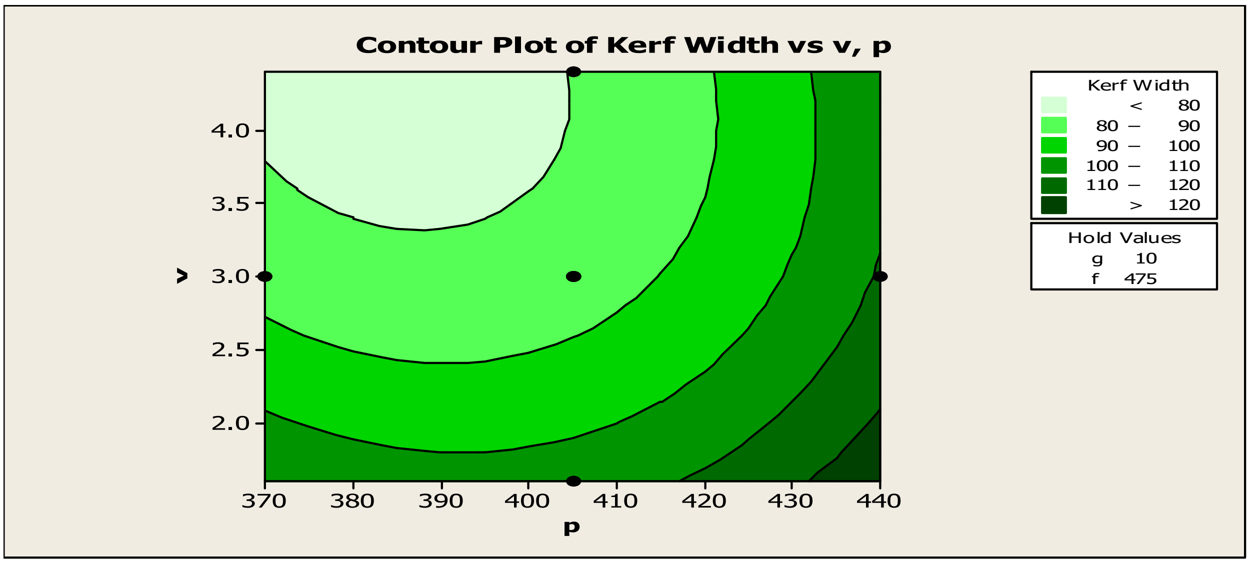

Fig 4.2 a) Contour plot of kerf width vs v, p with g=10 bar & f=475 Hz as constants

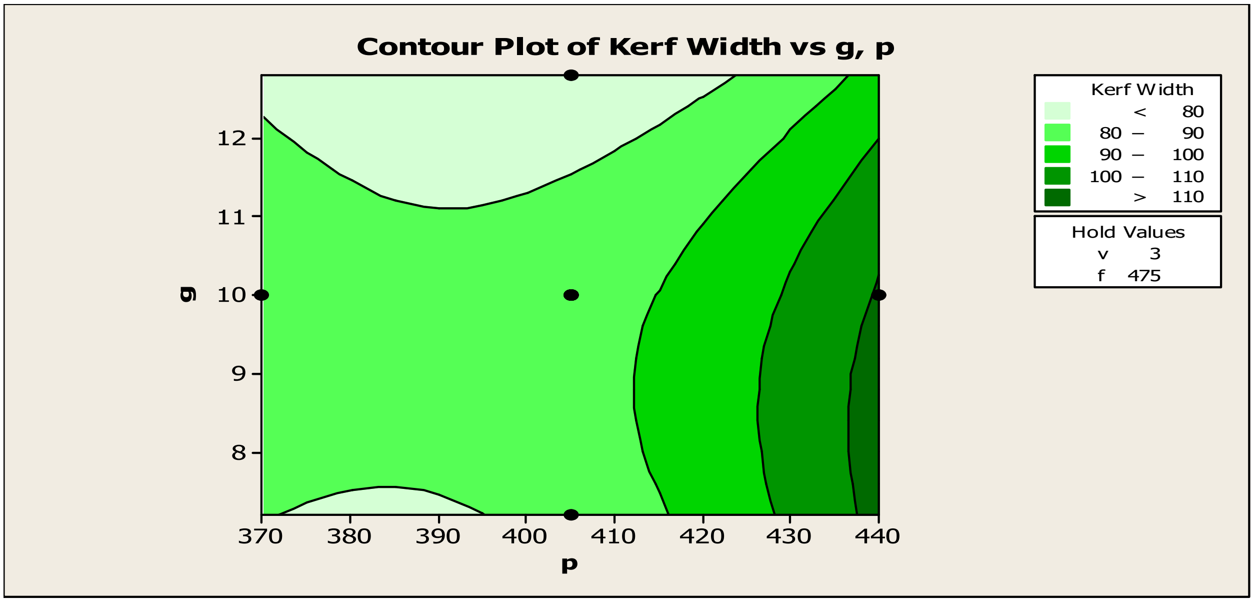

Fig 4.2 b) Contour plot of kerf width vs g, p with v= 3mm/sec & f=475 Hz as constants

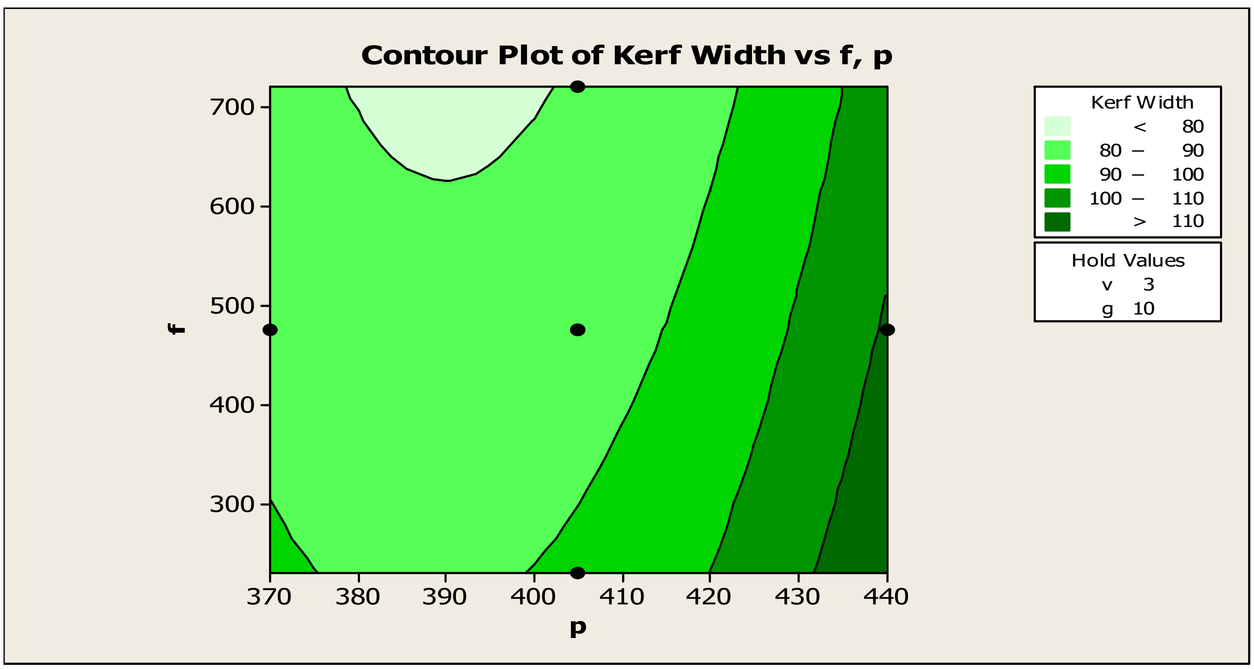

Fig 4.2 c) Contour plot of kerf width vs f, p with v= 3mm/sec & f=475 Hz as constants

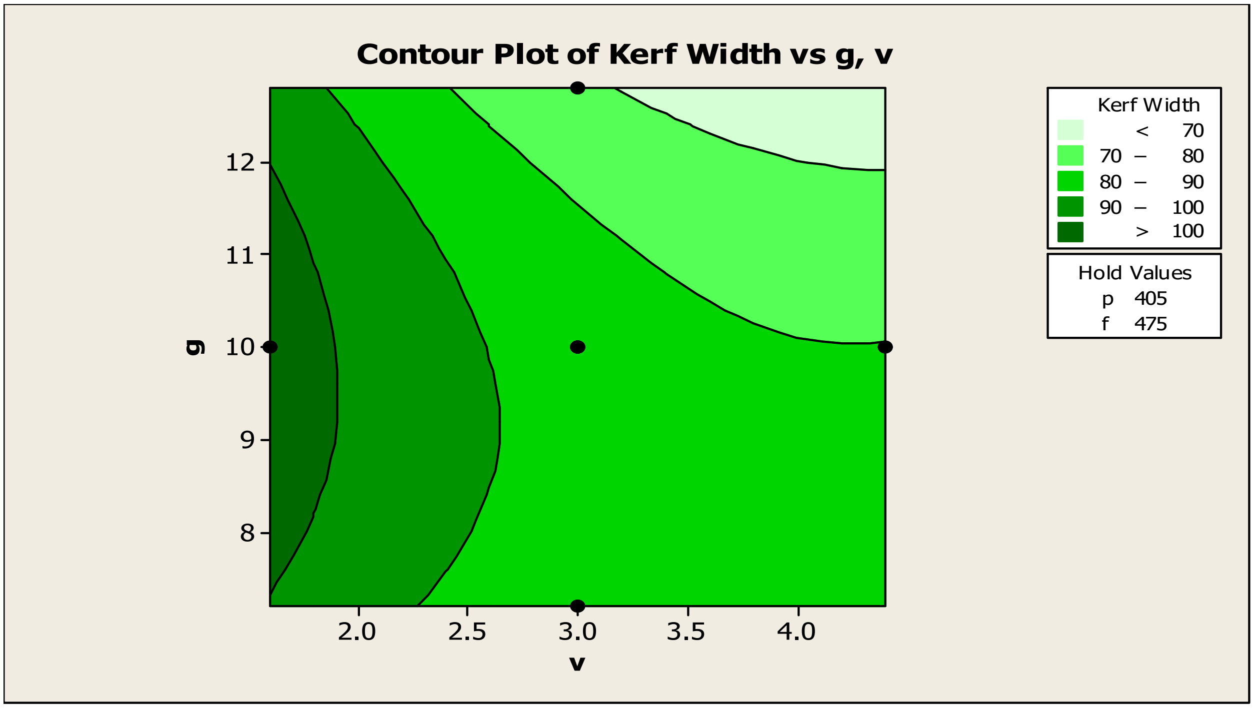

Fig 4.2 d) Contour plot of kerf width vs g, v with p= 405 watt & f=475 Hz as constants

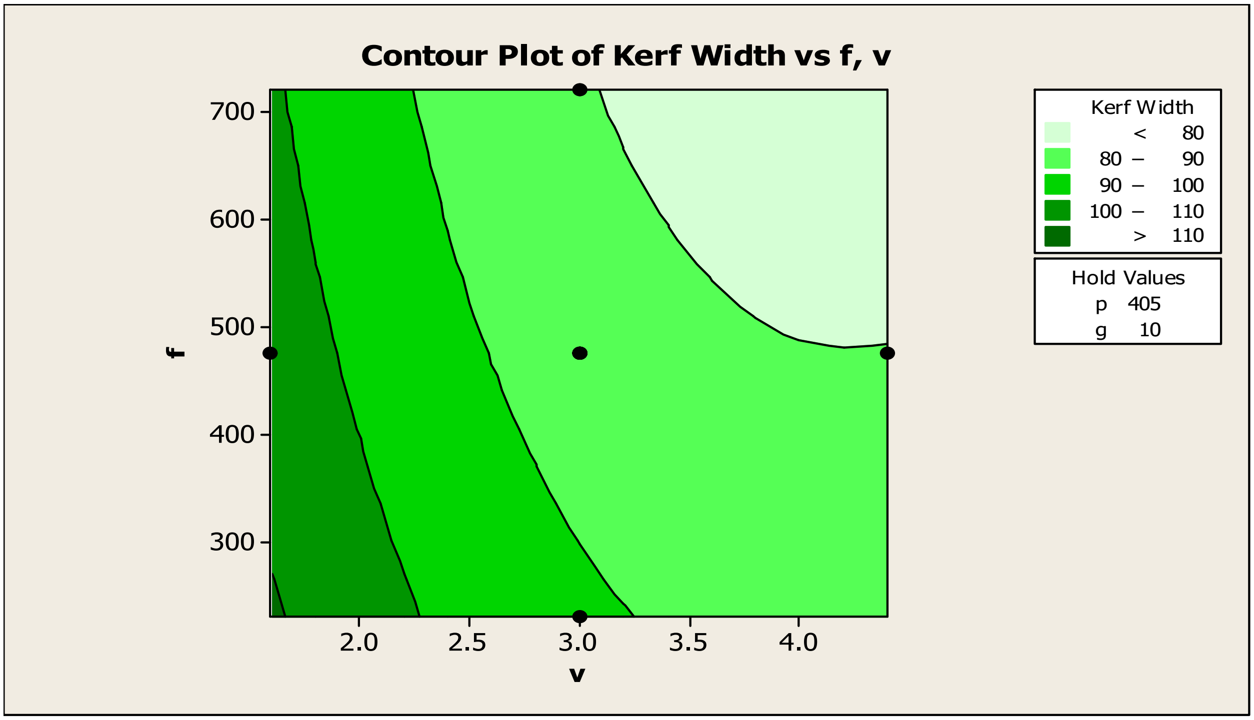

Fig 4.2 e) Contour plot of kerf width vs f, v with p= 405 watt & g=10 bar as constants

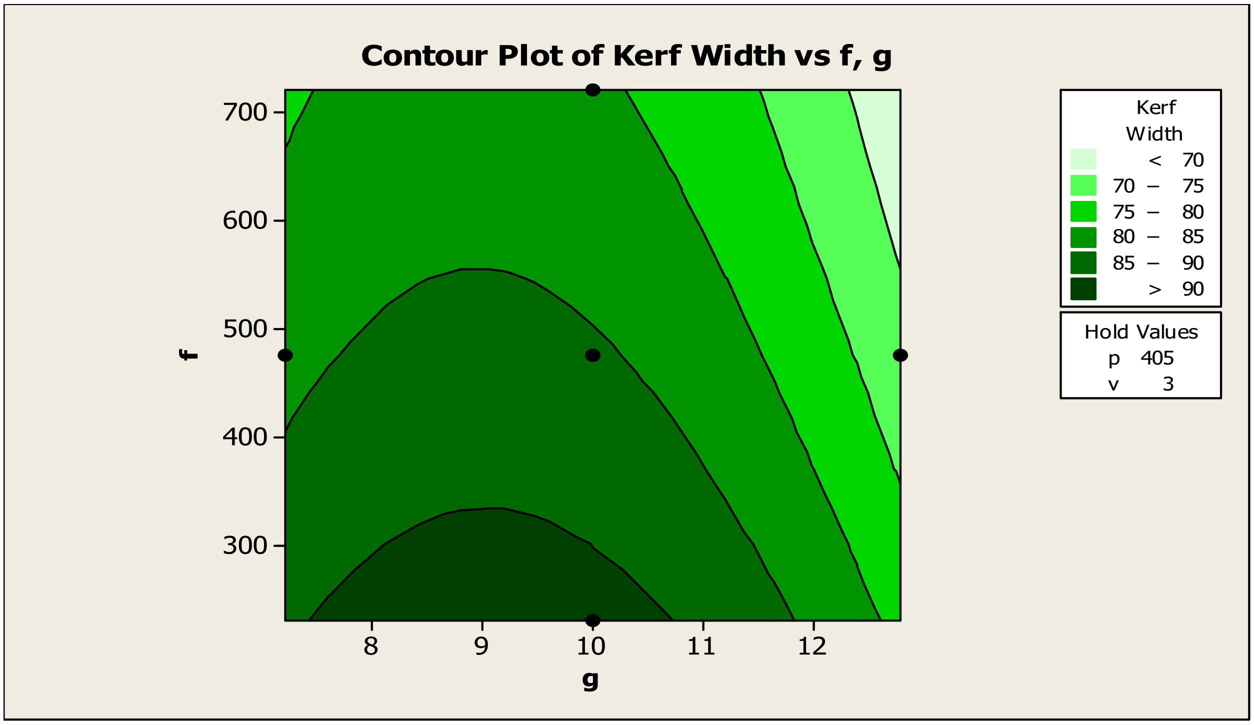

Fig 4.2 f) Contour plot of kerf width vs f, g with p= 405 watt & v=3 mm/sec as constants

The above results were compared with Teacher Learning Based Optimization technique, by establishing coding with the logic of optimizing the kerf width, and we have found that the optimized result obtained from RSM methodology and the optimized result obtained from TLBO, are quite identical to each other. The optimized value of kerf width found from TLBO technique is 53.52 µm, with respect to the parameters p=390.01 watt, v=4.4 mm/sec, g=10 bar, f=720 Hz. Hence we can establish that a better output can be obtained with minimized material wastage, using the optimum set of parameters.

Table 4.2 d) The first ten iterations out of hundred iterations performed altogether

Iteration number	Power (Watt)	Scanning Speed (mm/s)	Gas Pressure (Bar)	Frequency (Hz)	Kerf width (µm)
1	393.3495	4.4	12.8	438.6898	65.9989
2	376.4707	4.4	12.8	697.0553	55.8523
3	393.3129	4.1869	12.8	695.0385	54.5803
4	388.6841	4.2667	12.8	720	53.5832
5	390.0118	4.4	12.8	720	53.5202
6	392.1903	4.4	12.8	720	53.5202
7	391.3157	4.4	12.8	720	53.5202
8	391.6874	4.4	12.8	720	53.5202
9	391.6874	4.4	12.8	720	53.5202
10	391.6874	4.4	12.8	720	53.5202

It is found that at 53.52µm, the kerf width is saturated in further iterations, hence we can conclude that the optimized kerf width is obtained.

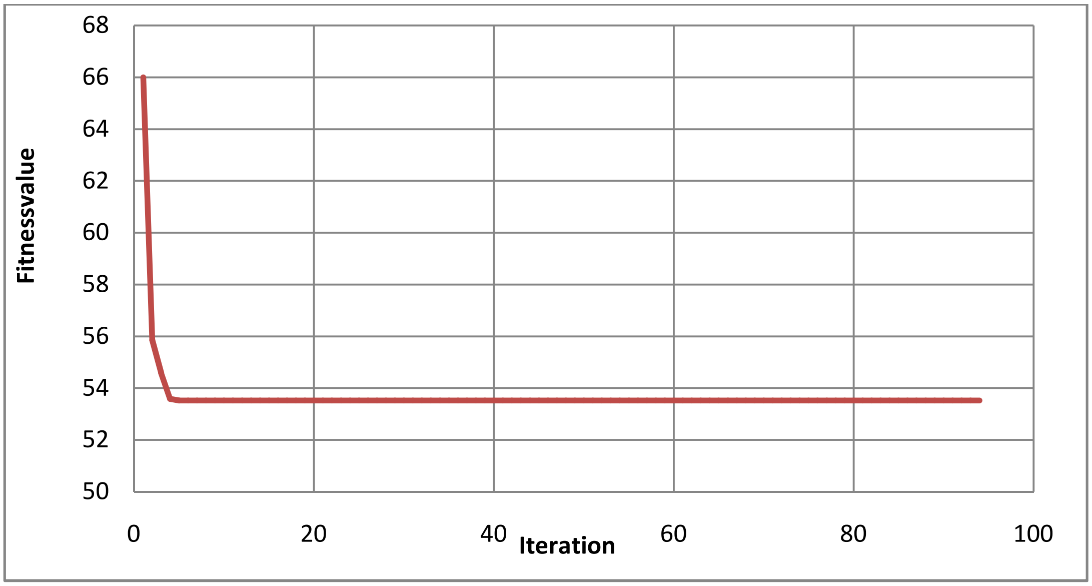

Fig 4.2 g) Fitness value vs Iterations curve

In the above circumstances we have found that our fitness value has reached saturation at 53.52µm, despite a repetitive iterations upto 100 times.

4.3) ANOVA analysis for expenditure during laser cutting operation

We have calculated the expenditure by taking into consideration of the following:

1) Machine efficiency

2) Machining time per job

3) Energy spent per job

4) Electric bill per unit

5) Electric bill of machining per job

6) Machinist cost per hour

7) Job length (1000 mm)

8) Machining Time

9) Energy Cost

10) Labor Cost

11) Gas Flow per hour

12) Gas Cost

Table 4.3 a) ANOVA table for top kerf width

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	14	4055.99	289.714	25.18	0.000
P	1	342.34	342.341	29.75	0.000
SS	1	92.88	92.876	8.07	0.012
GP	1	214.25	214.246	18.62	0.001
f	1	1.80	1.800	0.16	0.698
P*P	1	406.86	406.858	35.36	0.000
SS*SS	1	120.85	120.854	10.50	0.005
GP*GP	1	147.38	147.379	12.81	0.003
f*f	1	1.20	1.196	0.10	0.752
P*SS	1	42.47	42.468	3.69	0.074
P*GP	1	67.79	67.786	5.89	0.028
P*f	1	6.04	6.041	0.52	0.480
SS*GP	1	61.55	61.548	5.35	0.035
SS*f	1	1.55	1.552	0.13	0.719
GP*f	1	1.14	1.136	0.10	0.758
Error	15	172.60	11.507		
Lack-of-Fit	10	165.47	16.547	11.61	0.007
Pure Error	5	7.13	1.426		
Total	29	4228.59			

Table 4.3 b) Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.39215	95.92%	92.11%	79.66%

The R^2 value is 95.92%, which implies that the model is acceptable. The ANOVA table helps us to know the most significant parameters that influence the experiments.

The p- value (<.0001) signifies the important process parameters and combination of process parameters, which mostly affects the response. The ANOVA table 4.3 a) implies that laser power and gas pressure is always significant as a process parameter for response to expenditure.

The regression equation for top kerf width is as follows:

$$\mathbf{Cost} = 1551 - (8.08\times p) - (45.7\times v) + (39.12\times g) + (0.0358\times f) + (0.01075\times p^2) + (3.66\times v^2) - (1.011\times g^2) + (0.000012\times f^2) + (0.0652\times p\times v) - (0.0412\times p\times g) - (0.000140\times p\times f) - (0.981\times v\times g) - (0.00178\times v\times f) - (0.00076\times g\times f)$$

Based on the parametric data available with us, we have initiated a operating cost optimization by Response Surface Methodology and we have found that the minimized operating cost that resulted is Rs. 71.72. The cost that has been obtained is against the following parametric values as below:

Table 4.3 c) Parametric values for optimum cost obtained

Power (W)	Scanning Speed (mm/sec)	Gas Pressure (bar)	Frequency (Hz)
391.21	4.4	12.8	720

After obtaining results we have presented the surface plot and contour plots for the cost to understand the variation of cost with respect to the parametric values. The following contour plots obtained for cost response with respect to different parametric sets are presented below:

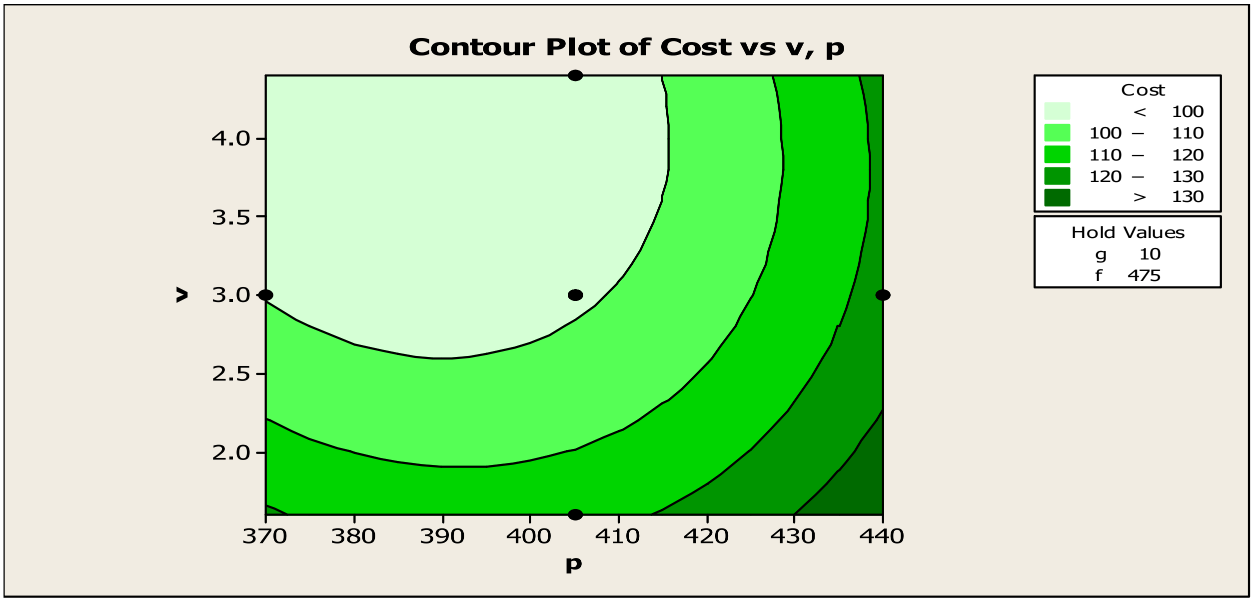

Fig 4.3 a) Contour plot of cost vs v, p with g=10 bar & f=475 Hz as constants

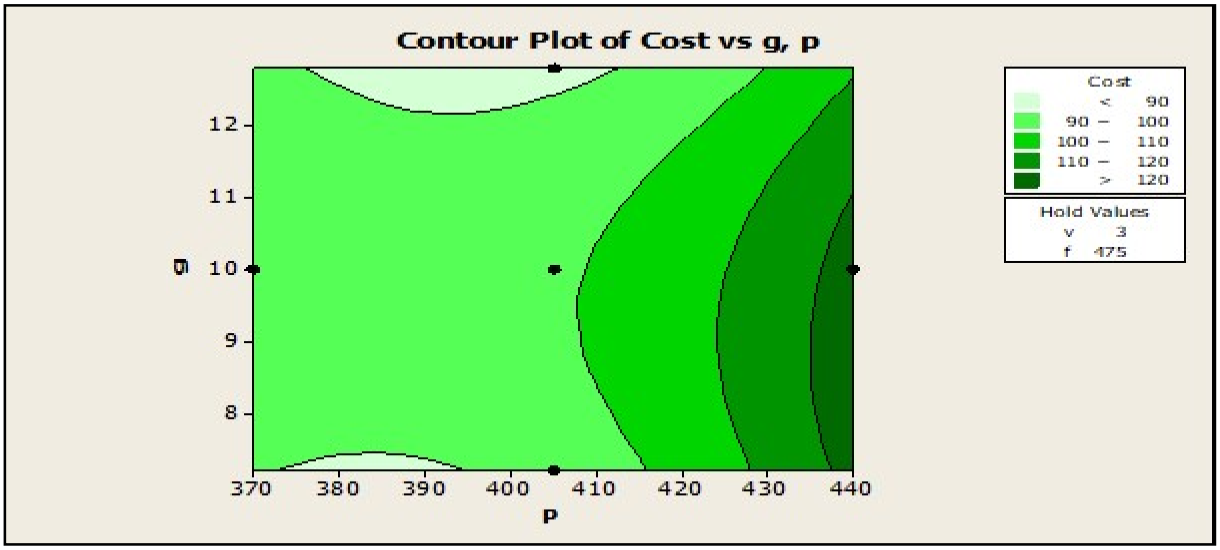

Fig 4.3 b) Contour plot of cost vs g, p with v=3mm/sec & f=475 Hz

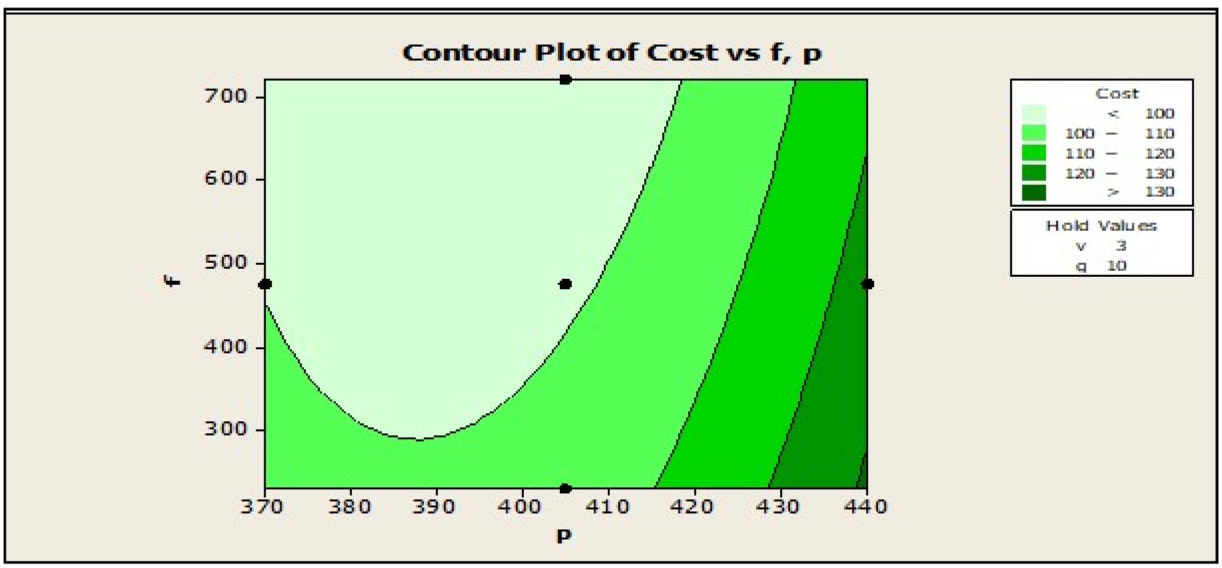

Fig 4.3 c) Contour plot of cost vs g, p with v= 3mm/sec & f=475 Hz as constants

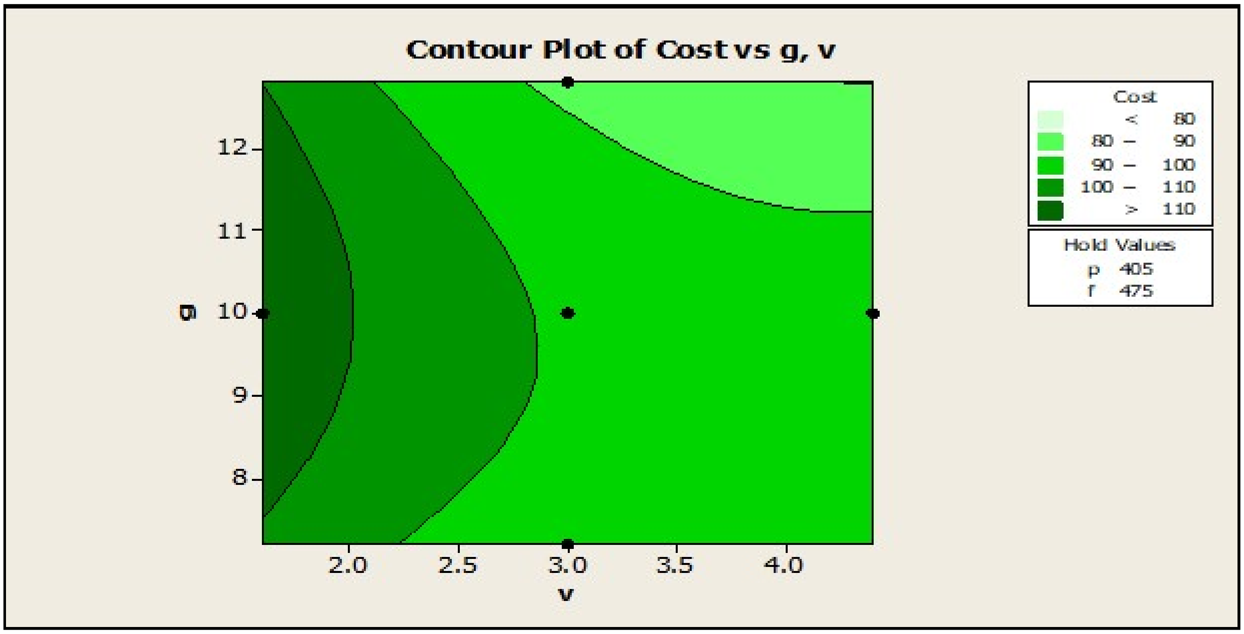

Fig 4.3 d) Contour plot of cost vs g, v with p=405 watt & f =475 Hz

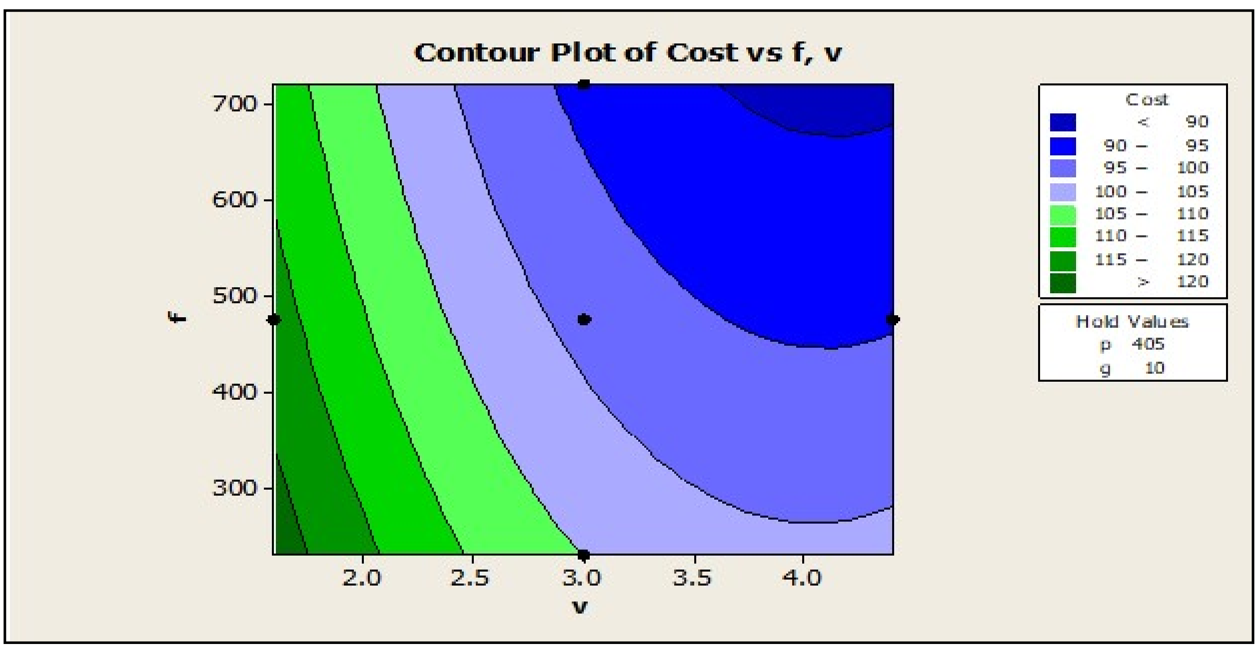

Fig 4.3 e) Contour plot of cost vs f, v with p= 405 watt & g=10 bar as constants

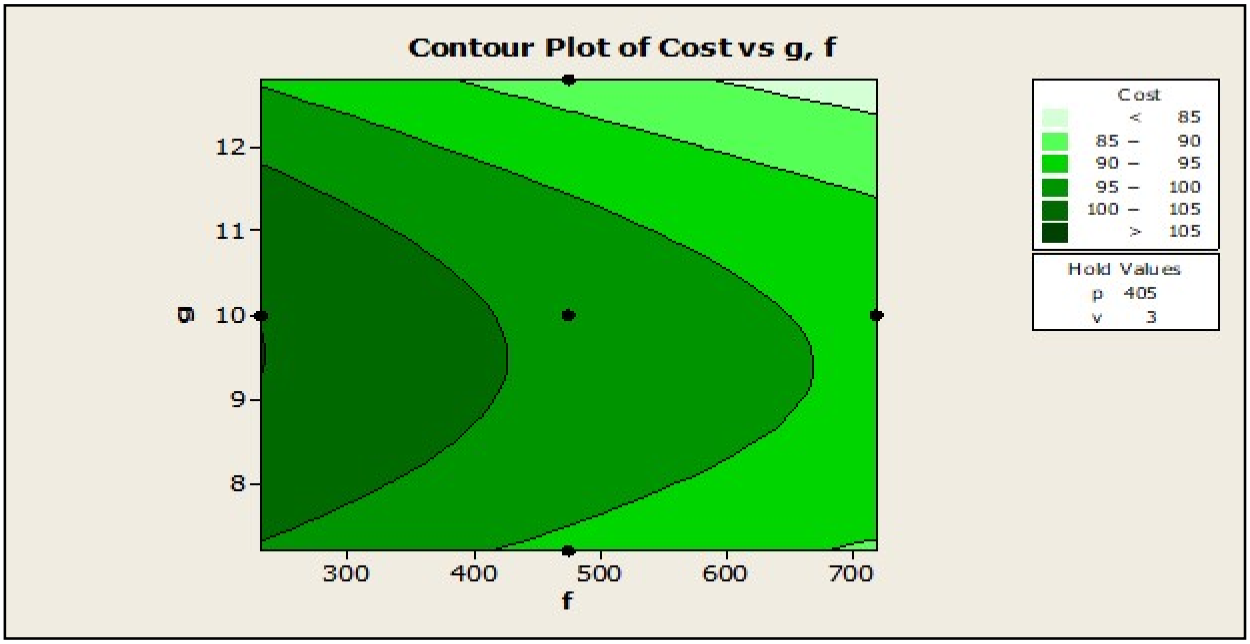

Fig 4.3 f) Contour plot of cost vs f, g with p= 405 watt & v=3 mm/sec as constants

The above results were compared with Teacher Learning Based Optimization technique, by coding in MATLAB with the logic of optimizing the cost, and we have found that the optimized result obtained from RSM methodology and the optimized result obtained from TLBO, are quite identical to each other. The optimized value of cost found from TLBO technique is 70.72 rupees, with respect to the parameters p=391.71 watt, v=4.4 mm/sec, g=12.8 bar, f=720 Hz. Hence we can establish that a cost effective cutting can be obtained with the set of these parameters.

Table 4.3 d) The first ten iterations out of hundred iterations performed altogether

Iteration number	Power (Watt)	Scanning Speed (mm/s)	Gas Pressure (Bar)	Frequency (Hz)	Cost (Rs)
1	377.1173	4.4	12.8	720	73.00
2	399.0916	4.4	12.8	720	71.30
3	387.4771	4.4	12.8	720	70.91
4	391.1514	4.4	12.8	720	70.72
5	391.8914	4.4	12.8	720	70.72
6	391.7082	4.4	12.8	720	70.72
7	391.7082	4.4	12.8	720	70.72
8	391.7082	4.4	12.8	720	70.72
9	391.7082	4.4	12.8	720	70.72
10	391.6849	4.4	12.8	720	70.72

It is found that at 70.72 rupees, the cost is saturated post further iterations, hence we can conclude that the optimized cost is obtained.

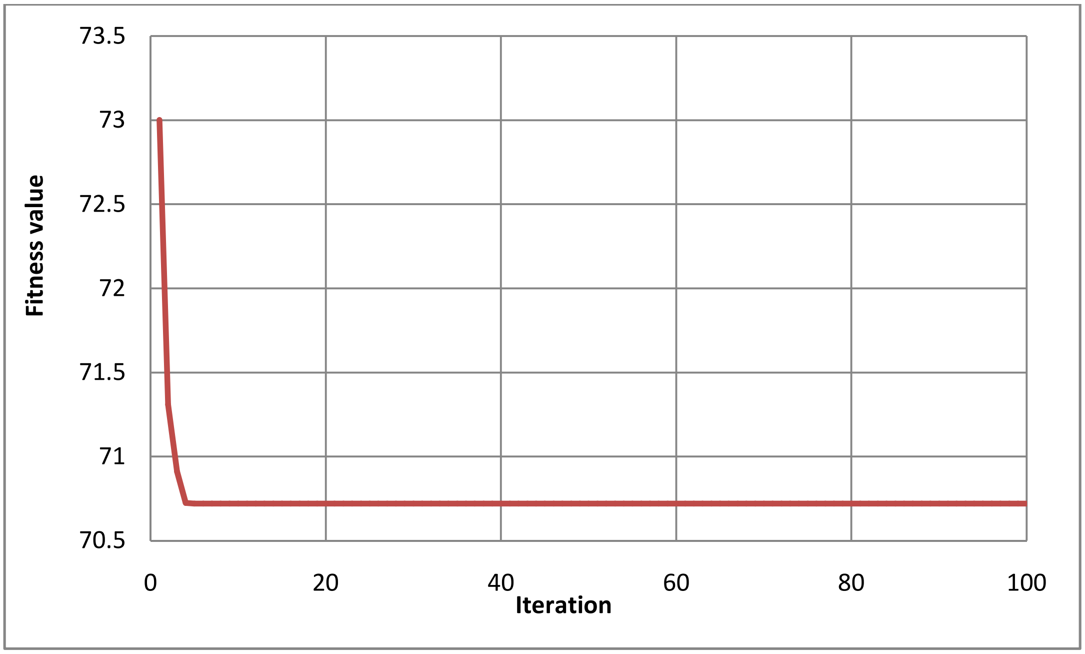

Fig 4.3 g) Fitness value vs Iterations curve

In the above circumstances we have found that our fitness value has reached saturation point at Rs.70.72, despite repetitive iterations upto 100 times.

4.4) Discussions

We have found that Top kerf width on the surface of the ceramic tile increases with increase in laser power and reduces with increasing scanning speed & keeping laser power between 370 W to 403 W at constant gas pressure of 10 bar and frequency of 475 Hz.

Top kerf width can be kept below 80 μm, with laser power range of 374 W to 395 W, and gas pressure below 4 bar, while keeping constant scanning speed of 3mm/sec and frequency of 475 Hz. Also at same scenario, the top kerf width can be reduced working at laser power between 370 W to 420 W and gas pressure of 12.8 bar and above.

With scanning speed kept at 3mm/sec and gas pressure at 10 bar, the minimum top kerf width can be achieved by keeping laser power between 380W to 400 W and frequency between 620 Hz to 720 Hz. A minimum kerf width can be achieved by working in the scanning speed range of 3.2 mm/sec to 5 mm/sec and a gas pressure range of 11.8 bar to 13 bar , by maintain constant laser power at 405 W and frequency of 720 Hz. At a frequency range of 475 Hz to 700 Hz and scanning speed range of 3.2mm/sec to 5 mm/sec, and keeping constant laser power of 405 W and gas pressure 10 bar, we can minimize kerf width over the top surface of the work piece. At the frequency range of 550 Hz to 720 Hz and gas pressure range of 12.5 bar to 13 bar, and keeping constant laser power and scanning speed at 405 W and 3mm/sec respectively, we can achieve a minimized top kerf width. The minimum cost can be achieved by keeping scanning speed range in between 3mm/sec to 5mm/sec and laser power in between 370 W to 415 W, by keeping gas pressure at 10 bar and frequency at 475 Hz. By keeping scanning speed at 3mm/sec and frequency 475 Hz, the cost decreases as gas pressure and laser power is increased. By maintaining scanning speed at 3 mm/sec and gas pressure at 10 bar, the cost decreases as frequency is increased and laser power is kept in between 370 W to 410 W. And the cost increases as we increase the laser power and keep the frequency is kept low. It is not recommended to work at the scenario where the laser power is 405 W and frequency is kept at 475 Hz, with the intention of minimizing cost. In this scenario, we it will not be an economical operation. Because of laser power of 405 W and gas pressure 10 bar, the cost decreases as we keep on increasing frequency and scanning speed. Due to high frequency and high gas pressure, the cost would be minimum with holding laser power at 405 W and scanning speed 3mm/sec. In this scenario there are chances of high expenditure due to this circumstance of holding such parameters.

Chapter - 5

General Conclusion and Future Scope of the Research

5.1 General Conclusion

In the present research work, a data analysis has been carried out with the help of response surface methodology and teaching learning based optimization technique. Based on the limitations and availability of time the following conclusions can be framed as below:

i. Parametric variation and its effects on kerf width and operating cost has been studied in the present work.
ii. Optimization of the kerf width and operating cost has been attempted to find the optimum operating condition. While analyzing the results, it is observed that the trends of variation of kerf width and operating cost are very similar with respect to the changes in operating parameters. Hence, multi-objective optimization is synonymous with single objective optimization in the present case.
iii. Within the range of parameters considered in the present study, minimum kerf width is obtained at laser power 391.574 W, scanning speed 4.4 mm/sec, gas pressure 12.8 bar and frequency 720 Hz with RSM and with TLBO.
iv. Within the range of parameters considered in the present study, minimum operating cost is obtained at laser power 391.21W, scanning speed 4.4 mm/sec, gas pressure 12.8 bar and frequency 720 Hz with RSM and with TLBO.

5.2 Future Scope

The future scope of this research and data analysis of the work includes the following:

The minimized kerf width of the top surface will help us to obtain overall minimized taper angle. This will further help the researchers to reduce the burden of dealing with the bottom kerf width. Moreover, researchers can focus only one top kerf width to achieve the goal for optimizing the taper angle.

The heat affected zone is another domain of study that can be taken for reference from this study of ours. Other type of lasers like femtosecond and picosecond lasers can be used to analyze the effect of the parameters during the operation.

Surface roughness can be studied in order to maintain the smoothness of the work piece during the operation, for quality output.

In industrial sector, maximum output with minimum expenditure is always desirable for competitive edge of the product, hence, our research work focuses on that area to minimize the cost during fiber laser cutting for an work piece length of 1000 mm. The researchers can further work on the management of release of gas pressure during the operation, which directly influences the expenditure. The other types of lasers such as femtosecond and picoseconds lasers can be used to analyze the impact of gas pressure and scanning speed along with its frequency variation and laser power.

Reference

[1] Paramasivan Kalvettukaran , Sandip Das, Sundar Marimuthu ,Dipten Misra(2020). Selection of process parameters of AISI 304 for laser processing of materials. Int. J. Computational Materials Science and Surface Engineering, Vol. 9, No. 1, 2020.

[2] Arif M. Varsi, Abdul Hafiz Shaikh (2018).Developing an algorithm for predicting depth as well as number of passes during CO2 laser machining on thermoplastic material. Journal of Laser Application, 30, 042007 (2018). https://doi.org/10.2351/1.5048055

[3]I Esmail , H. Yazdani Sarvestani, J Gholipur, B Ashrafi(2021).Engineered net shaping of alumina ceramics using picosecond laser. Optics & Laser Technology 135(2021) 106669. https://doi.org/10.1016/j.optlastec.2020.1066699

[4] Elyas Haddadi , Mahmoud Moradi, Ayub Karimzad Ghavidel, Ali Karimzad Ghavidel, Saleh Meiabadi(2021). Experimental and parametric evaluation of cut quality characteristics in CO2 laser cutting of polystyrene. Optik - International Journal for Light and Electron 184 (2019) 103–114.
https://doi.org/10.1016/j.ijleo.2019.03.040

[5] Mahmoud Moradi, Mojtaba Karami Moghadam, Mahmoud Shamsborhan, Zeinab Malekshahi Beiranvand, Alireza Rasouli, Mahdi Vahdati, Arash Bakhtiari, Mahdi Bodaghi (2021). Simulation, statistical modeling and optimization of CO_2 Laser cutting process of polycarbonate sheets. Optik - International Journal for Light and Electron Optics 225 (2021) 164932.
https://doi.org/10.1016/j.ijleo.2020.164932

[6] Girish Dutt Gautam , Arun Kumar Pandey (2018). Teaching learning algorithm based optimization of kerf deviations in pulsed Nd:YAG laser cutting of Kevlar-29 composite laminates. Infrared Physics & Technology 89 (2018) 203–217. https://doi.org/10.1016/j.infrared.2017.12.017

[7] Naresh , Pankaj Khatak (2021). Laser Cutting Technique: A literature Review, Materials Today: Proceedings.
https://doi.org/10.1016/j.matpr.2021.08.250

[8] T. Muangpool and S. Pullteap (2017). Reviews on laser cutting technology for industrial applications. PROCEEDINGS OF SPIE .
https://doi.org/10.1117/12.2300955

[9] John D. Kechagias, Konstantinos Ninikas, Panagiotis Stavropoulos, Konstantinos Salonitis (2021). A Generalised Approach on Kerf Geometry Prediction during CO2 Laser cut of PMMA Thin Plates using Neural Networks. Lasers in Manufacturing and Materials Processing (2021) 8:372–393.
https://doi.org/10.1007/s40516-021-00152-4

[10] Ray Tahir Mushtaq , Yanen Wang , Mudassar Rehman, Aqib Mashood Khan and Mozammel Mia (2020). State-Of-The-Art and Trends in CO2 Laser Cutting of Polymeric Materials—A Review Materials 2020, 13, 3839.
https://doi.org/10.3390/ma13173839

[11] Suresh. R, Sohit Reddy. K, Karthik Shapur (2018). Abrasive Jet Machining for Micro-hole Drilling on Glass and GFRP Composites. Materials Today: Proceedings 5 (2018) 5757–5761, © 2017 Elsevier Ltd. All rights reserved. Selection and/or Peer-review under responsibility of 7th International Conference of Materials Processing and
Characterization.

[12] Meltem Altin Karatas , Hasan Gokkaya(2018). A review on machinability of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) composite materials. Defence Technology 14 (2018) 318-326.
https://doi.org/10.1016/j.dt.2018.02.001

[13] D. Arola M. Ramulu(1996). A Study of Kerf Characteristics in Abrasive Waterjet Machining of Grapite/Epoxy Composite. Transactions of the ASME, Vol. 118, APRIL 1996.
https://materialstechnology.asmedigitalcollection.asme.org

[14] Daivik Kothwala1, Babu Patel, Ripal Patel(2019). Optimization & Experimental Investigation of Process Parameters on Kerf Width in Laser Cutting Process using AISI 2205. International Journal of Innovative Research in Science, Engineering and Technology, ISSN(Online): 2319-8753.
https://doi.org/10.15680/IJIRSET.2019.0803201

[15] Milos Madic, Miroslav Radovanovic and Marin Gostimirovic(2015). ANN modeling of kerf taper angle in CO2 laser cutting and optimization of cutting parameters using Monte Carlo method. International Journal of Industrial Engineering Computations 6 (2015) 33–42.
https://doi.org/10.5267/j.ijiec.2014.9.0031

[16] U Ashok Kumar, Shaik Mehtab Alam, P. Laxminarayana(2019). Optimization of Kerf Width & Kerf Taper Angle on Glass Fiber Reinforced Polymer by Abrasive Water Jet Machining using Taguchi Approach. International Journal for Research in Applied Science & Engineering Technology (IJRASET) ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.177 ,Volume 7 Issue X, Oct 2019. https://doi.org/10.22214/ijraset.2019.10067

[17] R.D.S.G. Campilho, A.M.G. Pinto , M.F.S.F. de Moura , I.R. Mendes , M.D. Banea , L.F.M. da Silva(2014). TAPER ANGLE OPTIMIZATION OF SCARF REPAIRS IN CARBON-EPOXY LAMINATES. https://www.researchgate.net/publication/228414260

[18] L.S. Jiao , E.Y.K. Ng , L.M. Wee , H.Y. Zheng(2011). Role of volatile liquids in debris and hole taper angle reduction during femtosecond laser drilling of silicon. Applied Physics A (2011) 104:1081–1084. https://doi.org/10.1007/s00339-011-6374-4

[19] Pratik P. Shukla , Jonathan Lawrence(2012). The influence of brightness during laser surface treatment of Si3N4 engineering ceramics. Optics and Lasers in Engineering 50 (2012) 1746–1751.
http://dx.doi.org/10.1016/j.optlaseng.2012.07.006

[20] Anzhe Wang, Xinyuan Zhao, Mingxu Huang , Yehong Cheng , Dongyang Zhang(2021). A systematic study on the quality improving of fracture toughness measurement in structural ceramics by laser notching method. Theoretical and Applied Fracture Mechanics 114 (2021) 102981.
https://doi.org/10.1016/j.tafmec.2021.102981

[21] C. Beausoleil, H. Yazdani Sarvestani, Z. Katz, J. Gholipour, B. Ashrafi (2020). Deep and high precision cutting of alumina ceramics by picosecond laser.. Ceramics International 46 (2020) 15285–15296.
https://doi.org/10.1016/j.ceramint.2020.03.069

[22] H. Yazdani Sarvestani, C. Beausoleil, M. Genest, B. Ashrafi (2020). Architectured ceramics with tunable toughness and stiffness.Extreme Mechanics Letters 39 (2020) 100844.
https://doi.org/10.1016/j.eml.2020.100844

[23] S. Y. Martowibowo A. Wahyudi(2012). Taguchi Method Implementation in Taper Motion Wire EDM Process Optimization. J. Inst. Eng. India Ser. C (October–December 2012) 93(4):357–364.
https://doi.org/10.1007/s40032-012-0043-z

[24] F Quintero, F Varas2, J Pou, F Lusqui˜nos , M Boutinguiza, R Soto, and M P´erez-Amor(2005). Theoretical analysis of material removal mechanisms in pulsed laser fusion cutting of ceramics. J. Phys. D: Appl. Phys. 38 (2005) 655–666.
https://doi.org/10.1088/0022-3727/38/4/021

[25] Shengqi Wu, Anand Gandh, Hongjiang Li, Mark Meinhart(2020). Experimental and numerical study of the effects of nozzle taper angle on spray characteristics of GDI multi-hole injectors at cold condition. Fuel 275 (2020) 117888.
https://doi.org/10.1016/j.fuel.2020.117888

[26] C Wandera and V Kujanpaa(2011). Optimization of parameters for fibre laser cutting of a 10mm stainless steel plate. Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture ,May 2011, 225: 641.
https://doi.org/10.1177/2041297510394078

[27] K. Abdel Ghany, M. Newishy (2005). Cutting of 1.2mm thick austenitic stainless steel sheet using pulsed and CW Nd:YAG laser.Journal of Materials Processing Technology 168 (2005) 438–447.
https://doi.org/10.1016/j.jmatprotec.2005.02.251

[28] Jian Li, Le Chang(2017). Limit loads for un-cracked and circumferential through-wall cracked pipe bends under torsion moment considering geometric nonlinearity. Thin-Walled Structures 116 (2017) 37–52.
https://dx.doi.org/10.1016/j.tws.2017.02.024