PARAMETRIC STUDY OF LASER CUTTING OF Ti-6Al-4V ALLOY

A thesis submitted towards partial fulfillment of the requirements

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Master of Technology in Laser Technology

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Submitted by

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Course affiliated to

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CERTIFICATE OF RECOMMENDATION

WE HEREBY RECOMMENDED THAT THE THESIS PREPARED BY **SATYAJIT MAHATO** ENTITLED **"PARAMETRIC STUDY OF LASER CUTTING OF Ti-6Al-4V ALLOY"** UNDER OUR SUPERVISION BE ACCEPTED IN FULLFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER TECHNOLOGYIN LASER TECHNOLOGY DURING THE ACADEMIC SESSION 2020-2022.

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CERTIFICATE OF APPROVAL

This forgoing Final Thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite for the degree for *Thesis Work* for which it has submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the Final Thesis only as a prerequisite for the *Thesis Work.*

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SYNOPSIS

Due to outstanding qualities, Titanium Grade 5 material (Ti-6Al-4V) is in high demand in a variety of sectors. Its excellent mechanical and physical properties like high toughness, high intense heat resistance, low denseness, erosion resistance have encouraged the use of Ti-64 in various applications such as aerospace industry, and also used in jewelry, spacecraft, automotive, marine, chemical, food processing, surgical tools, biomedical implant and other high-performance products. The hard and brittle nature of these titanium alloy makes them different to cut using traditional machining due to large cutting forces as well as several tools wear involved for hard-to-cut. Thus, non-contact Laser cutting can be used to make high-quality cuts by carefully managing various specification including laser beam power, traverse speed, assist gas pressure and frequency. A highly collimated laser beam strikes the workpiece with high energy such that the temperature of the workpiece exceeds its boiling point, resulting in vaporization and ablation occurs. In this paper, an experimental investigation of the laser cutting of 3mm thick titanium alloy using a fiber laser cutting cycle utilizing nitrogen assist gas. The point of present research is to upgrade kerf width and HAZ in the fiber laser cutting of Titanium grade 5 (Ti-6Al-4V) sheets. The study presents a systematic experimental investigation of different process parameters such as laser power, scanning speed, gas pressure, frequency for minimizing the response parameters like kerf width, HAZ, taper angle. After a series of experiments have been performed, optimize the process parameters for optimizing response for the desired response concerning minimal laser power, maximizing scanning speed, increasing productivity and less machining time. The scanning electron microscope (SEM) was used to evaluate the cut quality and the Analysis Of Variance (ANOVA) was used to confirm the proposed model's accuracy.

Keywords: *– Titanium alloy; Laser cutting; Design of Experiment (DoE); Surface profile.*

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1. Introduction

Laser cutting is a process in which it is possible to cut metal or non-metal raw materials of different material thicknesses. Laser cutting has been a widely accepted high technology production process. The fact that laser cutting technology offers reduced contamination (reduced waste, less hazardous waste, reduced material waste) of the workpiece presents certain advantages over the traditional mechanical cutting process. Laser cutting also allows us to cut smaller diameter holes with complex detail and good edge quality in sheets, plates, tubes, or box-section.

1.1 Titanium alloy:

Today, Ti-6Al-4V is the most commonly used in the aerospace industry accounting for more than 80% of its consumption. The high strength-to-weight ratio, high fracture hardness, at raised temperatures, superior corrosion resistance, tiredness resistance, and ability to sustain creep at relatively high temperatures are all reasons for its widespread use in the aerospace industry. Components constructed of Ti alloy powder metallurgical manufactured, with formed alloys being the most frequent in the aerospace applications. In the fabrication of aircraft components, virtually all types of traditional machining processes are used, including turning, milling, drilling, grinding, and so on. on the other hand, Titanium and its alloys, are thought to be difficult to machine, Because of the limited thermal conductivity of the tool/workpiece contact, high temperatures have a substantial impact on the tool's lifetime as well as the material's qualities. Furthermore, the machinability is even further hampered by the high temperature strength and low Young's modulus.

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1.2 Laser cutting:

Laser cutting on sensitive and complicated materials like titanium requires precise parameter control to achieve best cutting results because of the high dense power and rapid cutting speed. Compared to traditional cutting technologies such as electric discharge machining, plasma arc cutting, oxyacetylene flame cutting, and machine-driven cutting, laser cutting is a non-contact material processing technology with a comparatively high cutting speed. Performed by various ordinary and non-conventional techniques where Laser Cutting is last options. Laser cutting is efficient for soft and hard, such as paper and diamonds.

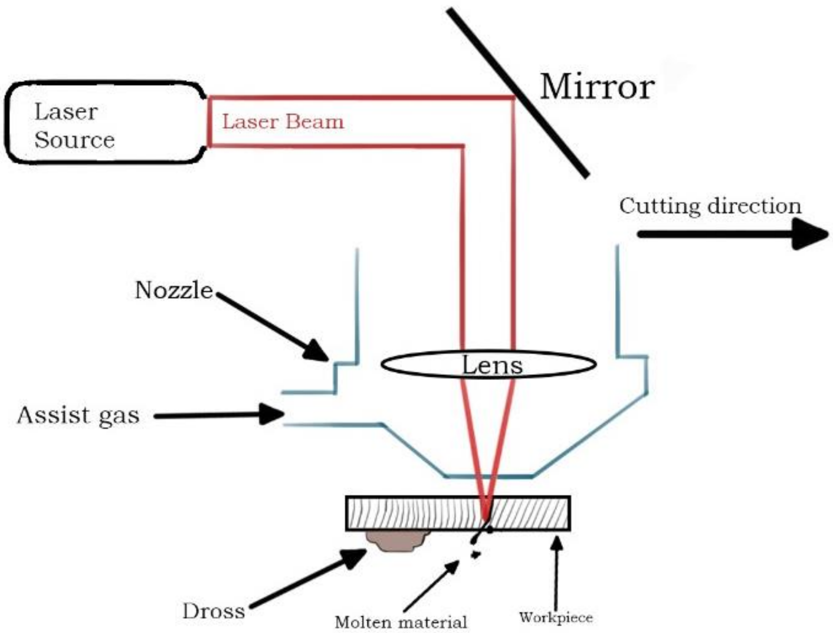


Fig. 1.1 Diagram of laser cutting process

Laser cutting is one of the non-traditional techniques for removing material from a work item by ablation using thermal energy. When a powerful electromagnetic laser beam is concentrated on a target, the focused section of the target quickly heats up to melting or vaporization temperature, and raw material is blown away with the use of helping gas or assist gas. This method is more adaptable for cutting complex shapes and produces less noise. Due to the reduced rate of wastage of materials compared to traditional mechanical cutting, the laser cutting technique provides a sustainable strategy for future manufacturing.

To cut into a workpiece, laser cutting uses both continuous and pulsed beams. The majority of laser cuts are made with a continuous laser source. Each pulse burns and vaporizes the material until it achieves the desired result. The laser cutter can cut with high precision regardless of the part's composition. Due to the rapid growth of laser cutting techniques, it has been discovered that laser cutting is one of the most popular among all cutting techniques, in addition to being a cheap and manageable alternative to CNC and all other common conventional and non-conventional cutting approaches. The manufacturing industry's application of laser cutting can be attributed to its high precision, repeatability, and reproducibility over a short period of time with minimal waste.

1.2.1 Working principle of laser cutting:

Laser cutting is a two-dimensional (2D) procedure that involves corresponding motion in the middle of the laser source and the work piece’s material upper side. The laser emits a steady, highly concentrated beam, which is reproduced by the deflector and falls onto the task after passing through the converging lens. The focused-power intensity of the laser melts and/or vaporizes the material in the focal zone due to the rapid rise in temperature. Allows high-pressure gas to flow in the direction of the laser source, causing molten metal to be blown out and cutting edges to form. During the cutting process, these pressurized gasses, known as assist gasses, can chemically react with the job. In a small focused beam diameter, a taper angle of degrees and a narrow cutting width in a narrow heat-affected zone.

Rather than mechanical qualities, the effectiveness of laser beam cutting is determined by the thermal characteristics and, to a lesser extent, optical features of the material being cut. Laser cutting controls the energy balance between the radiant energy of the laser beam and the heat conduction in the workpiece, the energy lost in the environment, and the energy required for the phase transition in the workpiece. Mechanisms relating to laser features such as frequency, wavelength, and power density, as well as processing parameters such as assist gas and pressure, and material specifications such as dimensions and composition.

1.3 Different types of laser cutting:

The laser cutting process three different categories,

1.3.1 Fusion cutting:

In this cutting process, the laser energy is concentrated on the base material, which supplies the energy for melting with a stressed assist gas for molten material ablation and also improves the cutting process. Clean or fusion cutting is referred to as inert gas-assisted cutting, whereas gas cutting refers to a procedure that includes an exothermic response. This method is more efficient since it uses less energy to ablate materials. The main issue with fusion cutting is the production of striations and dross.

1.3.2 Sublimation cutting:

In this operation, the base substance is vaporized along the cutting layer. To blow away the vapor generated during light-matter interaction, a pulsed laser beam and a jet of inert assist gas are utilized coaxially. This cutting process produces a narrow kerf width and a high-quality surface in this process.

1.3.3 Photochemical ablation:

In this process, When the quanta energy of a laser beam exceeds the chemical binding energy of molecules, bonds are broken, resulting in material ablation. High-energy photons cause electronic excitation to occur more quickly. The breakdown of chemical bonds between atoms also causes ionization. Photochemical ablation can be seen in polymers and glasses. This procedure makes use of UV lasers. Because it generates little heat during the machining process, this procedure is sometimes referred to as cool ablation.

1.4 Methods of cutting:

Cutting is one of the most basic operations in industrial machining, and it is used to cut a variety of materials such as metals, polymers, and ceramics. Cutting is the process of using a sharply focused force to separate or open a physical item into two or more sections. Cutting is the removal of material from the workpiece's surface. Mechanical qualities of many materials (heat conductivity, hardness, brittleness, elasticity, etc.) As a result, several types of cutting processes are necessary for machining various structural materials:

1.4.1 Conventional methods:

In traditional procedures, macroscopic chips are often generated by shear deformation. The tool and the workpiece come into close proximity in conventional machining. The cutting tool is softer than the workpiece. The application of cutting forces causes material removal, which is classified as a mechanical energy domain. Surface smoothness and precision are both sacrificed in this procedure. All types of materials can be used at a low cost.

The following are examples of traditional cutting methods:

- Abrasive wheel cutting
- Wire saw cutting
- Diamond cutting
- Lathe machine etc

1.4.2 Non-conventional methods:

Non-conventional cutting, is a relatively recent development that has found wide use in a variety of current applications. Non-traditional cutting techniques include diverse electrical, chemical, mechanical, thermal, or a mix of these processes, as opposed to traditional procedures that require tool bits. Material removal may take place concurrently with chip growth or may not take place at all. There may not be any actual tools available.

Methods of cutting that aren't traditional:

- Laser beam machining (LBM)
- Electron beam machining (EBM)
- Electro discharge machining (EDM)
- Plasma arc machining (PAM)
- Electro chemical machining (ECM)
- Wire electro discharge machining (WEDM) etc.

1.4.3 Hybrid methods:

Cutting processes, both traditional and nontraditional, have a number of limitations that affect their cutting efficiency as well as the precision, accuracy, and quality of the cut dimension. To improve their performance, a few new machining processes have been devised. "Controlled and simultaneous interactions of two or more machining machines, tools, and/or energy sources that affect performance characteristics" [3]. These combine the advantages of two different processes to create a new one that is more well-organized and effective than either of them.

Hybrid methods are:

- Hybrid laser assisted water jet machining
- Electro chemical discharge assisted wire machining etc.

1.5 Choice of laser cutting:

Lasers come in a range of shapes and sizes, but the most typically used in cutting are the Nd:YAG and CO_2 lasers. Fiber lasers with high output power have recently been used in a range of applications. Furthermore, the Nd:YAG laser can generate higher peak pulse powers.

The Nd:YAG laser, an optically pumped solid-state laser with a wavelength of 1.06 μm, and the CO_2 laser, an electrically pumped gas laser with a wavelength of 10.6 μm, are now employed for cutting. Because of the YAG crystals' poor heat conductivity. These lasers can only provide a moderate amount of power. Their efficiency is a few percentage points. CO_2 lasers, on the other hand, may produce radiation with a power of many thousands of watts due to their comparatively high efficiency of more than 10%.

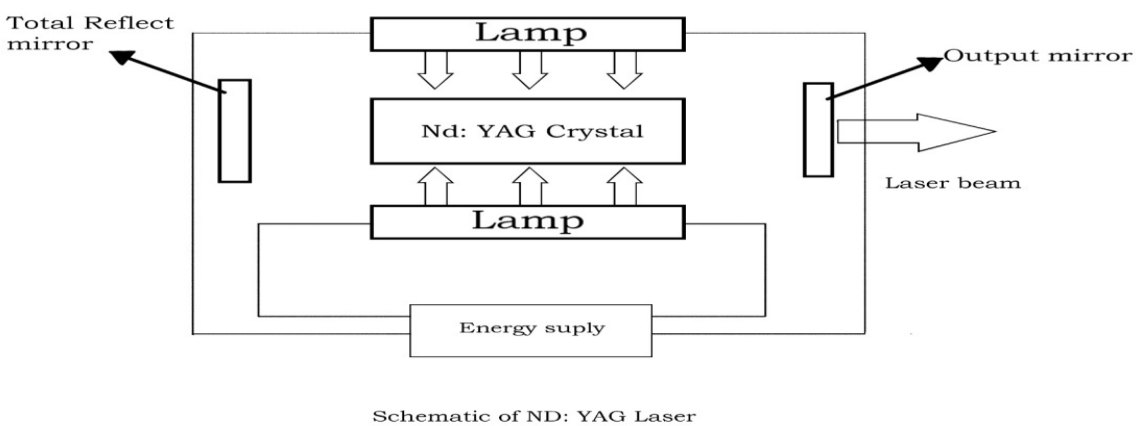


Fig. 1.2 Diagram of Nd:YAG laser

Furthermore, the shorter wavelength allows for greater energy density and cutting quality by focusing on a smaller location. This is only true for the lowest order radiation mode, which is more difficult to achieve with Nd:YAG lasers than with CO_2. As a result, both Nd:YAG and CO_2 lasers can be used to cut thin materials with a thickness of a few millimeters. If cutting materials with thicknesses between 10mm is required, or if a faster cutting acceleration is obtained. The requisite power can only be generated by a CO_2 laser. The CO_2 laser, on the other hand, is usually more expensive than the Nd:YAG laser.

Aside from wavelength and power, the quality of the beam is the most significant attribute of a greater dense power laser for cutting. The beam must first be as close to the fundamental TEM_{00} radial mode as feasible, which implies that the radial intensity distribution has only one maximum along the beam axis, ensuring that the beam may be focused ideally to achieve a high cutting speed and maximum thickness. Second, for a superior-quality edge cut, both the radiation power and its radial distribution must be held constant for a short period of time.

1.5.1 CO_2 laser:

The CO_2 laser, a type of gas laser commonly used in industrial processing, is substantially more efficient than the Nd:YAG laser, producing far higher continuous wave output powers and superior light quality. These lasers utilize gas mixtures primarily composed of nitrogen and oxygen. This approach involves employing an electric glow discharge to mix helium with a small amount of carbon dioxide (CO_2) molecules. The gas heating produced in this method can be modified by continuously circulating the gas blend via the optical cavity zone. CO_2 lasers with a CW output power create of 3-10 KW. The axial and transverse flow are both very fast. CO_2 lasers are the most extensively used in industry because they have the maximum power output. CO_2 lasers offer a number of benefits, including high electrical efficiency, low operating costs, and the potential to grow up to higher powers.

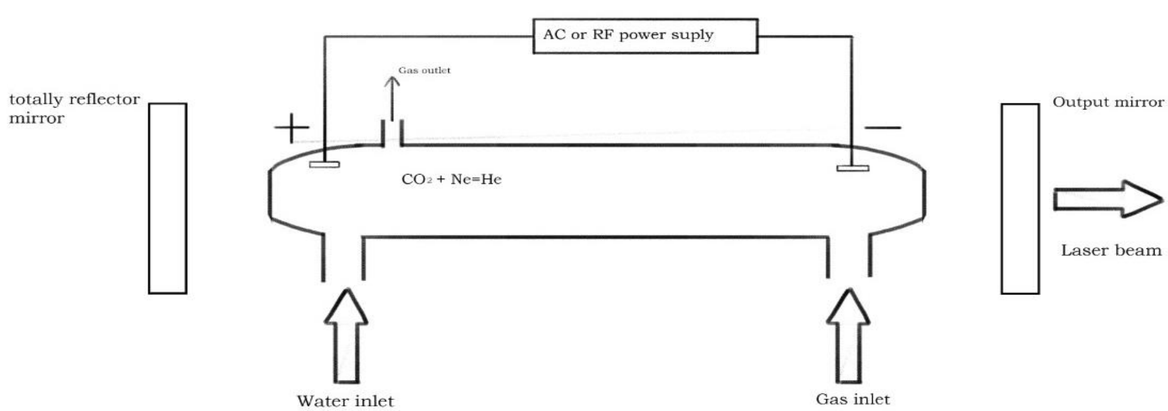


Fig. 1.3 Diagram of CO_2 laser

1.5.2 Fiber laser:

In a fiber laser, the active medium is the laser's core. A rare earth element has been added to the fiber. The most popular type is a silica-based single-mode optical fiber laser. Fiber lasers have been advocated as a feasible alternative to solid-state and CO_2 lasers in various materials processing applications.

Fiber laser is a type of solid state laser in active medium is a glass fiber doped with unique earth elements as Nd, Yb, or Er. Fiber lasers can be a good substitute to CO_2 lasers, especially for cutting thin sheet (less than 4 mm) or superior reflecting materials. Following fiber laser cutting, subsequent welding of edges created without further machining procedures has demonstrated to have the same mechanical performance as laser welded milled edges.

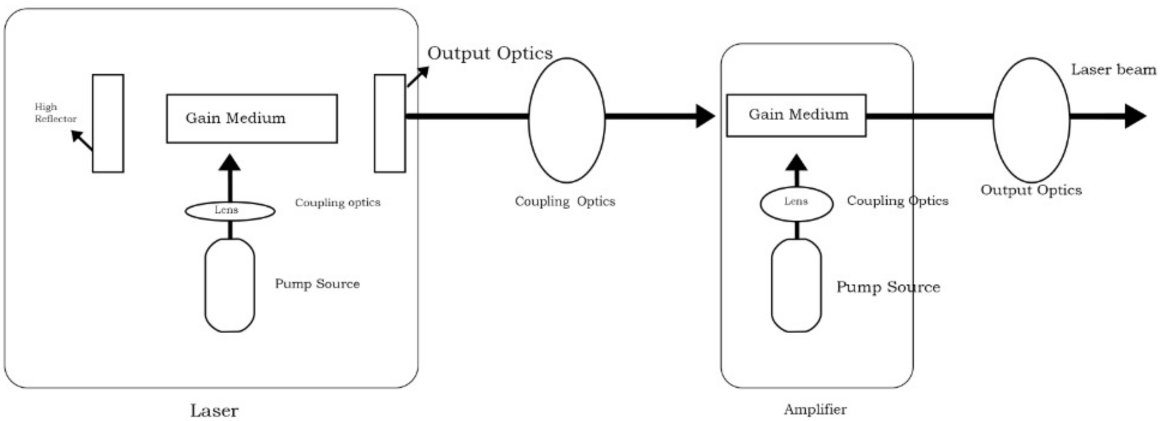


Fig. 1.4 Diagram of Fiber laser

1.6 Mechanism of material removing in laser cutting:

When a high-intensity pulse is delivered to a material's surface, the absorbed energy can melt or evaporate the material. These are the steps involved in cutting, the primary material elimination process in laser beam cutting is based on the creation of a huge high temperature flux, which causes the material on which the laser light is focused to melt and vaporize. An appropriate lasing source is employed to produce a laser beam of the desired wavelength. A small-diameter laser beam emanates from a lasing medium. The beam is then focused onto the material surface using a suitable converging element, such as a lens. As a result, there is a substantial amount of energy concentrated at that location. Once the laser heat is absorbed by the surface material, the optical energy is converted to heat. Depending on the heat source and substrate material, this entire process can be vaporized, boiled, abated, or phase exploded.

1.6.1 Vaporization:

When an atom or molecule is initially freed from the extreme of an external surface where it is heated past its melting point to its vaporization temperature, it is said to be converted from the condensed state (solid or liquid) to the vapor state. Part of the laser's energy is utilized to melt the material in this situation, and the liquefied material is brought into direct contact with the substance itself. A portion of the molten substance is also vaporized by the laser. The produced steam generates steam or back pressure, which pushes the steam away from the target, putting force on the molten substrate, and expelling it to the side.

1.6.2 Boiling:

This condition necessitates a relatively lengthy pulse time and contains the nucleation of foreign vapor bubbles that can form on the liquid's external surface, in most liquids, or at the liquid-solids boundary. At the absorption depth ($1/\alpha$, when the absorption coefficient is α), boiling occurs. The vaporization temperature, which corresponds to the surface pressure, is set, as is the surface pressure.

1.6.3 Ablation:

Ablation is a technique for removing material that is used in two ways. To begin, a high-energy quantum is generated using a power source. If the energy in the workpiece's atoms exceeds the threshold energy, every molecule can be broken into atoms and eliminated from the material. On the other hand, an energy beam with a high focused power density on the material is used in the other way. The workpiece can be vaporized rather than melted because of the high power. Common power sources include excimer and femto-second lasers. The machined surface retains very little heat-affected layer, which is an important feature of these techniques. As a result, micro-shapes can be machined with extreme dimensional accuracy, and the surface layer has fewer flaws.

1.6.4 Phaser explosion:

To achieve this, the laser fluency must be powerful enough and the pulse duration short enough that the temperature of the material surface and the area immediately beneath it reaches around 90% of the thermodynamic critical temperature. The substance changes fast from a superheated liquid to a vapor or liquid droplet mixture, resulting in homogeneous bubble nucleation. Because the occurrence rate grows significantly near the critical temperature, homogeneous nucleation is conceivable. Explosive boiling is another name for this.

1.7 Laser cutting parameters:

Due to the advantage of high speed, we have found that laser cutting has always been a good choice in industrial applications. To improve quality with minimal manufacturing cost, time, process safety and increased productivity, the process parameter settings must be selected in the best way. These optimal parameters play a very important role in ensuring product quality, improving productivity and reducing manufacturing costs in the fully automated manufacturing process.

The following are the primary factors that influence the laser cutting process:

i. Beam Power
ii. Wavelength
iii. Beam characteristics
iv. Cutting Speed
v. Assist gas and Gas Pressure
vi. Focal Position

1.7.1 Beam power:

The irradiated area and beam power combine to form beam intensity. Because it enables the material to heat up faster, a high intensity allows for faster cutting. As a result, heat is allowed to transfer into the material for a shorter period of time. The thickness of the material that can be sliced is determined by the intensity of the beam. Increased dross production is caused by a greater beam power combined with a high cutting speed. More liquid raw metal means more debris in the cutting edge, hence higher beam power means more dross.

The power of the beam is related to the cut depth. It's measured in fluency, power density, and energy density, among other things. One of the most crucial aspects of laser cutting. Extreme power causes a wider kerf breadth and a thicker recast layer, resulting in more dross. Higher energy, Spatter, HAZ, and recast layer production are all more likely.

1.7.2 Wavelength:

To create the required cut, the laser light's electromagnetic source is turned into heat energy within the material. The absorptivity of the substance, which is controlled by the wavelength, determines the amount of change. By adopting a shorter wavelength beam, the process stability is improved. At shorter wavelengths, Fresnel absorptivity is higher. Plasma impacts are low since the plasma's absorptive coefficient roughly varies with the square of the wavelength. Aluminum alloys cannot be exposed to longer wavelength light because it is more reflective. As a result, higher threshold power densities are needed for coupling with the chosen material.

1.7.3 Beam characteristics:

The following are the most important laser cutting beam characteristics:

- **Beam mode**

The beam mode specifies how evenly the energy intensity is distributed across the beam's zone. The beam's capacity to focus is described by the mode, which might be compared to the sharpness of a cutting knife. Because the fundamental or Gaussian distributed

TEM_{00} mode has the smallest focal dimensions and consequently the highest power density for a given laser beam intensity, it is chosen for cutting. As the kerf width decreases, the cutting speed and material width that can be cut increase. Because higher order or multi order beams are more spread out, they have a larger focal sport and, as a result, a lower power density for the same output power.

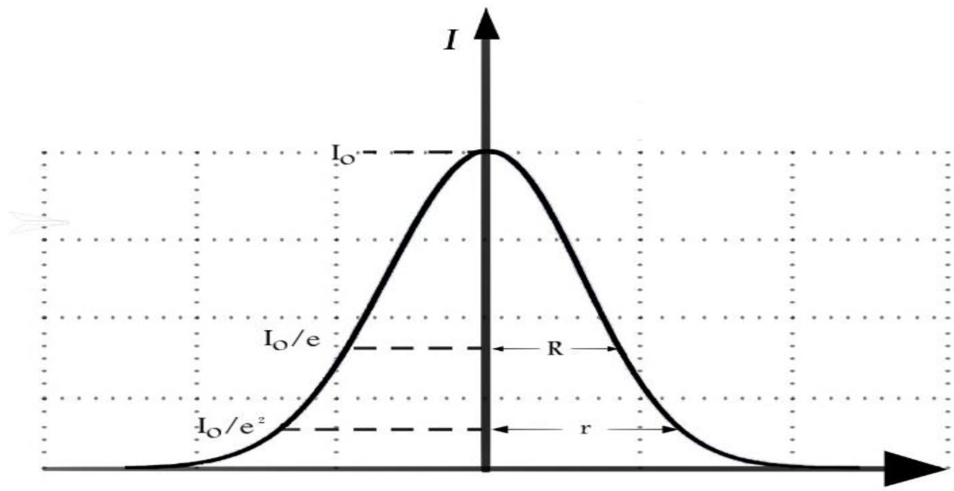


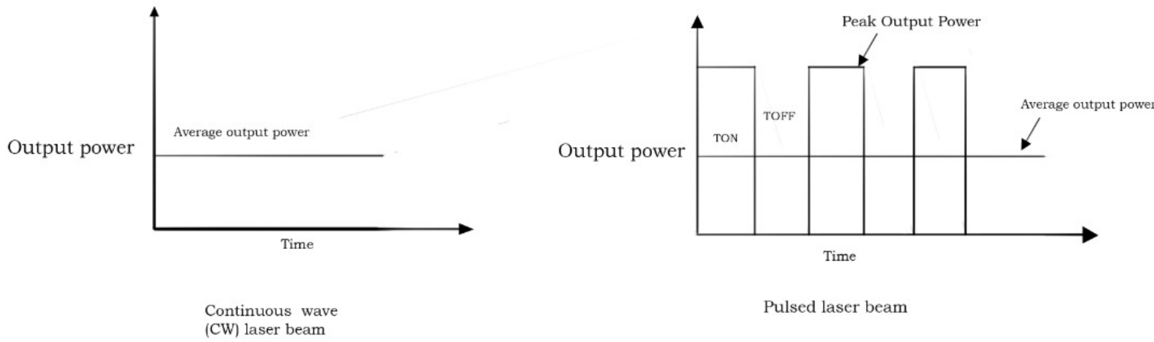
Fig. 1.5 Schematic of Gaussian distribution mode

- **Beam angle**

The absorption is affected by both polarization and incidence angle. When the beam is circularly polarized, cutting rates are faster at higher power levels. A beam that is plane-polarized in the cutting plane is shown to be more efficiently absorbed for angles of incidence greater than 80^0 but less than 90^0. When the beam is polarizing along the cutting path, the resulting cut may have a fine kerf with sharp, straight edges.

- **Beam form**

Both pulsed and continuous beams can be used for laser cutting, while continuous beams are more common. The pulse duty cycle has an effect on the surface roughness, which decreases as the pulse duty increases. The pulse duty cycle is defined as the ratio of pulse on time to total pulse time. Figures show continuous and pulsed wave beam shapes, respectively.



- **Beam stability**

In order for the beam power, mode, and focusing ability to remain constant throughout time, the beam must be stable. An unstable beam has an impact on laser cutting accuracy and surface quality. As a result, a consistent beam reduces product variability and increases superiority. The laser beam's stability is determined by the laser resonator and beam delivery system architecture.

1.7.4 Cutting speed:

The maximum speed feasible for a given laser power diminishes as the width of the piecework increases. The quality of the surface and the kerf breadth, which differ from material to material, are also affected by traverse speed. When the cutting speediness is too slow, extreme scorching of the cut edge occurs, lowering edge quality and increasing the HAZ's breadth. The cutting speed of a material is inversely to its width. To minimize burning, the speed must be reduced when crossing steep curves, which implies a reduction in beam power.

1.7.5 Assist gas and Gas pressure:

Assist gas serves three purposes: (1) ejection of molten material, (2) increased cutting process by exothermic reaction, and (3) protection of the lens from back spatter. A novel gas, such as nitrogen, must discharge molten matter while preventing drips from hardening on the dross on the underside. An energizing gas, such as oxygen, is involved in an exothermic reaction with the material. It's impossible to use a laser beam for high-speed, high-quality cutting without an assist gas if the thickness is more than a few tenths of a millimeter. The importance of assist gas develops as the breadth of the material increases.

Aside from its primary function, the assistance gas also serves to chill the molten liquid. The solidifying effect is influenced by elements such gas thermal conduction and pressure. Because increased gas pressure allows for more heat convection, it results in a lower HAZ.

When cutting with novel gas, the gas pressure should be higher possible to avoid the production of debris.

1.7.6 Focal position:

During the laser cutting process, the divergence of the laser beam is extremely important. The best results (lowest kerf thickness) are obtained when the focus point is on or slightly below the material surface. For thick plates, it may be preferable to set the focus one-third of the plate width below the surface.

1.8 Characteristic of laser cut samples:

The preparation of a qualified cutting program, which contains the tested process parameter values or the value range to generate an end user-specified quality level cut, ensures cut quality. The development process can be carried out quickly and easily using pre-existing techniques or predictive methods.

The following are a few of them:

1.8.1 Kerf width

During through-thickness cutting, the kerf is the slot molded. The kerf width is described as the breadth of the cut at the bottom in optimal laser cutting, and it is usually much larger than the focused beam diameter. The kerf width of the material's bottom side is usually thinner than the upper side. The width of the gas jet determines the kerf width in gas assisted thermal cutting procedures.

1.8.2 Heat Affected Zone (HAZ)

As the power incident per unit length and the cutting thickness grow, the HAZ widens. When cutting near heat components, the HAZ width is important. As a result, there are times when the maximum limit is established for the incident beam output or plate thickness, or the lowest limit is set for the cutting speed.

1.8.3 Recast layer

The re-melted layer is either molten slag (solidified oxide) or a very adherent form (hardened substance) that forms at the bottom of the incision. Burrs might appear as prolonged drops or as a rough covering of whiskers. Slag can be mechanically removed after cutting or separated during processing with a gas jet directed from the bottom of the material.

1.8.4 Surface Roughness

The presence of sputtering (remaining molten material released from the cutting) and discoloration on the surface characterizes the surface condition after cutting.

1.8.5 Tapper Angle

High laser power can limit taper angle creation, allowing the heat to permeate all the way down through the thickness of the working material. Higher laser power penetrates the material more effectively, resulting in a larger kerf with less taper. As a result, by raising the laser power, the material removal rate is increased, and the taper formation is reduced. High cutting speeds imply that the laser beam moves faster, resulting in less time spent at a single point location. As a result of the shorter energy input time, larger taper angles were created at high cutting speeds, which were not fully communicated to the thickness of the working material.

1.9 Material Considerations:

Laser cutting is an effective technique, which used for both metal and non-metal. The absorptivity at that wavelength, thermal conductivity, melting point and boiling point temperatures, heat of response, viscosity and surface tension of the molten material are all factors that influence the effectiveness of a laser in treating a certain substance.

1.9.1 Metals

Metals are generally conductive for both heat and electricity and absorb light at a certain wavelength of range according to material's optical properties. Some metals having high reflectivity than absorptivity, in this case cutting from the laser is quite difficult. To avoid the reflectivity, a coating is required for good absorption. Metals like steel, aluminum and its alloy, copper and its alloys, titanium and its alloys, etc. are usually cutting by laser beam machining.

1.9.2 Polymers

The strong laser beam used to cut polymers tends to tear down the polymer chains. As a consequence of re-solidified melting, edges generated when cutting thermoplastics seem polished. Because additional energy is required to disruption down the bonds as the polymer's strength increases, charring around the cut edge is likely to occur. Polyester and polycarbonate are easy to machining (cut), whereas polyvinyl chloride, phenolic, and polyimide might leave a substantial quantity of disintegrated material along the cut edge.

1.9.3 Ceramics

Ceramics are solids that are inorganic, nonmetallic, crystalline, amorphous, hard, brittle, thermally stable at high temperatures, less dense than metals, more elastic than metallic conductors, and have a very high melting point, including excellent electrical and thermal insulation. Ceramics can be covalently or ionically linked. The excessive oblique temperature gradients related to laser machining can generate extraordinarily excessive thermal stresses that reason cracking in ceramic materials, they are characteristically brittle. The thermal conductivity decreases quickly with growing temperature in such resources, notably decreasing thermal diffusion into the frame of the job.

1.9.4 Composites

In the case of composite materials, cutting circumstances are governed by individual one of the component materials because composites are made up of various materials. This could cause the other materials to degrade throughout the cutting process. When the basic materials' characteristics are alike, the composite material is easier to machining with a laser. During composite machining, extreme caution must be taken to keep harmful gases and materials contained.

1.10 Applications and Benefits of laser cutting:

Industrial lasers are used for cutting, which is one of the most essential and effective applications. Laser cutting is efficient for both very soft and very hard materials. Laser cutting technology has a very wide range of uses in modern applications, such as medicine, engineering and different branches of science. Laser cutting on ceramic, silicone and polymer substrates is widely used in the electronics industry. Laser is used in medical surgery to cut stents that save lives and test tubes.

The following are the general benefits of laser cutting over traditional cutting technologies including plasma arc cutting, electrical discharge machining, oxyacetylene flame cutting, and mechanical cutting.

- As a result, the kerf width is narrowed, resulting in less waste.
- Cutting rates that are relatively fast.

- Due to the low overall heat input, the heat-affected zone is tiny. As a result, the base material experiences minimal damage, making it fit for temperature-sensitive and flammable products. In addition, residual stress and distortion are minimal.
- Because it's a noncontact technique, there's no friction or mechanical tool forces that could harm sensitive workpiece.
- Suitable for both very soft and very hard materials such as paper and diamond.
- As a result, the cut ends are square rather than curved, as is the case with many other thermal cutting procedures.
- High flexibility and low noise.

1.11 Drawback of laser cutting:

- Lasers have a difficult to cutting highly shiny and conductive materials like Au & Ag.
- For harden able materials, the melting and fast cooling involved with the procedure results in a solid edge on the cut part.
- Traditionally, laser beam cutting has been partial to cutting thin materials with a thickness of less than a few millimeters.
- A laser cutting system has a comparatively high initial capital cost.
- Certain materials (polymers) may yield hazardous exhaust gases during laser processing.

1.12 Survey of past research

1. Yasssin M. Ahmed and Khairul S. Mohamed observed that Titanium is not a rare substance as it ranks ninth most great supply and fourth most aboundant structural metal located in the earth, which is exceeded only by Al, Fe, and Mg. it is rarely found in high concentrations and never discovered in a pure state. The issue that rises with the titanium and its alloy is sustaining the titanium without the metal phase changed, due to the temperature higher,. Due to the physical and mechanical properties, titanium has many benefits for high melting temperature and lightweight compared with steel, which has expanded uses.

2. Leonardo D. Scintilla and L. Tricarico studied cut edge quantity can be considered concerning CO_2 and Nd:YAG laser cutting. Except that for Ti-6Al-4V cut at lower cutting speed (10 m/min) and lower assist gas pressure (0.3MPa), dross height values are below about 200µm for all materials investigated. This investigation cut edge, surface Roughness (Ra) values are less than 3µm studied. Much higher cutting speeds with respect to CO_2 lasers operating in continuous wave also to CO_2 and Nd:YAG lasers in pulse mode were obtained.

3. Attia boudjemline, Mohammed Boudjemline and Emin Bayraktar investigated surface quality of Ti-6Al-4V using CO_2 laser cutting of 5mm thick sheet and obtained a fixed laser power 2KW the desired working zone lies between 2250 and 2400 mm/min for assist gas pressure between 12 and 14 bar. They studied in work for cutting speed is the main factor affecting surface roughness, incrasing the cutting speed it leads to roughness decrease. Assist gas pressure has no significant effect on surface roughness.

4. Anil P. Varkey, Shajan Kuriakose and V narayanan Unni observed laser cutting may be used for quality cuts by proper control of different process parameters. They experimented on 5000W CO_2 laser cutting system. The assist gas used is Nitrogen and its passes through a nozzle of 1mm diameter which remain constant during experiments and laser frequency is 8500 Hz, the titanium alloy sheet (Ti-6Al-4V) of thickness 2mm is used as work material. The difficult-to-cut Titanium alloy sheet has been successfully cut using a pulsed CO_2 laser beam. The hybrid approach of design of experiment (DOE) and genetic algorithm (GA) has simultaneously optimized the response kerf tapper and surface roughness.

5. Varit Poshyananda, Jidsucha Darayen, Kritttima Tumkhanon, Chedtha Puncreobutr, Atchara Khamkongkaeo and Boonrat Lohwongwatana observed the parameters optimization in laser cutting process is a key to produce high accuracy and high quality products. To enhance the quality of laser cutting , higher cutting speed is always good for production rate and low HAZ layer. However occasionally the geometry of the work piece and machine capability were posed as a limit. Increasing the laser power will not increase the HAZ width. The quality of cut can be improved because higher temperature of molten metal has lower viscosity and therefore the liquid pool could be ejected out easily. Too high assist gas pressure leads to the increase in nitrogen-rich phase in recast layer, if the assist gas pressure is too low. Heat affected zone and recast region becomes large and irregular. The experimented assist gas pressure at 8bar is the best value for cutting 2mm Ti-6Al-4V sheet. Finally recast layer is physically more brittle than HAZ layer. Unlike the HAZ which can be eliminated by sheet treatment or polishing r, recast layers require mechanical process to remove.

6. Bekir Sami Yilbas, S.S.Akhtar , C. Karatas observed laser hole cutting in Ti-6Al-4V alloy is carried out slightly higher values at the top circumference as compared to that corresponding to the bottom circumference of hole cut and the morphological changes around the kerf surface are examined incorporating optical and scanning electron microscopes. The irregular striation patterns are formed at the kerf surface which is associated the high melting and the cooling rates at the kerf surface. The assisting gas has effect on the region of the hole entry, in which case, the striation patterns inclines slightly in the direction of the cutting. The top surface of the hole is free from resolidified material, however, some small dross attachments are observed at the bottom edge of the hole.the kerf surface is free from cracks and the dense recast layer of about 5µm is formed at the kerf surface. The heat-affected zone around the cut edge is small, which is attributed to the low thermal conductivity of titanium alloy.

7. D. Pramanik et al. studied laser cutting is to be must cost-effective green manufacturing and fast machining technique. An investigated has been performed to modify the kerf angle 50 watt-ns multi-diode pump laser obtain successful cutting on titanium alloy. Under certain critical machining conditions, it is apparent that kerf angle, power setting, duty cycle, pulse frequency and scanning speed can change on the basis of machining with a minimum kerf taper and heat-affected-zone.

8. J. Wang, Zhaorui Sun, Lianwang Gu and Hamidreza Azimy investigated surface roughness of the cutting edge at low cutting speeds, due to the excessive increase in the temperature of the cutting gap area and the melted particles of most waste, the amount of

cutting edge was increased from 6 to 10 m/min, there were no traces of sticky particles at the bottom of the cutting edge. Enhancing the laser power, the surface roughness in the lower area of the cutting edge was raised due to the increase in the amount of melt volume.

9. Amrish Ray. D, Senthilvelan. T observed modeling and optimization the Titanium alloy cutting conditions of wire-EDM (electrically discharge machining) for better surface roughness and material removal rate. They used cutting parameters taken to study pulse-on-time, pulse-off-time and wire feed rate, they investigated measured response includes surface roughness and material removal rate. After the machining is done the surface characteristics are studied using scanning electron microscope(SEM) and finally its conclude optimal condition was found to be at pulse on time 1µs, pulse off time 17µs and wire feed rate 3.85mm/min.

10. Arun kumar Pandey, Avinash kumar Dubey investigated simultaneously optimize kerf taper and surface roughness in the laser cutting of Titanium alloy sheet (grade 5). They developed regression model for kerf taper and surface roughness have been taken as objective function for the genetic algothm based multi-objective optimization. They used for experiment to work pulse Nd:YAG laser beam also used assist gas Nitrogen (N_2). They developed regression models for kerf taper and surface roughness have been found reliable and adequate for predicting the kerf taper and surface roughness values at 90% and 95% and pulse frequency (that is directly proportional to pulse energy) have been found the most significant control factor for cutting material.

11. A. Tamilarasan and D. Rajamani investigated multi-response optimization approach for the Nd:YAG laser cutting parameters on titanium superalloy sheet (Ti-6Al-4V). they utilized to plan Box-Behnken design the experiments and response surface methodology. They studied a low cutting speed and high pulse width produce a minimal deviation of kerf values and low pulse width leads to pores and dross as a result of melting on the kerf surface. They observed multi-response optimization, the optimal parameters settings are as: pulse width of 1.89ms, pulse energy of 4.40J, cutting speed of 10.16mm/min and gas pressure of 7.98kg/cm2. These settings yields high MRR (material removal rate) and low KD (kerf depth).

12. L.D. Scintilla, G. Palumbo, D. Sorgente, L. Tricario investigated 1mm thick TI6Al4V sheets cutting high power solid-state fiber lasers CO_2 and Nd:YAG sources. They experimented activity carried out following main effects of the fiber laser cutting

parameters (the cutting speed and assist gas pressure) on mechanical properties and strain behavior of 1mm Ti6Al4V butt joints whose edges were creating by fiber laser cutting, cut performed with the lowest value of assist gas pressure 0.3MPa value show failure in weld bead. The cutting condition most suitable for laser welding characterized by assist gas pressure value 0.6MPa and cutting speed 20m/min.

13. B.El Aoud, M. Boujelbene, A. Boudjemline, E. Bayraktar, S. Ben Salem, I. Elbadawi experimented 3mm thick titanium alooy sheets cutting by high power CO_2 laser cutting, they usedfor experiment parameters like laser power, cutting speed, gas pressure and they analyzed cut edge microstructure and optimize the surface roughness using Taguchi-Method. The best surface quality is obtained at high laser power coupled with high cutting speed. The combination of laser cutting parameters P=3KW, V=2400mm/min and g_p=2bars were determined as the optimum one to achieve smallest roughness.

14. A. Sen, B. Doloi, B. Bhattacharyya observed Ti-6Al-4V sheet cutting using four process parameters such as avg. power 2.5-30W, no. of passes 1-8; scan speed of 50-100 Hz during micro-grooving (notch) of Ti-6Al-4V using 50W fiber laser. Depth and width tends to decreases with the higher scan speed but surface roughness has a tendency to gradually decreases to low spot over lapping, discontinuous power density. Higher pulse frequency, increase power density resulted smooth cut surfaces.

15. J. Wang et al. have made an experimental study to find out the features of the heat affected zone appearing at the time of laser heating of a Ti6Al4V superalloy plate workpiece. Determination of the quality and nature of emission and absorption of the Ti6Al4V alloy has been made in their experiments. In the study of parameters, it is noticed that an increase in the power induces the depth and width of the HAZ to increase and also induces a decrease when laser spot size and the laser scan speed increase.

16. L. D. Scintilla et al. investigated titanium alloy Ti6Al4V laser cutting using 2KW fiber laser. The cutting process was performed in continuous wave mode using Argon as helping gas and investigated the effect of cutting speed and shear gas pressure on the HAZ thickness, roughness and dross attachments of ti-64 alloy. Here found that, increasing the cutting speed and then decreasing heat input from 12J/mm (v=10m/min) to 6J/mm (v=20mm/min) at laser power 2KW, an HAZ increase. This behavior contrasts lower heat should supply surrounding material less heat in the unit time, which means thinner HAZ layer on cutting edge.

17. V. Parmar, A. Kumar and S. Datta observed that Ti6Al4V was machinable at higher cutting speeds and lower power than SS316L, despite higher melting temperature of Ti6Al4V. using 400W fiber laser machining system with cutting speed (75 to 800 mm/min) in the presence of Argon (10 bar pressure) as assist gas cutting on 3mm Ti6Al4V. at 300W laser power and velocities of 150mm/min or less, material separation was observed in Ti6Al4V but not in SS316L. An investigated into the laser machined surface confirmed that the primary mode of material separation in both the material was melt & blow cutting.

18. J. Vora, R. Chaudhari and C. Patel investigated laser cutting of Ti6Al4V was accomplished using Taguchi method. They used input parameters such as laser power, cutting speed and gas pressure whereas surface roughness (SR), kerf width, dross height and material removal rate (MRR) were investigated as output variables. Their paper objectives are higher MRR, minimum SR, minimum dross and minimum kerf. Their ouput values maximum MRR of 3.654g/s, minimum SR of 5.25µm and minimum kerf width of 302.839µm and minimum dross height of 0.1684mm could be obtained at a laser of 1742W, a cutting speed of 8m/min and gas pressure of 6bar.

1.13 Objective of the present research

➢ Process parameter selection
➢ How response changes (kerf width, cut-of-depth, surface roughness, heat-affected zone, etc.)
➢ Optical measurement of the kerf width, surface roughness, heat-affected zone, and cut-of-depth.
➢ Classification and measuring of cut width
➢ Compare response concerning laser parameter
➢ Optimize the parameters of the laser to minimize the unwanted response.
➢ Design of experiment (DoE)

1.14 Purpose of work:

The purpose of this thesis work is to access how different laser cutting parameters used with nitrogen as assist gas affected Ti-6Al-4V sheets, to reveal which process parameters of laser cutting that has a big effect on the cut part. The alloy used for this study is Ti-6Al-4V; an alloy frequently used for manufacturing engine parts in the aerospace industry and also needs a biomedical implant.

CHAPTER 2

2. EXPERIMENTAL INVESTIGATION OF LASER CUTTING OF Ti-6Al-4V

2.1 INTRODUCTION

A parametric investigation of laser cutting of Titanium-64 alloy researched during test. Four input parameters like laser power, frequency, scanning speed, and gas pressure of fiber laser affect the characteristics of laser cut samples like kerf width of the top and bottom surfaces, heat-affected zone, and tapper angle. We have taken thickness of 3mm*100mm*100mm titanium plate Grade 5 of each sample for our experiment and used a fiber laser cutting machine and nitrogen gas as the assist gas. The primary aim of this experiment is to optimize the kerf width, tapper angle, and heat-affected zone during the cutting of titanium alloy and study the influence of input parameters like laser power, scanning speed, frequency, and gas pressure in cut quality in less power as well as moderately high scanning speed.

2.2 Experimental Setup and measuring equipment

2.2.1 Fiber laser cutting machine

The MEHTA Fiber laser cutting machine is utilized for all cutting tests. It delivers a constant Q-switched laser beam. The essential bureau houses the CNC-controlled Laser Source as well as a workstation. The laser is controlled by a control center joined to the main cabinet side walls. At the back of the machine, there is a chiller unit that is utilized for cooling. The assist gas is provided through a gas chamber joined to the main cabinet. The laser beam output and the assist gas output are coaxial. A voltage controller is likewise present, which guarantees that the machine gets a steady voltage input.

Fig. 2.1 MEHTA Fiber laser cutting machine

Fig. 2.2 Experimental setup

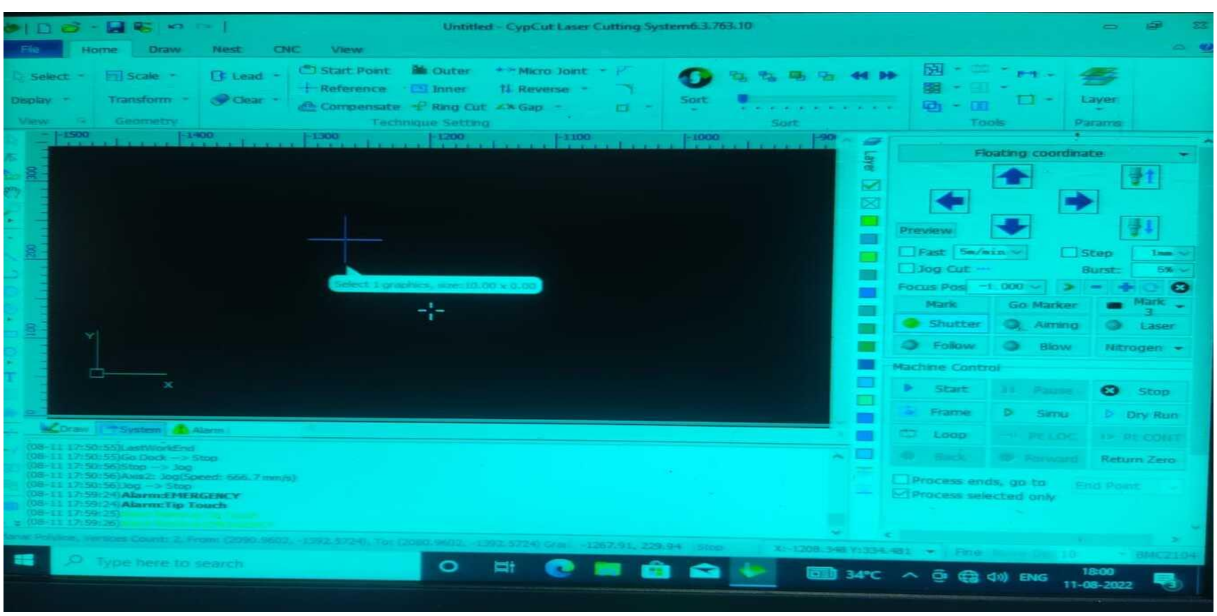


Fig. 2.3 Software setup

Table 2.1 Specification of Fiber Laser Metal Cutting Machine

Parameters	Value
Maximum Output Power	1500 W
Maximum Cut Speed	8 m/min
Maximum Gas Pressure	15 bar
Maximum Frequency	5000 Hz
Mode of Operation	Continuous Wave
Assist gas	Nitrogen and Oxygen
Wavelength	1064 nm
Laser spot diameter	50 µm
Nozzle height	0.8 mm
Nozzle diameter	1.5 mm
Focus depth	1 mm

2.2.2 Optical Microscope

The responses of all the samples were seen using a ZEISS Stemi 508 optical microscope. Data were acquired using the Scope Image 9.0 program. The marking width was measured using various magnification factors.

Fig. 2.4 Optical microscope

2.3 Experimental Methods

Titanium alloy is chosen in this study. The laser cutting of 3mm thicker sample with help of 1500w fiber laser of beam diameter 50μm with the help of nitrogen as an assist gas. For all experiments distance between the nozzle and sample is fixed. Initially, a number of tests were carried out to determine the best process parameters for laser cutting 3mm Titanium alloy. The Table 2.3 below shows the procedure parameters that were chosen for this study. The range of parameters decides the response outcome throughout the experiments. The laser cutting is powered on, and the input settings are configured according to the experiment design using the Cypcut laser cutting programme. The desired laser action path is then selected. The laser's shutter button is closed and the laser is turned on once all of the parameters and frame for laser activity have been checked. The laser then travels along its predetermined path, completing the laser activity. While the lasing action is in progress, all necessary precautions have been taken. Using a ZEISS optical microscope stemi 508, all responces such as kerf and heat affected zone are measured for each of the sample. The data is captured digitally and stored in a computer using the scope image software.

Table 2.2 Chemical compositions of titanium alloy sheet (Ti-6Al-4V) (grade 5)

Ti%	Al%	V%	Sn%	Fe%	C%	N%	H%	O%
89.9970	5.7500	3.9900	0.0090	0.2200	0.0200	0.0100	0.0030	0.0010

Table 2.3 Control factors and their level used in experiment

Factors	**Symbol**	**unit**	**Low level**	**High level**
Laser Power	P	watt	750	1500
Scanning Speed	V	m/min	0.5	1
Gas Pressure	g_P	bar	10	14
Frequency	f	Hz	1000	5000

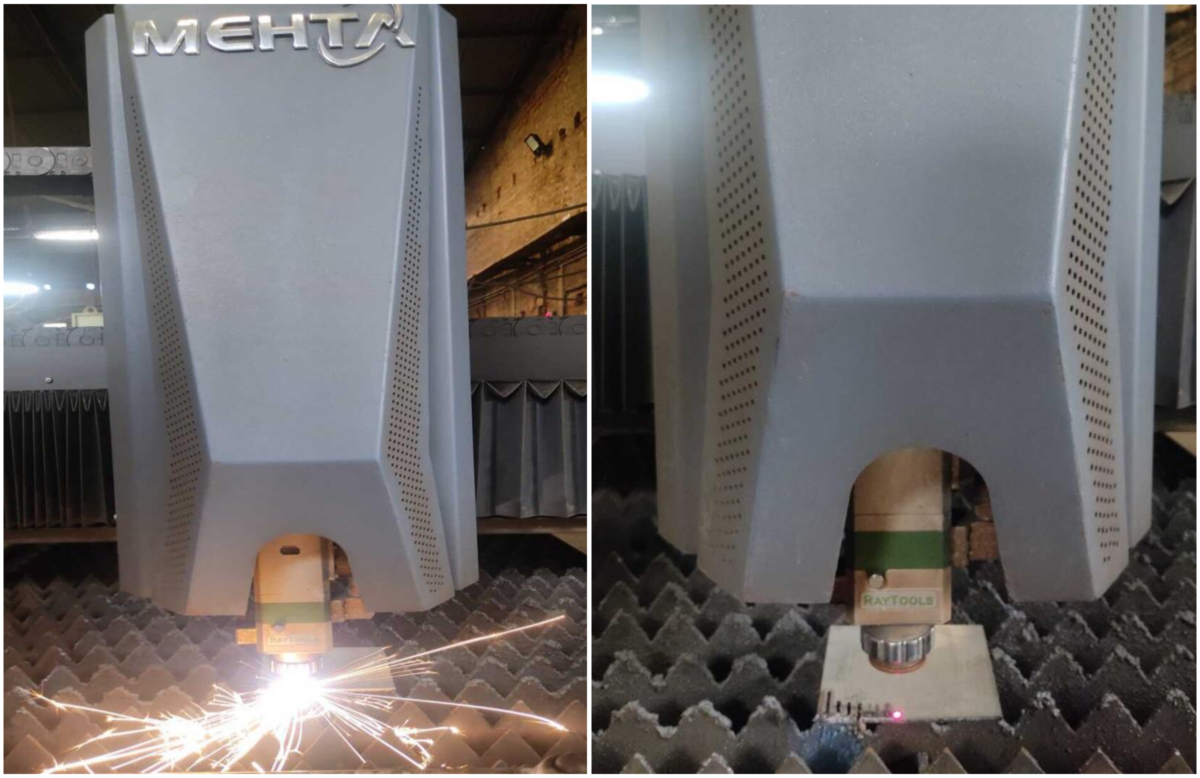


Fig. 2.5 Experimental set of laser cutting of Ti-64 alloy

The experiment are designed and optimize using response surface methodology (RSM) method. This is statistical method for modeling and analyzing of various variables. The RSM looks into a good approximation relationship between input and output variables in order to find the best operating conditions for a system or a portion of the factor field that meets the requirements. 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 cuts down on the amount of time it takes to conduct an experiment. Experiments can be used to improve product and process design, explore the influence of many factors on performance, and so on. To validate or evaluation of RSM model here we use ANOVA (Analysis of Variance).

2.3.1 Design of experiment

Four input process parameters laser power, scanning speed, gas pressure and frequency affects the response parameters like kerf width on the top surface, heat-affected zone, kerf width on the bottom surface and taper angle. The Table 2.4 below shows the procedure parameters that were chosen for this study.

Table 2.4 Design layout

Sl. No.	Laser power P(w)	Scanning speed V(m/min)	Gas pressure G_P(bar)	Frequency f(Hz)
1	750	0.75	10	3000
2	1125	0.75	12	3000
3	1500	0.75	12	1000
4	1500	0.5	12	3000
5	750	0.5	12	3000
6	750	0.75	12	1000
7	1125	1	14	3000
8	1500	1	12	3000
9	1125	0.75	10	5000
10	1125	0.75	12	3000
11	750	1	12	3000
12	1125	0.75	12	3000
13	1500	0.75	12	5000
14	1500	0.75	14	3000
15	1125	0.5	10	3000
16	1500	0.75	10	3000
17	1125	1	12	5000
18	1125	0.5	12	1000
19	1125	0.75	10	1000
20	1125	1	10	3000
21	1125	0.5	12	5000

22	1125	1	12	1000
23	1125	0.75	14	1000
24	750	0.75	14	3000
25	1125	0.75	14	5000
26	750	0.75	12	5000
27	1125	0.5	14	3000

2.4 Results and discussions

The process parameters (laser power, scanning speed, frequency, and gas pressure) and relative response parameters (Kerf width on the top and bottom surface, heat-affected zone, and taper angle) are discussed below in Table 2.5. Using response surface methodology we get design layout, and numerically calculated response from the experimented samples. From this table we get a fixed response for a fixed input process parameter.

Table 2.5 Design layout and numerically calculated response

SL No.	Laser power P(W)	Scanning speed V (m/min)	Gas pressure g_p(bar)	Frequency f(HZ)	Kerf width on the top surface (µm)	Heat affected zone (µm)	Kerf width on the bottom surface (µm)	Taper angle (deg)
1	750	0.75	10	3000	116.241	2981.66	663.20	5.20871898
2	1125	0.75	12	3000	148.551	2913.26	973.04	7.82431824
3	1500	0.75	12	1000	137.087	2977.89	965.37	7.85986441
4	1500	0.5	12	3000	142.987	3177.89	908.37	7.26958192

5	750	0.5	12	3000	137.316	3185.68	843.52	6.71284187
6	750	0.75	12	1000	123.759	3162.91	680.79	5.30409508
7	1125	1	14	3000	135.264	2842.66	818.84	6.4996234
8	1500	1	12	3000	160.006	3000.80	725.78	5.38677761
9	1125	0.75	10	5000	135.375	3538.08	790.16	6.22808587
10	1125	0.75	12	3000	135.223	3474.82	856.81	6.85767772
11	750	1	12	3000	124.027	2753.23	662.62	5.12940511
12	1125	0.75	12	3000	138.991	3168.68	957.72	7.77026764
13	1500	0.75	12	5000	163.743	2749.41	877.78	6.78667037
14	1500	0.75	14	3000	156.309	2717.09	887.26	6.94586913
15	1125	0.5	10	3000	171.423	3269.43	923.46	7.14419359
16	1500	0.75	10	3000	154.434	2618.12	904.42	7.12490352
17	1125	1	12	5000	137.165	2170.57	818.75	6.48089138
18	1125	0.5	12	1000	137.239	3387.41	1070.05	8.8369351
19	1125	0.75	10	1000	122.081	2960.92	801.69	6.46220511

20	1125	1	10	3000	142.989	2441.11	910.11	7.28594139
21	1125	0.5	12	5000	127.610	3618.55	995.79	8.23335905
22	1125	1	12	1000	150.743	2412.59	832.05	6.47828556
23	1125	0.75	14	1000	144.779	3035.16	834.01	6.55294874
24	750	0.75	14	3000	125.874	3071.53	771.14	6.13827274
25	1125	0.75	14	5000	142.945	3090.67	872.06	6.92858957
26	750	0.75	12	5000	122.036	3429.25	843.48	6.85635705
27	1125	0.5	14	3000	133.320	3443.15	917.73	7.44827381

2.4.1 Effect of Process Parameters on Kerf Width on the Top Surface

The microscopies view of the response of the top kerf width shown in the Fig. 2.6 the measurement of kerf width taken from optical microscope. Kerf width of top surface varying process parameters (laser power, gas pressure, scanning speed and frequency).

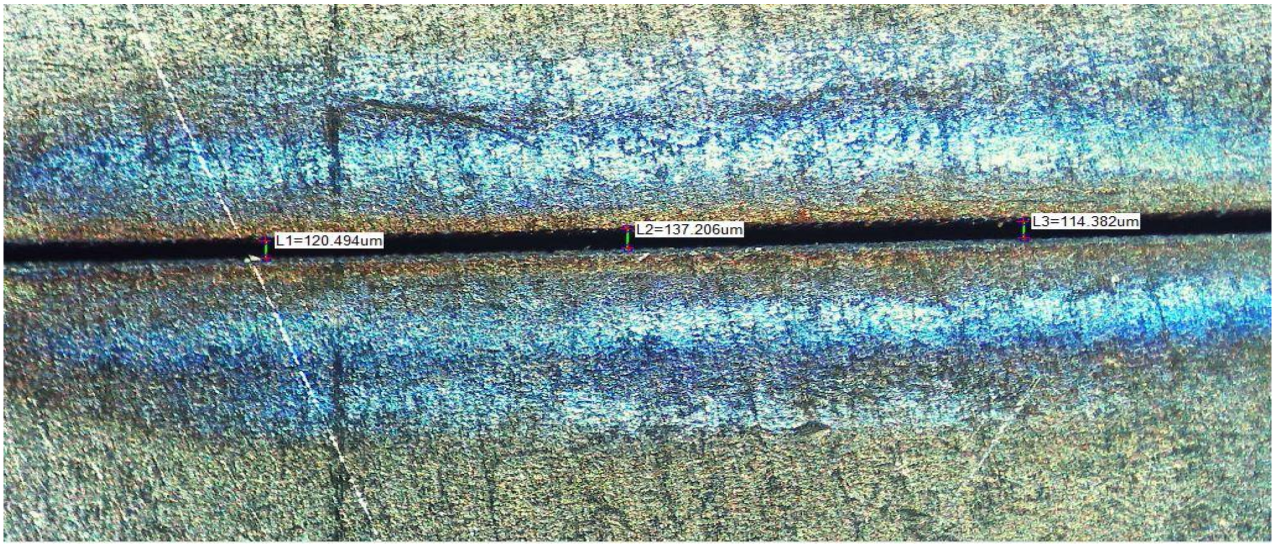


Fig. 2.6 kerf width on the top surface (magnification)

Microscopic views of the laser machined surface (laser power = 750 w,

scanning speed = 1 m/min, gas pressure = 12 bar, frequency = 3000 Hz)

Table 2.6 ANOVA of response surface quadratic model for kerf width on the top surface

Source	Sum of squares	DF	Mean square	F-Value	P-Value	
Regression	4745.78	22	215.72	6.35	0.042	significant
A- Laser Power	9.99	1	9.99	0.29	0.617	
B- Scanning Speed	1137.85	1	1137.85	33.49	0.004	significant
C- Gas Pressure	205.70	1	205.70	6.05	0.070	
D- Frequency	5.99	1	5.99	0.18	0.696	
A^2	53.64	1	53.64	1.58	0.277	

B^2	821.58	1	821.58	24.18	0.008	significant
C^2	80.95	1	80.95	2.38	0.198	
D^2	96.57	1	96.57	2.84	0.167	
AB	88.53	1	88.53	2.61	0.182	
AC	2.35	1	2.35	0.07	0.805	
AD	9.43	1	9.43	0.28	0.626	
BC	810.07	1	810.07	23.84	0.008	significant
BD	142.59	1	142.59	4.20	0.110	
CD	57.21	1	57.21	1.68	0.264	
A^2B	46.70	1	46.70	1.37	0.306	
A^2C	44.00	1	44.00	1.30	0.319	
A^2D	22.69	1	22.69	0.67	0.460	
AB^2	22.40	1	22.40	0.66	0.462	
AC^2	23.10	1	23.10	0.68	0.456	
B^2C	723.84	1	723.84	21.31	0.010	significant
B^2D	150.22	1	150.22	4.42	0.103	
BC^2	306.89	1	306.89	9.03	0.040	significant
Error	135.90	4	33.97			
Lack of Fit	41.49	2	20.75	0.44	0.695	
Pure Error	94.41	2	47.20			
Total	4881.68	26				

Table 2.7 Fit statistics of response surface methodology model

Std. Dev.	5.82876
R^2	97.22%
Adjusted R^2	81.91%

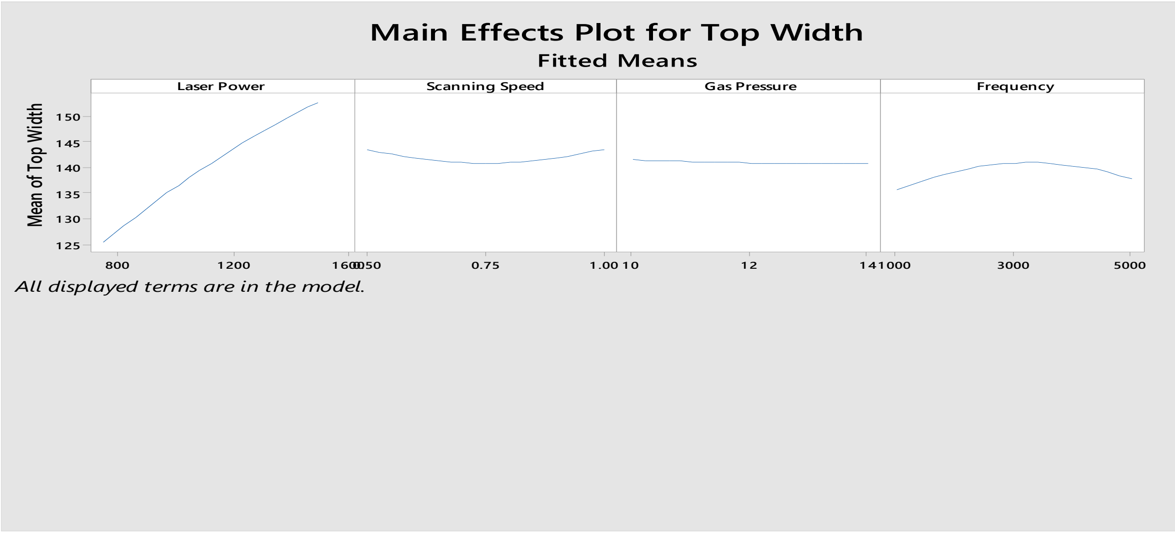
The p- value (<0.05) signifies the important process parameters and combination of process parameters, which mostly affects the response. The ANOVA Table 2.6, tells that scanning speed and gas pressure always significant as a process parameter for response to top kerf width. The R^2 value is greater, which signifies the statistical data closer to regression line.

Regression Equation:-

Top Kerf Width $= 2749 - 0.347 * P - 5559 * V - 272 * g_P - 0.0138 * f$
$+ 0.000254 * P^2 + 2238 * V^2 + 6.82 * g_P{}^2 - 0.000001 * f^2 + 0.604 * P * V -$
$0.0194 * P * g_P - 0.000017 * P * f + 541 * V * g_P + 0.1020\, V * f - 0.000945\, g_P * f$
$- 0.000137 * P^2 * V - 0.000017 * P^2 * g_P + 0.000000 * P^2 * f - 0.143\, P * V^2$
$+ 0.00227 * P * g_P{}^2 - 152.2 * V^2 * g_P - 0.0693 * V^2 * f - 12.39 * V * g_P{}^2$

The combined effects of Laser power, Scanning speed, Gas pressure and Frequency on the top kerf width were studied using regression analysis.

Fig. 2.7 Analysis of main effect plot for top width



From the above main effect plot of top width it is observed that increase laser power will increase top width because more laser power more energy involved. Increase scanning speed will decrease top width upto certain time cause laser move faster less time to deliver energy to the material after certain limit it will increase. For gas pressure almost near same top width increase gas pressure. Top width increase with frequency because more frequency will cause more average power and that will accumulate more energy. For maximum top width the parameters combination will be – Laser power 1500 W, scanning speed 1 m/min, gas pressure 10 bar and frequency 2000 Hz.

❖ **Analysis of 3 D surface plots with respect to kerf width on top surface:**

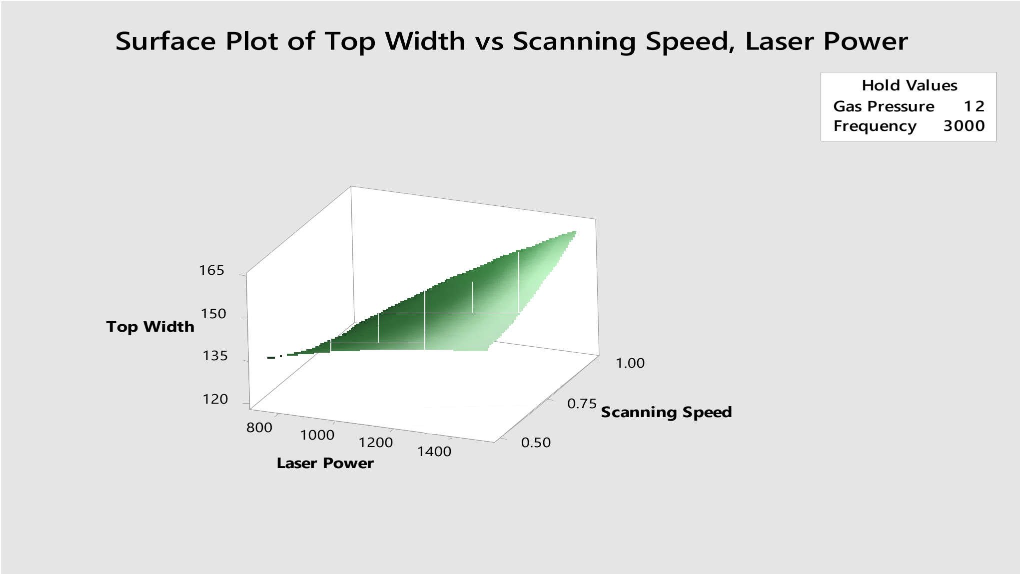


Fig. 2.8 Top kerf width vs Laser power & Scanning speed

At constant gas pressure (12 bar) and frequency (3000 Hz), kerf width on the top width vs scanning speed and laser power plot indicates at fixed scanning speed, increasing laser power top width will be increasing and at fixed laser power, increasing scanning speed top width increasing. When laser power increase and scanning speed increase the top width also be increase.

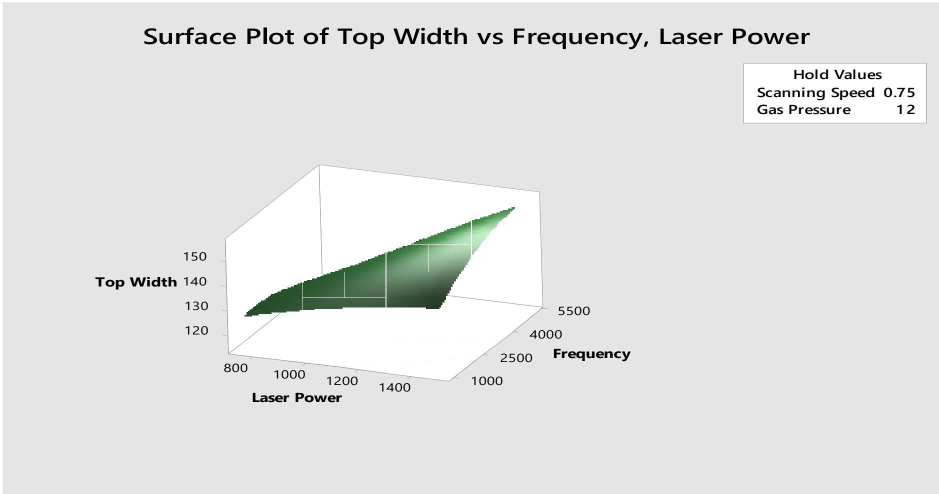


Fig. 2.9 Top kerf width vs Laser power & Frequency

At constant gas pressure (12 bar) and scanning speed (0.75 m/min), kerf width on the top surface vs frequency and laser power plot indicates at fixed frequency, top width increasing by increasing laser power and fixed laser power, increasing frequency there top width will be increase. When minimum frequency and maximum laser power there also be top width increase.

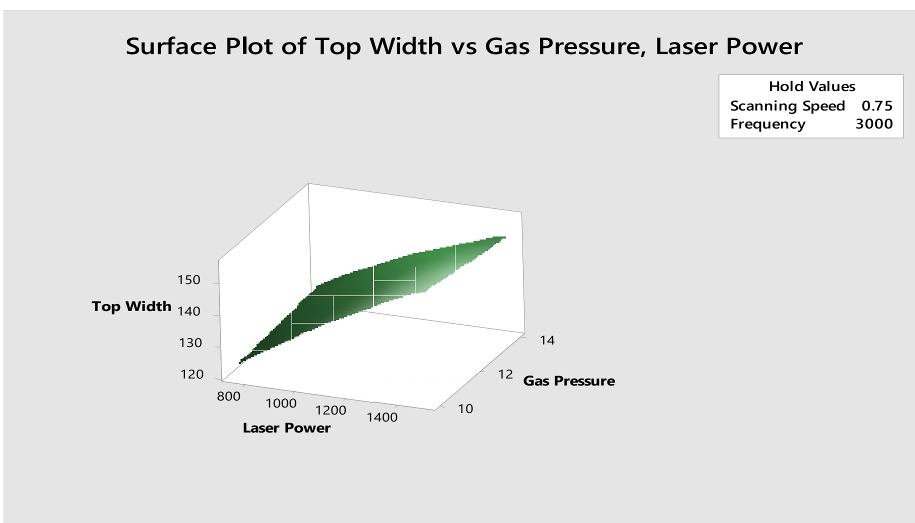


Fig. 2.10 Top kerf width vs Laser power & Gas pressure

At constant scanning speed (0.75 m/min) and frequency (3000 Hz), kerf width on the top surface vs gas pressure and laser power plot indicates at fixed gas pressure, the top width increasing by increasing laser power and fixed laser power, increasing gas pressure the top width will be increase. Also increase laser power and gas pressure the top width kerf also be increased.

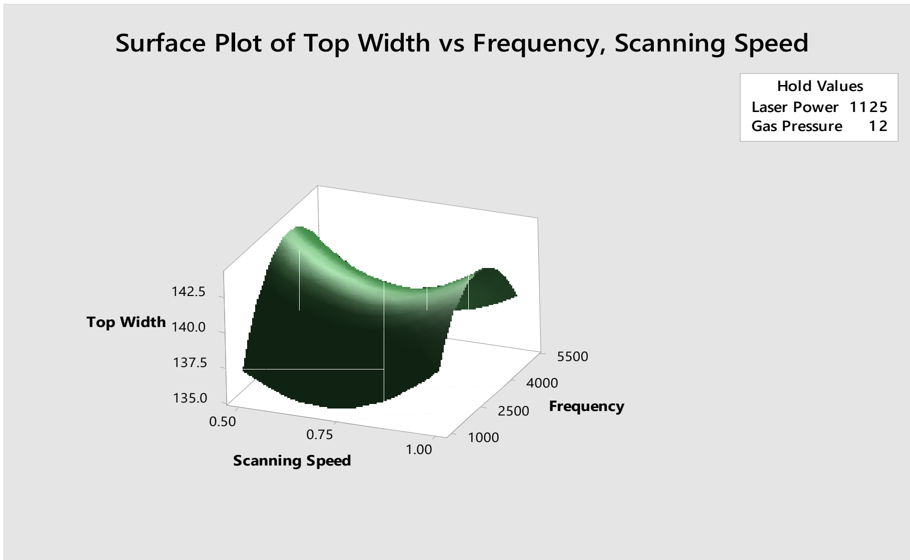


Fig. 2.11 Top kerf width vs Scanning speed & Frequency

At constant laser power (1125 W) and gas pressure (12 bar), kerf width on the top surface vs scanning speed and frequency plot indicates at fixed scanning speed, increasing frequency top width at a certain time it will increased and maximum frequency the top width will be decreased. When increasing scanning speed and frequency the top width kerf at primary stage it will decrease and after maximum scanning speed the top width moderate increased.

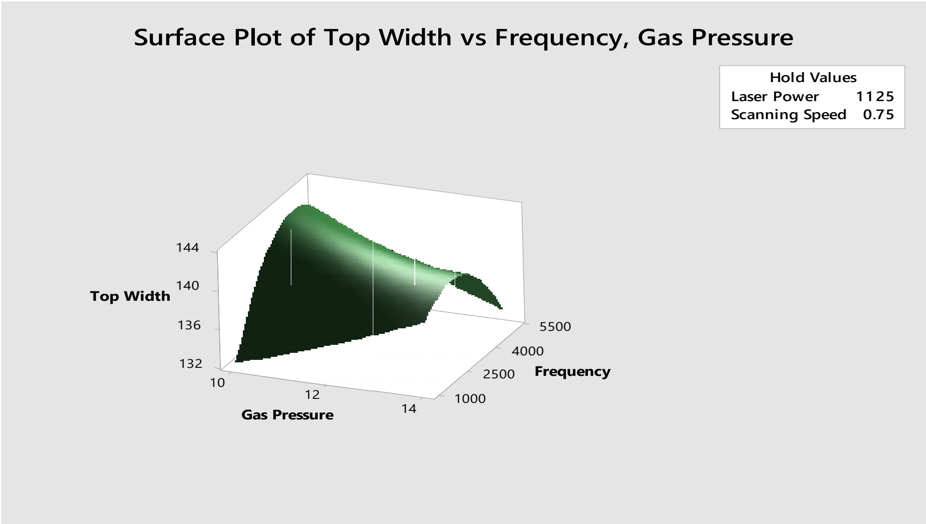


Fig. 2.12 Top kerf width vs Gas pressure & Frequency

At constant laser power (1125 W) and scanning speed (0.75 m/min), kerf width on the top surface vs gas pressure and frequency plot indicates at fixed frequency, decreasing gas pressure the top width decrease and increasing gas pressure top width increased. When increasing gas pressure and frequency the top width kerf at initial increase after reaching maximum frequency the top width will be decreased.

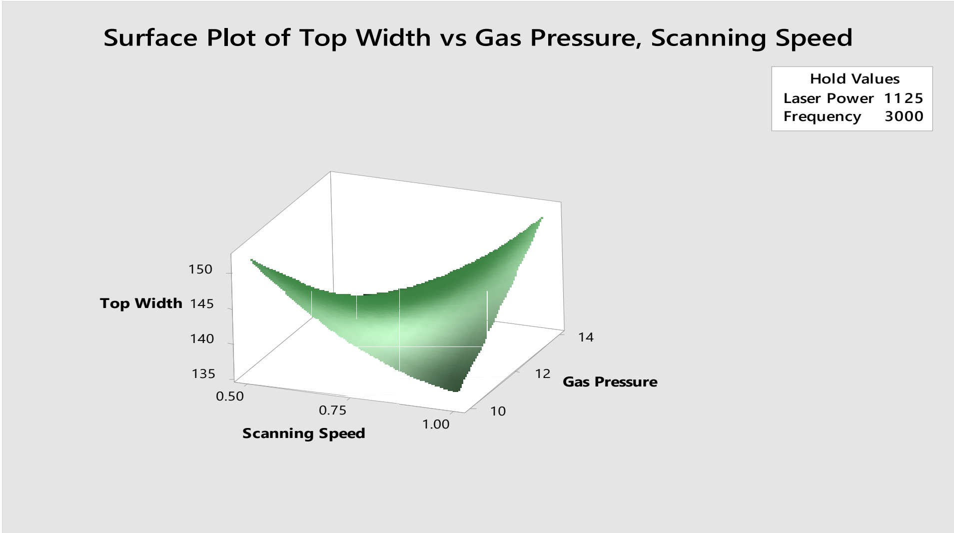


Fig. 2.13 Top kerf width vs Scanning speed & Gas pressure

At constant laser power (1125 W) and frequency (3000 Hz), kerf width on the top surface vs scanning speed and gas pressure plot indicates at fixed gas pressure, increasing scanning speed the top width will be decreased and fixed scanning speed, increasing gas pressure the top width will be increased. When increasing scanning speed also be increasing gas pressure the top width kerf primarily decreased and after reaching top gas pressure then top top width kerf will be increased. Here minimum gas pressure and minimum scanning speed the higher top width will be obtain.

2.4.2 Effects of Process Parameters on Heat-affected Zone (HAZ)

The microscopies views of the response of the heat affected zone shown in the Fig. 2.14 the measurement of kerf width taken from optical microscope. Heat affected zone varies with varying process parameters (laser power, gas pressure, scanning speed and frequency).

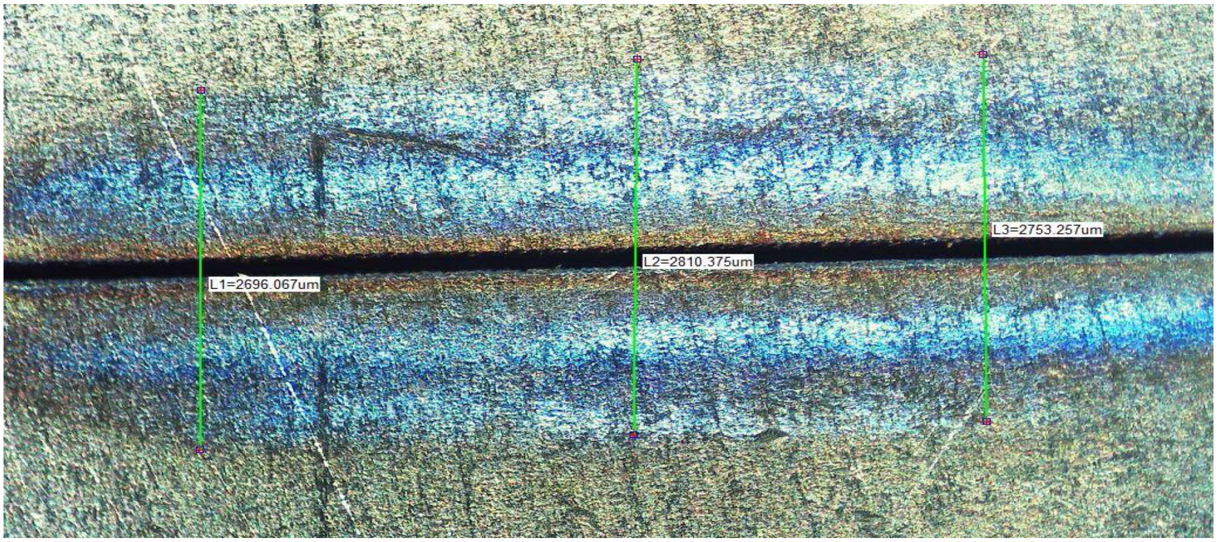


Fig. 2.14 heat-affected Zone on the top surface (magnification)

Microscopic views of the laser machined surface (laser power = 750 w, scanning speed = 1 m/min, gas pressure = 12 bar, frequency = 3000 Hz)

Table 2.8 ANOVA of response surface quadratic model for HAZ on the top surface

Source	Sum of Squares	DF	Mean Square	F-Value	P-Value	
Regression	2936496	17	172735	3.73	0.025	significant
A- Laser Power	598755	1	598755	12.93	0.006	significant
B- Scanning Speed	378141	1	378141	8.17	0.019	significant
C- Gas Pressure	245995	1	245995	5.31	0.047	significant
D- Frequency	102295	1	102295	2.21	0.171	
A^2	461060	1	461060	9.96	0.012	significant
B^2	211111	1	211111	4.56	0.061	
C^2	204504	1	204504	4.42	0.065	
AB	556341	1	556341	12.02	0.007	significant
AD	61213	1	61213	1.32	0.280	
BC	179762	1	179762	3.88	0.080	
BD	55971	1	55971	1.21	0.300	
CD	72845	1	72845	1.57	0.241	
A^2B	410986	1	410986	8.88	0.015	significant
AB^2	177228	1	177228	3.83	0.082	
B^2C	74247	1	74247	1.60	0.237	
BC^2	123499	1	123499	2.67	0.137	

C^2D	63895	1	63895	1.38	0.270	
Error	416667	9	46296			
Lack of Fit	258559	7	36937	0.47	0.812	
Pure Error	158108	2	79054			
Total	3353162	26				

Table 2.9 Fit statistics of response surface methodology model

Std. Dev.	215.166
R^2	87.57%
Adjusted R^2	64.10%

The p- value (<0.05) signifies the important process parameters and combination of process parameters, which mostly affects the response. The ANOVA Table 2.8, tells that laser power always significant as a process parameter for response to heat-affected zone.
The R^2 value is greater , which signifies the statistical data closer to regression line.

Regression Equation:-

Heat-affected Zone (HAZ) = $-63446 + 29.11 * P + 93779 * V + 7121 * g_P$

$+ 3.54 * f - 0.01043 * P^2 - 30348 * V^2 - 265\, g_P^2 - 44.8 * P * V - 0.000165 * P * f$

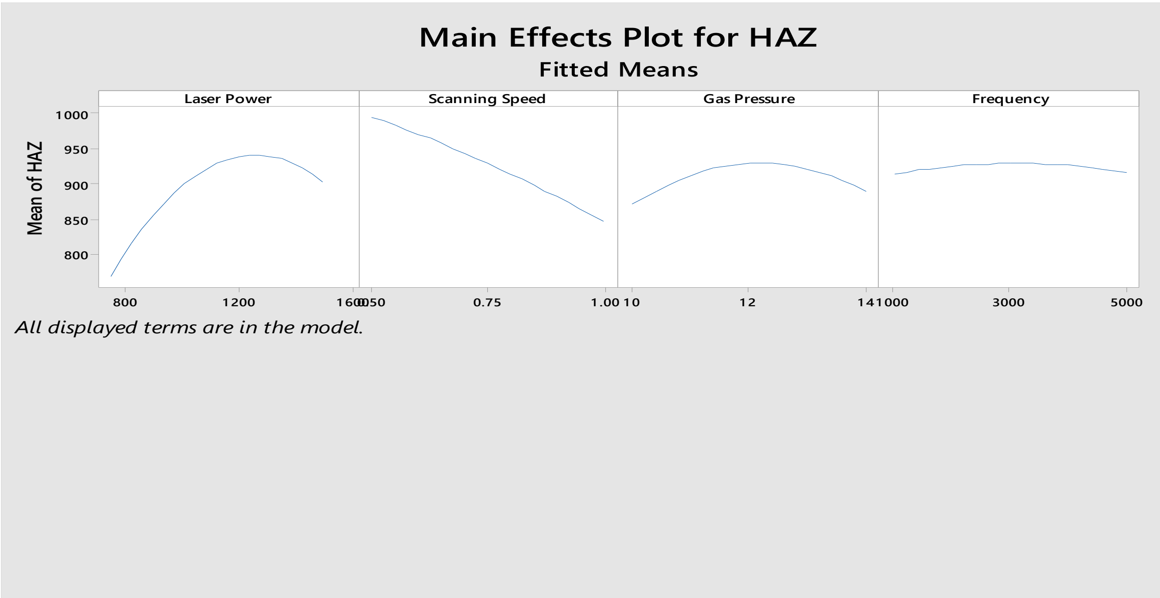
$- 7852 * V * gP - 0.237 * V * f - 0.497 * gP * f + 0.01289 * P^2 * V + 11.00 * P * V^2$

$+ 1335 * V^2 * g_P + 248 * V * g_P^2 + 0.0193 * g_P^2 * f$

The combined effects of Laser power, Scanning speed, Gas pressure and Frequency

on the heat-affected zone were studied using regression analysis.

Fig. 2.15 Analysis of main effect plot for HAZ



From the above main effect plot of heat affected zone it is observed increase laser power heat affected zone increasing certain time after certain limit the HAZ zone decrease cause more laser power it will absorb more energy the heat zone will be more. Decreasing HAZ with increase scanning speed cause high laser move faster at that time material interaction time less that's why it will decrease. When increase gas pressure HAZ moderate increase cause when laser beam spot the material energy absorbed then melt after ready plasma gas pressure ablate the material. Decreasing HAZ with increase frequency cause no of pulse very fast interaction to material less time power beam to material the HAZ will be decreased. For maximum HAZ the parameters combination will be – Laser power 1200 W, scanning speed 0.5 m/min, gas pressure 12 bar and frequency 2000 Hz.

❖ **Analysis of 3 D surface plots with respect to HAZ width on top surface:**

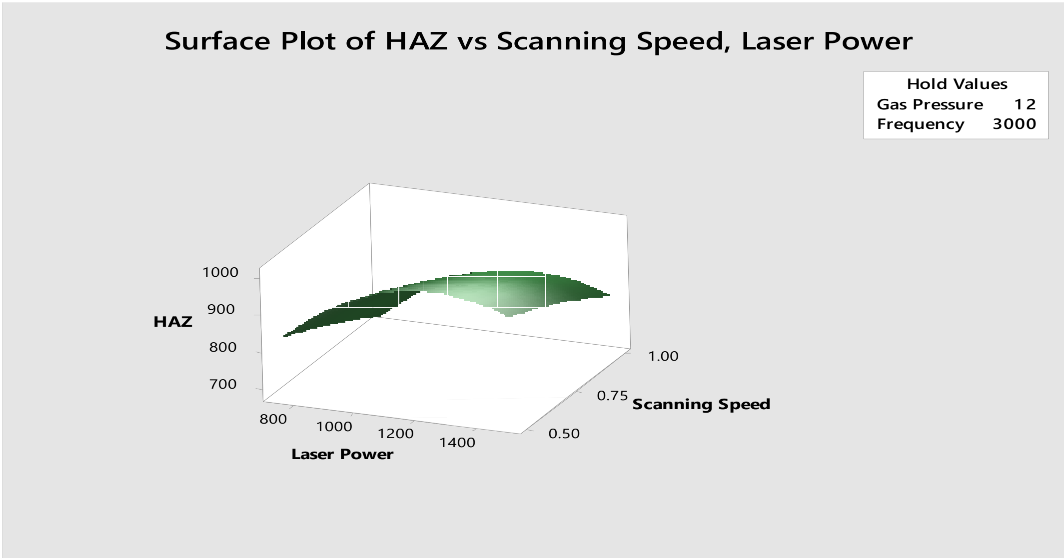


Fig. 2.16 HAZ width vs Laser power & Scanning speed

At constant gas pressure (12 bar) and frequency (3000 Hz), HAZ width on the top surface vs laser power and scanning speed plot indicates at fixed scanning speed, increasing laser power the heat –affected zone will be effect range between laser power, the heat zone increase but increase laser power the heat zone decrease. When scanning speed increase also increase laser power the heat-affected zone moderate decrease.

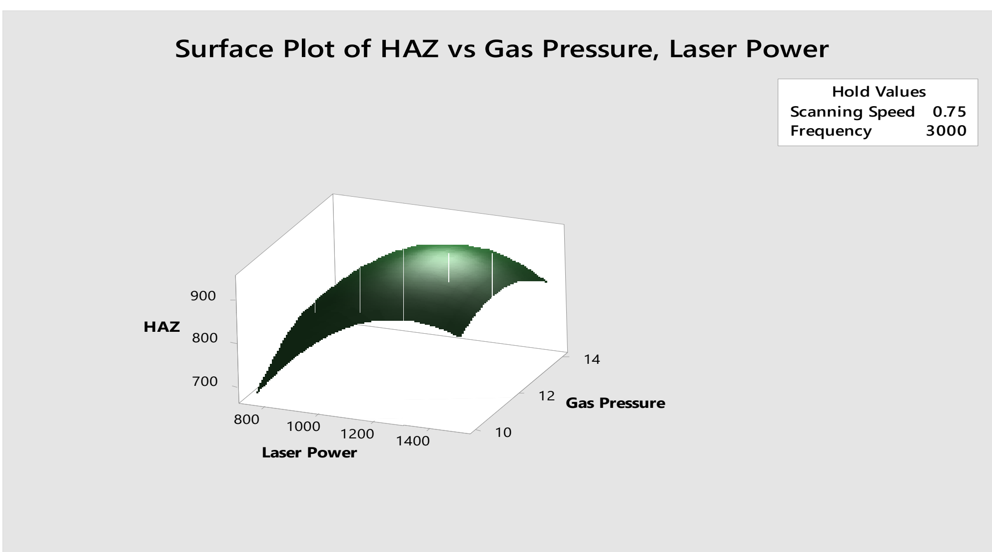


Fig. 2.17 HAZ width vs Laser power & gas pressure

At constant scanning speed (0.75 m/min) and frequency (3000 Hz) heat-affected zone width on the top surface vs gas pressure and laser power plot indicates at fixed gas pressure, the heat-affect zone moderate increase increasing laser power and increase gas pressure will be moderate decrease. Decreasing gas pressure also decrease laser power the heat zone will be decreased.

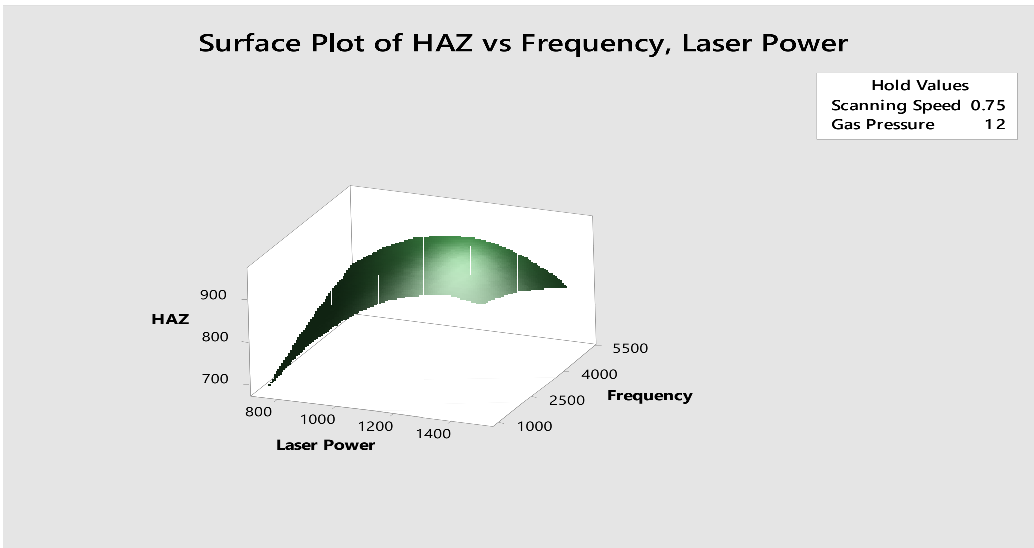


Fig. 2.18 HAZ width vs Laser power & Frequency

At constant scanning speed (0.75 m/min) and gas pressure (12), heat affected zone width on the top surface vs laser power and frequency plot indicates at fixed frequency, increasing the heat affected zone increase, increasing laser power & fixed laser power moderate frequency increase heat affected zone increasing. At low frequency high laser power the heat affected zone width decrease.

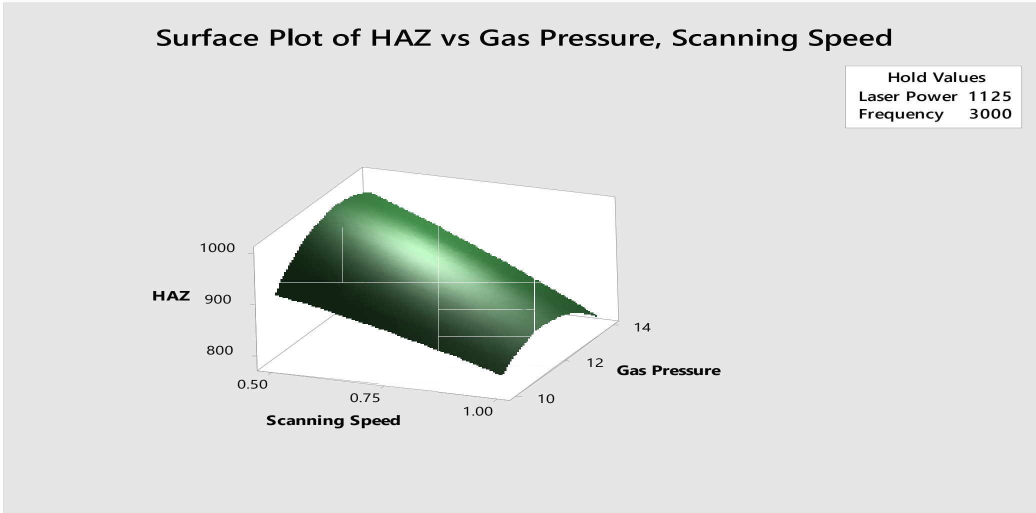


Fig. 2.19 HAZ width vs Scanning speed & Gas pressure

At constant laser power (1125 W) and frequency (3000 Hz), heat affected zone width on the top surface vs scanning speed and gas pressure plot indicates at fixed gas pressure, HAZ decreasing with increase scanning speed and increase gas pressure HAZ will be moderate decreasing. At decreasing gas pressure, HAZ increase by increasing scanning sped.

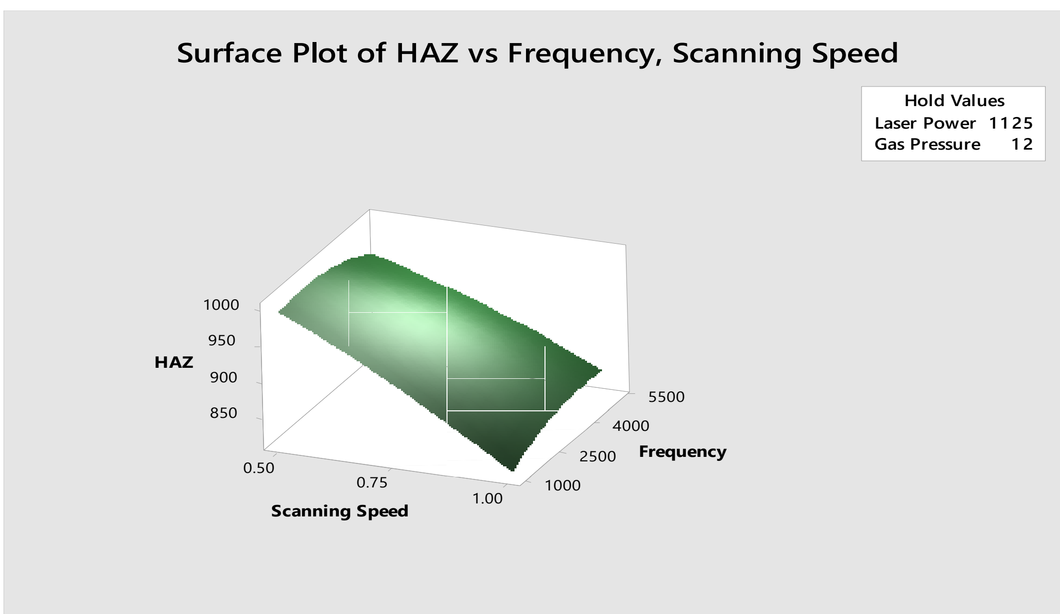


Fig. 2.20 HAZ width vs Scanning speed & Frequency

At constant laser power (1125 W) and gas pressure (12 bar), heat affected zone width on the top surface vs scanning speed and frequency plot indicates at fixed frequency, HAZ width decreasing by increasing scanning speed & fixed scanning speed, HAZ will moderate decreased by increasing frequency. When both increasing heat affected zone width decreasing.

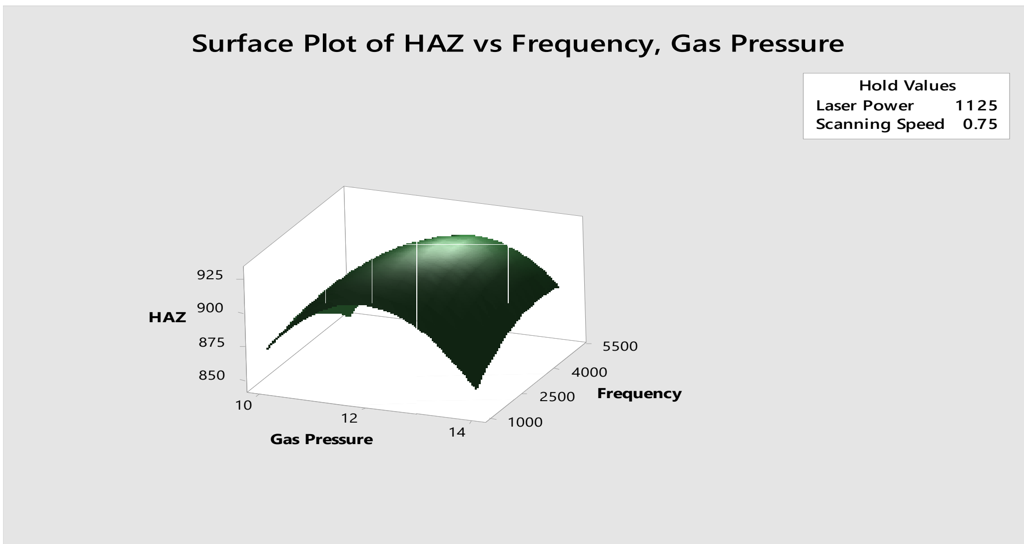


Fig. 2.21 HAZ width vs Gas pressure & Frequency

At constant laser power (1125 W) and scanning speed (0.75 m/min), heat affected zone width on the top surface vs gas pressure and frequency plot indicates at fixed frequency, HAZ will be decreasing by increasing gas pressure & moderate frequency increasing the heat affected zone increasing. When both increasing the HAZ initially increasing then deacreasing.

2.4.3 Effects of Process Parameters on Kerf Width on the Bottom Surface

The microscopies views of the response of the bottom kerf width in the Fig. 2.22 the measurement of kerf width taken from optical microscope. Kerf width of bottom surface varies with varying process parameters (laser power, gas pressure, scanning speed and frequency).

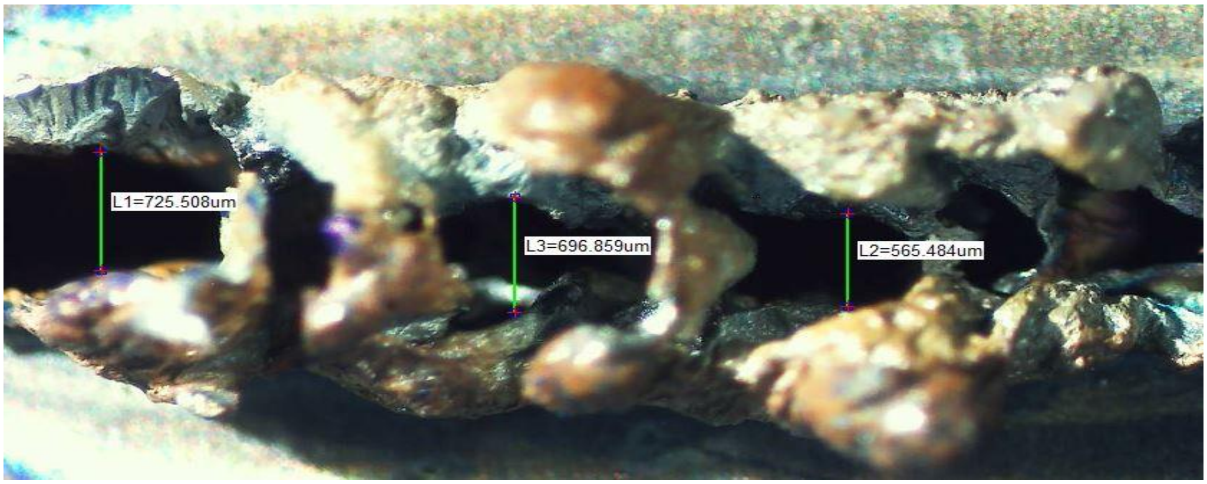


Fig. 2.22 kerf width on the bottom surface (magnification)

Microscopic views of the laser machined surface (laser power = 750 w,

scanning speed = 1 m/min, gas pressure = 12 bar, frequency = 3000 Hz)

Table 2.10 ANOVA of response surface quadratic model for kerf width on the bottom surface

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Regression	224746	14	16053.3	5.42	0.003	significant
A- Laser Power	4099	1	4099.3	1.38	0.262	
B- Scanning Speed	35	1	34.7	0.01	0.916	
C- Gas Pressure	14110	1	14109.9	4.76	0.050	significant

D-Frequency	15289	1	15289.0	5.16	0.042	significant
A^2	48596	1	48595.9	16.40	0.002	significant
B^2	12069	1	12069.1	4.07	0.066	
C^2	18033	1	18033.1	6.09	0.030	significant
AB	7204	1	7204.0	2.43	0.145	
AC	3912	1	3912.4	1.32	0.273	
AD	15659	1	15659.1	5.29	0.040	significant
BC	4517	1	4516.8	1.52	0.241	
AB^2	7357	1	7357.1	2.48	0.141	
B^2C	6634	1	6634.3	2.24	0.160	
BC^2	12790	1	12790.3	4.32	0.060	
Error	35552	12	2962.6			
Lack of Fit	27575	10	2757.5	0.69	0.719	
Pure Error	7976	2	3988.2			
Total	260297	26				

Fig. 2.11 Fit statistics of response surface methodology model

Std. Dev.	54.4301
R^2	86.34%
Adjusted R^2	70.41%

The p- value (<0.05) signifies the important process parameters and combination of process parameters, which mostly affects the response. The ANOVA Table 2.10, tells that scanning speed and gas pressure always significant as a process parameter for response to heat-affected zone. The R^2 value is greater, which signifies the statistical data closer to regression line.

Regression Equation:-

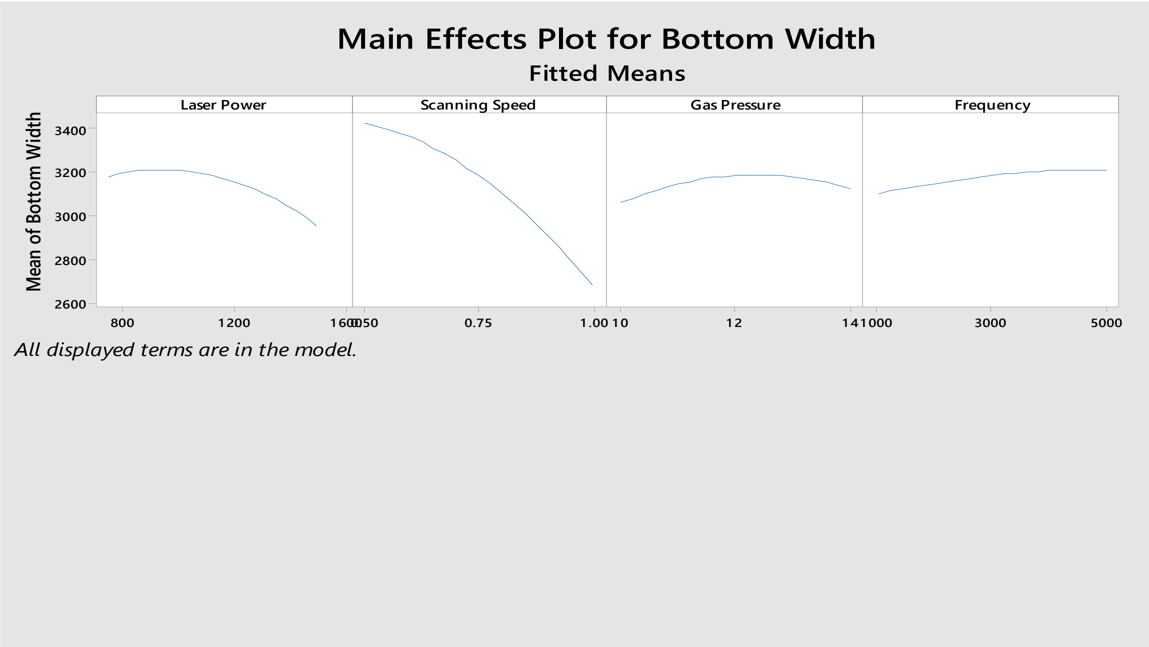
Bottom Kerf Width = $-6259 + 1.159 * P - 783 * V + 1384 * g_P + 0.0944 * f$

$- 0.000640 * P^2 + 7256 * V^2 - 63.2 * g_P^2 + 3.36 * P * V - 0.0417 * P * g_P – 0.000083 * P$

$* f - 1106 * V * g_P - 2.24 * P * V^2 - 399 * V^2 * g_P + 69.3 * V * g_P^2$

The combined effects of Laser power, Scanning speed, Gas pressure and Frequency on the heat-affected zone were studied using regression analysis.

Fig. 2.23 Analysis of main effect plot for bottom width



From the above main effect plot of bottom width it is observed bottom width decrease with increase laser cause more laser power heat will more energy the bottom width has decreased. Increasing scanning speed that effect decreasing bottom width cause high power beam faster move by higher scanning speed. Moderate increase bottom width with increase gas pressure cause material ablate rate very fast with power beam. Increasing frequency bottom width will be increase, more laser beam interaction time more to material with increase frequency the bottom width will be increased. For maximum bottom width the parameters combination will be – Laser power 1000 W, scanning speed 0.5 m/min, gas pressure 13 bar and frequency 5000 Hz.

- **Analysis of 3 D surface plots with respect to kerf width on bottom surface:**

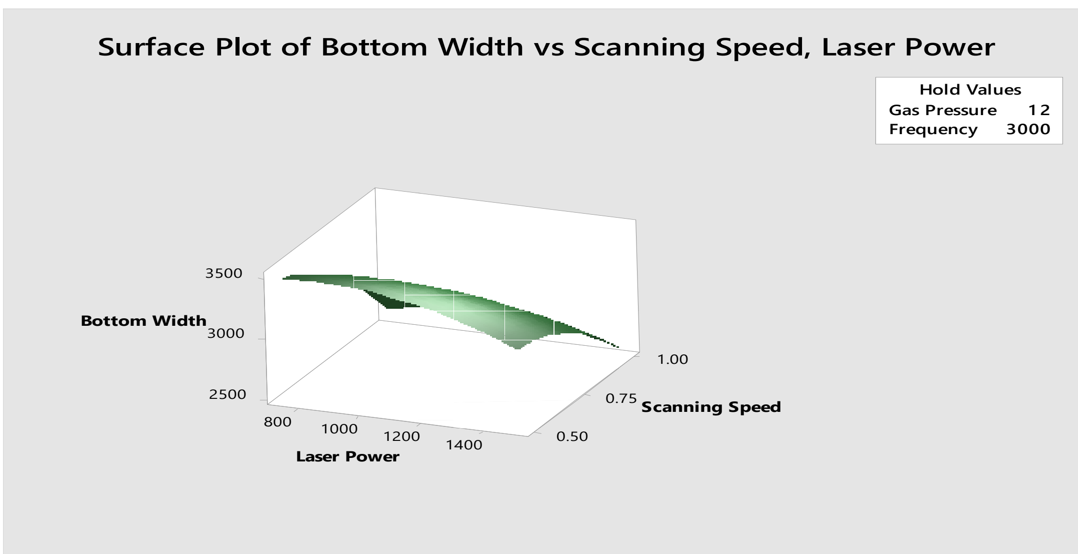


Fig. 2.24 Bottom width vs Laser power & Scanning speed

At constant gas pressure (12 bar) and frequency (3000 Hz), kerf width on the bottom surface vs laser power and scanning speed plot indicates at fixed laser power, decreasing bottom with by increasing scanning speed & also decreasing bottom width by increasing laser power. At bottom width on the bottom surface moderate decreasing by decreasing scanning speed and increasing laser power.

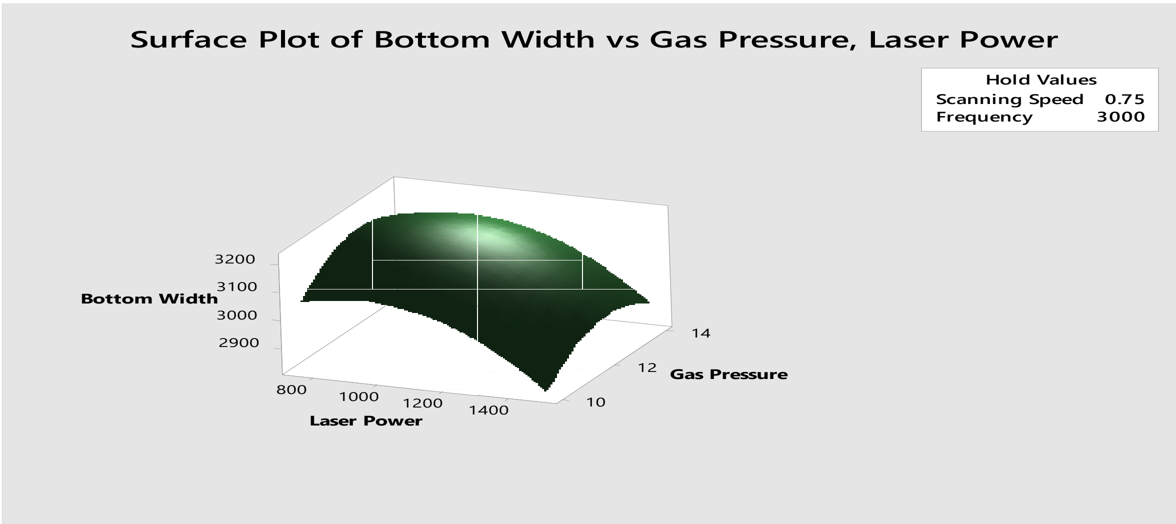


Fig. 2.25 Bottom width vs Laser power & Gas pressure

At constant scanning speed (0.75 m/min) and frequency (3000 Hz), kerf width on the bottom surface vs laser power and gas pressure plot indicates at fixed gas pressure, increasing the laser power the bottom width will be decreased & fixed laser power, the bottom width moderate increasing by increasing gas pressure. At low gas pressure and increasing laser power the bottom width on the bottom surface will be increasing.

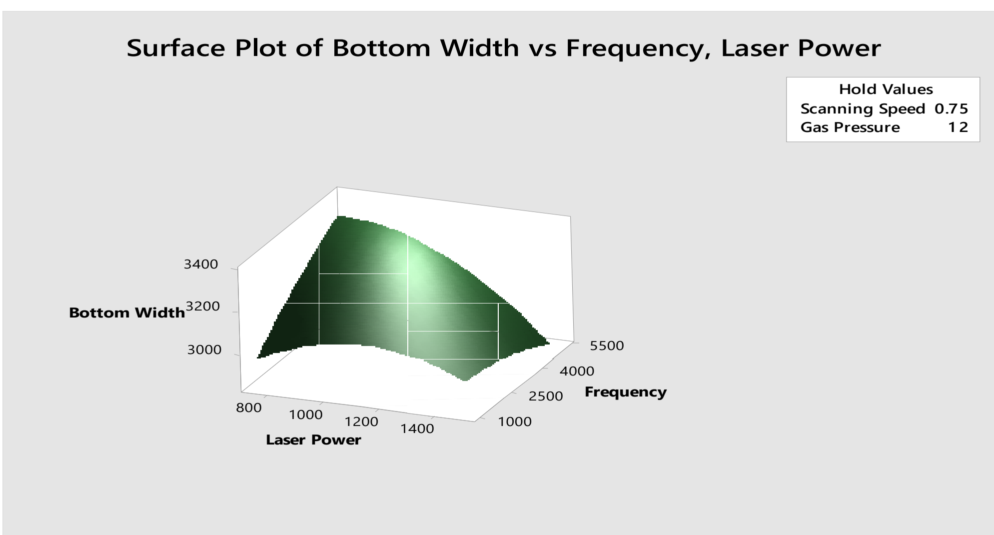


Fig. 2.26 Bottom width vs Laser power & Frequency

At constant scanning speed (0.75 m/min) and gas pressure (12 bar), kerf width on the bottom surface vs laser power and frequency plot indicates at fixed frequency, the bottom width moderate decrease by increasing laser power & fixed laser power, the bottom width also be decreasing by increasing frequency. At low laser power and high frequency the bottom width wll be increase.

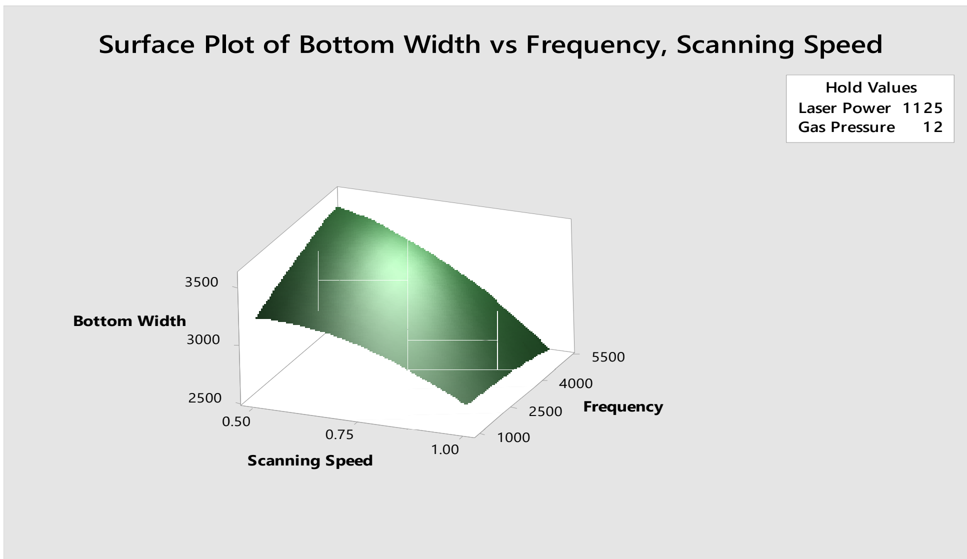


Fig. 2.27 Bottom width vs Scanning speed & Frequency

At constant laser power (1125 W) and gas pressure (12 bar), kerf width on the bottom surface vs scanning speed and frequency plot indicates at fixed frequency, the bottom width decreasing by increasing scanning speed & fixed scanning speed, the bottom width moderate decreasing by increasing frequency. At low frequency and high scanning speed the bottom width also be increased.

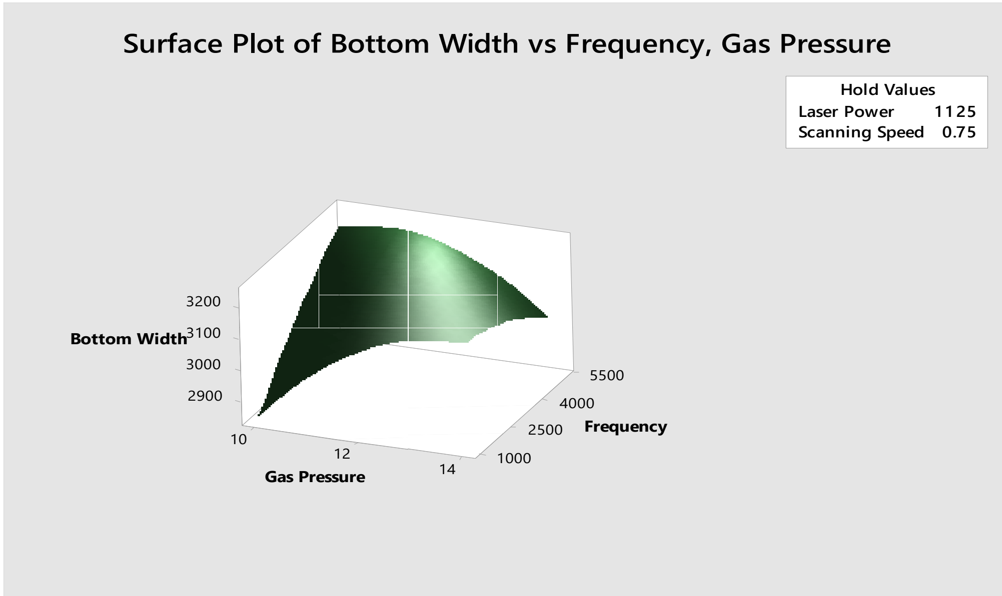


Fig. 2.28 Bottom width vs Gas pressure & Frequency

At constant laser power (1125 W) and scanning speed (0.75 m/min), kerf width on the bottom surface vs gas pressure and frequency plot indicates at fixed increasing gas pressure the bottom width will be increased & fixed gas pressure, increasing frequency the bottom width moderate decrease. At low gas pressure and high frequency the bottom width will be increased.

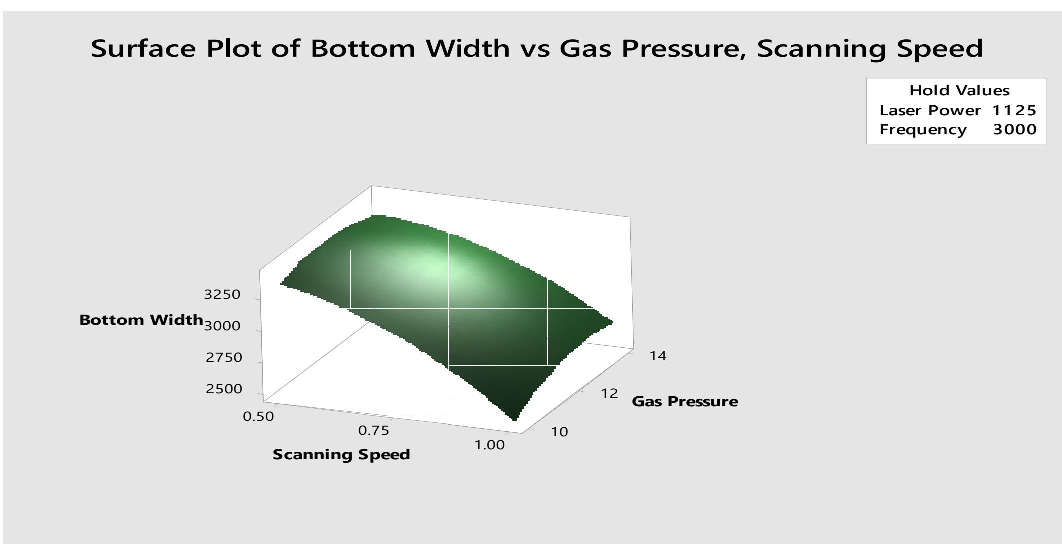


Fig. 2.29 bottom width vs Scanning speed & Gas pressure

At constant laser power (1125 W) and frequency (3000 Hz), kerf width on the bottom surface vs scanning speed and gas pressure plot indicates at fixed gas pressure, the bottom width decreasing by increasing scanning speed & fixed scanning speed, increase gas pressure the bottom width moderate increasing. At low gas pressure and low scanning speed the bottom width will be increased.

2.4.4 Effects of Process Parameters on Taper Angle

Taper angle changes with changing process parameters (laser power, scanning speed, gas pressure and frequency).

Table 2.12 ANOVA of response surface quadratic model for taper angle

Source	Sum of Squares	DF	Mean Square	F-Value	P-Value	
Regression	18.4602	14	1.31858	5.68	0.002	significant
A- Laser Power	0.5097	1	0.50974	2.20	0.164	
B- Scanning Speed	0.0812	1	0.08115	0.35	0.565	
C- Gas Pressure	1.8153	1	1.81534	7.82	0.016	significant
D- Frequency	1.6645	1	1.66447	7.17	0.020	significant
A^2	4.3629	1	4.36286	18.80	0.001	significant
B^2	0.5454	1	0.54541	2.35	0.151	

C^2	2.0333	1	2.03327	8.76	0.012	significant
AB	0.4695	1	0.46946	2.02	0.180	
AC	0.3616	1	0.36162	1.56	0.236	
AD	1.7233	1	1.72325	7.42	0.018	significant
BC	0.8102	1	0.81017	3.49	0.086	
AB^2	0.5067	1	0.50673	2.18	0.165	
B^2C	0.2424	1	0.24243	1.04	0.327	
BC^2	1.4818	1	1.48178	6.38	0.027	significant
Error	2.7851	12	0.23209			
Lack of Fit	2.1951	10	0.21951	0.74	0.696	
Pure Error	0.5900	2	0.29502			
Total	21.2453	26				

Table 2.13 Fit statistics of response surface methodology model

Std. Dev.	0.481760
R^2	86.89%
Adjusted R^2	71.60%

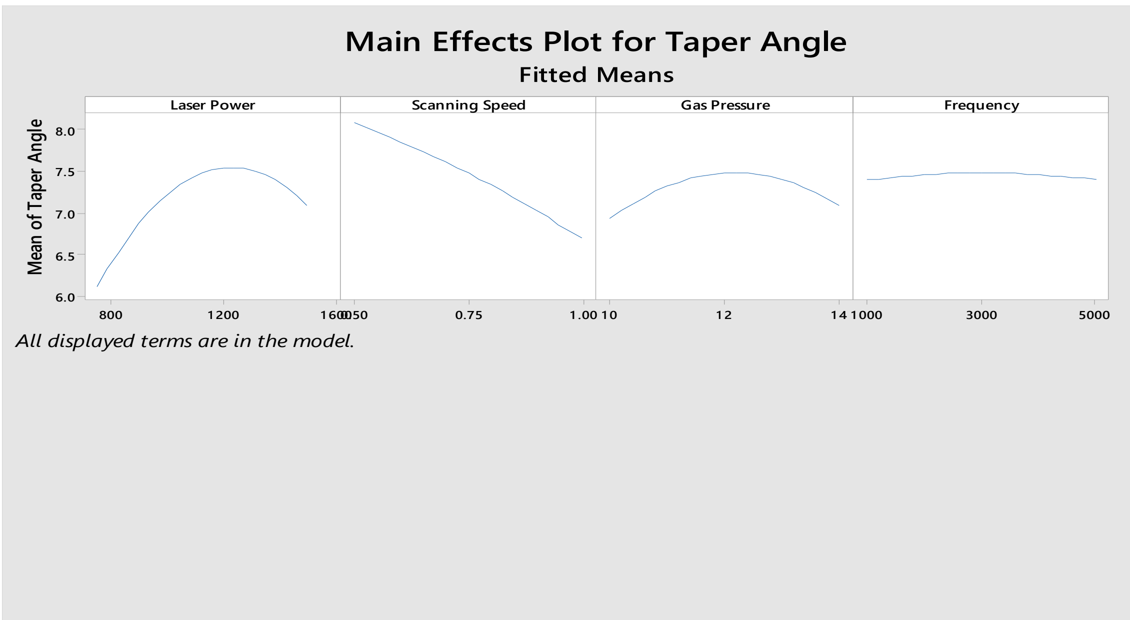
The p- value (<0.05) signifies the important process parameters and combination of process parameters, which mostly affects the response. The ANOVA Table 2.11, tells that scanning speed and gas pressure always significant as a process parameter for response to heat-affected zone. The R^2 value is greater than 90%, which signifies the statistical data closer to regression line.

Regression Equation:-

Taper Angle = -83.5 + 0.01292 * P + 37.8 * V + 15.69 * g_P + 0.000985 * f - 0.000006 * P^2 + 48.8 * V^2 - 0.671 g_P^2 + 0.0271 * P * V - 0.000401 * P * g_P - 0.000001 * P * f - 14.82 * V * g_P - 0.0186 * P * V^2 - 2.41 * V^2 * g_P + 0.745 * V * g_P^2

The combined effects of Laser power, Scanning speed, Gas pressure and Frequency on the heat-affected zone were studied using regression analysis.

Fig. 2.30 Analysis of main effect plot for taper angle



From the above main effect plot of heat affected zone it is observed that increase laser power the taper angle certain time it will increase after at certain limit it will decrease. Decreasing taper angle with increase scanning speed. Moderate increase taper angle with increase gas pressure. Moderate same taper angle with increasing frequency. For maximum taper angle the parameters combination will be – Laser power 1200 W, scanning speed 0.50 m/min, gas pressure 12 bar and frequency 2000 Hz.

❖ Analysis of 3D surface plot for taper angle:

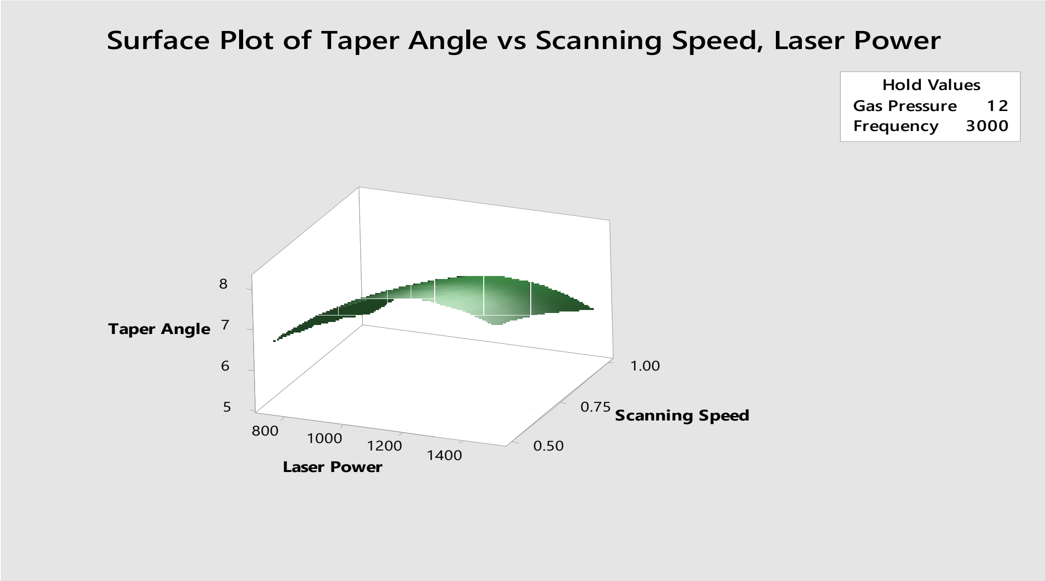


Fig. 2.31 Taper angle vs Laser power & scanning speed

At constant gas pressure (12 bar) and frequency (3000 Hz), taper angle vs laser power and scanning speed plot indicates at fixed scanning speed, increasing laser power the taper angle will be moderate decreasing & fixed laser power, taper angle moderate decreasing with increasing scanning speed. At high scanning speed and high laser power the taper angle will be decreasing.

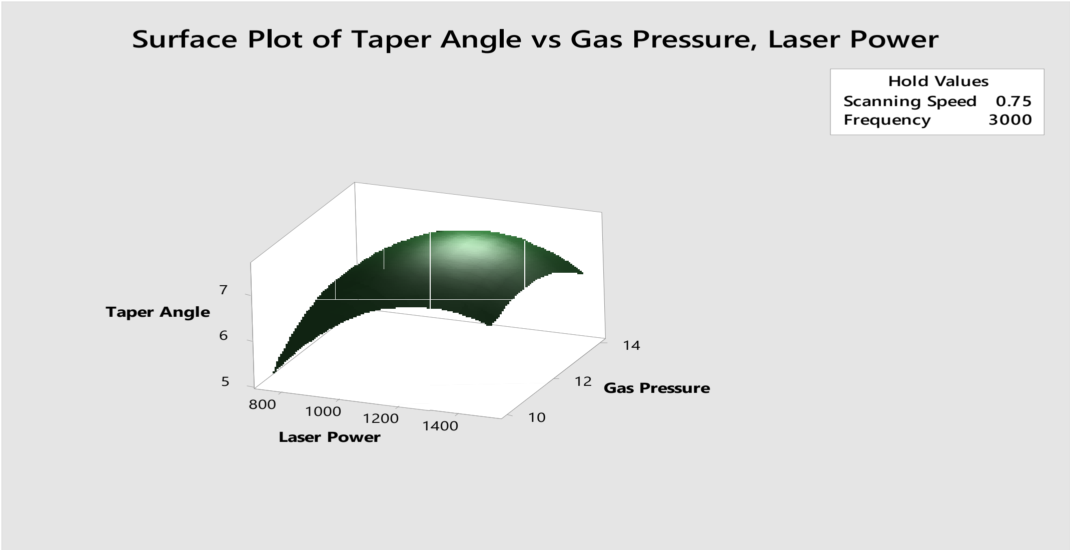


Fig. 2.32 Taper angle vs Laser power & Gas pressure

At constant scanning speed (0.75 m/min) and frequency (3000 Hz), taper angle vs laser power and gas pressure at fixed gas pressure taper angle increase with increasing laser power & fixed laser power taper angle moderate increase with increasing gas pressure. At low gas pressure taper angle decrease with increase laser power.

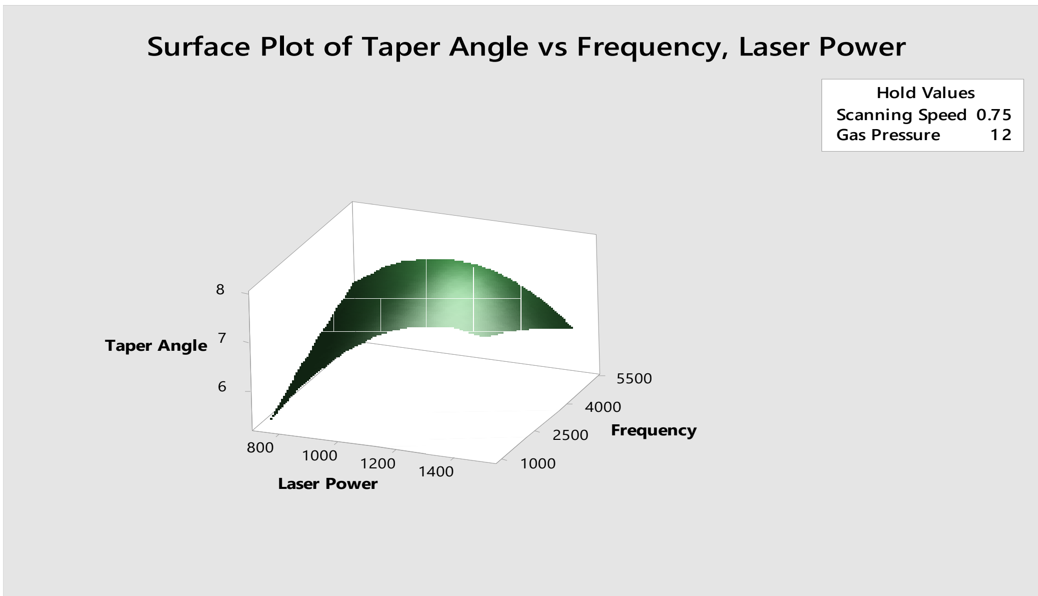


Fig. 2.33 Taper angle vs Laser power & frequency

At constant scanning speed (0.75 m/min) and gas pressure (12 bar), taper angle vs laser power and frequency plot indicates at fixed frequency taper angle increase with increasing laser power & fixed laser power taper angle decrease with increasing frequency. At low laser power taper angle increase with increasing frequency.

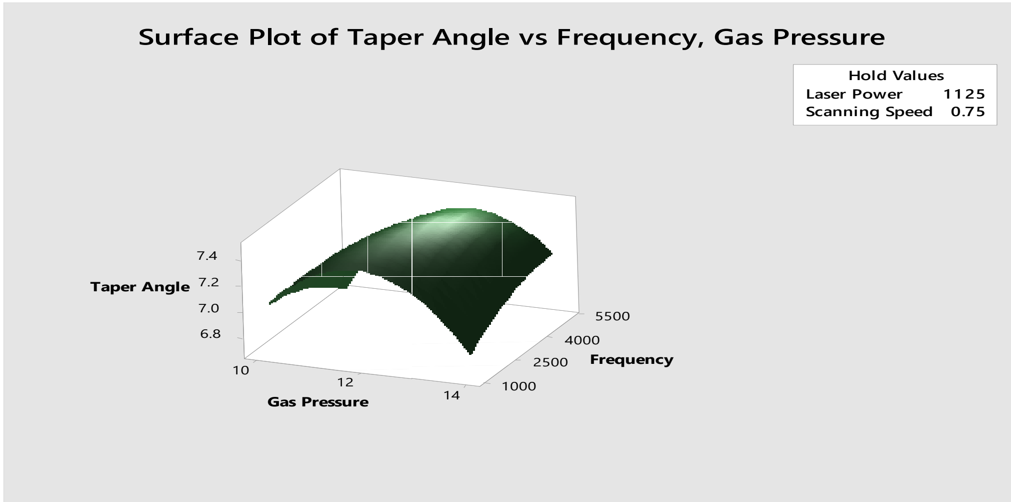


Fig. 2.34 Taper angle vs Gas pressure & Frequency

At constant laser power (1125 W) and scanning speed (0.75 m/min), taper angle vs gas pressure and frequency at fixed frequency taper angle decrease with increasing gas pressure & fixed gas pressure taper angle increase with increasing frequency. At low frequency taper angle moderate decrease with decreasing gas pressure.

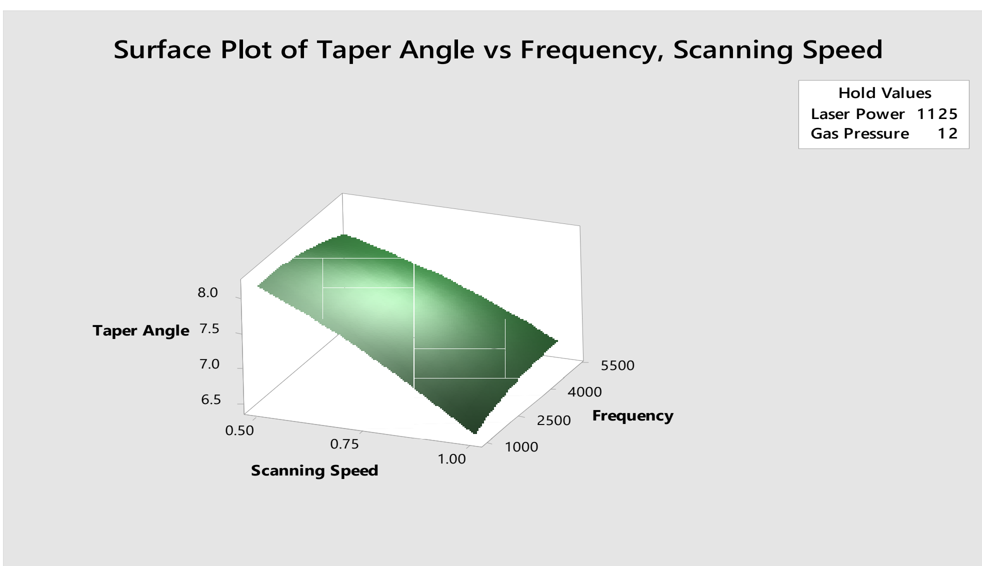


Fig. 2.35 Taper angle vs Scanning speed & Frequency

At constant laser power (1125 W) and gas pressure (12 bar), taper angle vs scanning speed and frequency plot indicates at fixed frequency taper angle decrease with increasing scanning speed & fixed scanning speed taper angle moderate increase with increasing frequency. At low frequency taper angle increase with increasing scanning speed.

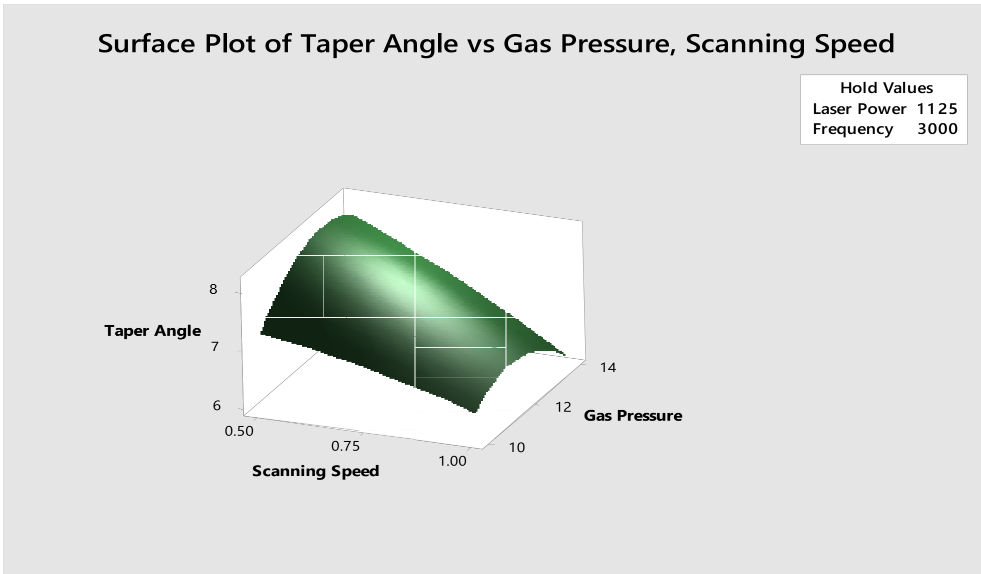


Fig. 2.36 Taper angle vs Scanning speed & Gas pressure

At constant laser power (1125 W) and frequency (3000 Hz), taper angle vs scanning speed and gas pressure plot indicates at fixed gas pressure taper angle decrease with increasing scanning speed & fixed scanning speed taper angle moderate decrease with increasing gas pressure. At low scanning speed taper angle increase with increasing gas pressure.

2.5 Optimization

The criterion is to find the optical parameters of minimizing responses at relatively low operating cost by minimizing the line energy, i.e., by minimizing laser power P and maximizing scanning speed V, maximizing the scan speed also helps to minimize the machining time, thereby increase productivity.

Table 2.14 Criterion of numerical optimization

Responses	Goal	Target	Upper Limit	Importance
Top width	Minimum	116.241	171.423	1
HAZ	Minimum	2170.57	3618.55	1
Bottom width	Minimum	662.62	1070.05	1
Taper angle	Minimum	5.13	8.84	1

The goal of optimization to minimize the top width, bottom width, HAZ and taper angle response.

Table 2.15 Optimum parameters for minimizing

Sl. No	Laser power P (W)	Scanning speed V(m/min)	Gas pressure g_p (bar)	Frequency F (Hz)	Kerf width on the top surface (µm)	Heat affected zone (µm)	Kerf width on the bottom surface (µm)	Taper angle (deg)	Desirability
1	750.000	1	10.000	1000	110.485	537.713	2215.65	4.06631	0.99212
2	906.766	1	10.195	1000	119.612	675.816	2361.79	5.29568	0.93158
3	750.000	1	10.000	5000	104.082	670.882	2597.26	5.38052	0.89589
4	973.916	1	10.000	1097.64	122.161	715.363	2365.04	5.64652	0.87228
5	750.000	1	14.000	3254.24	128.494	666.923	2599.23	5.14445	0.85709

At 750 W laser power, 1 m/min scanning speed at moderate 10 bar gas pressure and around 1000 Hz frequency, optimum solution obtained.

CHAPTER 3

3. CONCLUSION AND SCOPE

3.1 General conclusion

In the present work, experimental investigation is carried out by laser cutting on 3mm thick titanium alloy using fiber laser. The entire work is performed using Nitrogen gas as assist gas had an important role to reduce the kerf width of both top and bottom surfaces, taper angle and heat affected zone width during laser cutting. The study of kerf width on top & bottom surface, heat affected zone width and taper angle has been accomplished. The optimum process parameters (laser power, scanning speed, gas pressure and frequency) are identified through the trial experiments. The desired through cut is obtained at laser power 750 W, scanning speed 1 m/min, gas pressure 10 bar and frequency 1000 Hz.

The following conclusion are drawn from the current research work:

1. Kerf width on the top surfaces, heat affected zone width and taper angle increase with increasing laser power and decreases with increasing scanning speed at constant gas pressure and frequency.
2. Kerf width on the top surfaces, heat affected zone width decreases and kerf width on the bottom surfaces and taper angle increases with increasing gas pressure at fixed scanning speed and frequency.
3. Kerf width on the top surfaces increases with increasing frequency at fixed laser power and gas pressure.
4. Kerf width of the top surfaces decreases with increasing frequency at fixed scanning speed and gas pressure.
5. Kerf width on the bottom surface decreases with increasing frequency at constant scanning speed and gas pressure and decreases with increasing frequency at constant laser power and scanning speed.
6. Kerf width on the bottom surface decreases with decreasing scanning speed at fixed laser power and frequency.
7. Heat-affected-zone increases with increasing frequency at constant laser power and scanning speed, decreases with increasing frequency at constant laser power and gas pressure.
8. Taper angle decreases with increasing frequency at constant scanning speed and gas pressure, increase with increasing frequency at fixed laser power and scanning speed.

3.2 Future scope

After the completion of the thesis there are many aspects to study further on cutting of Titanium alloy. The future scope of this research includes:

1. To study the surface characteristics of the cutting zone by scanning Electron Microscope and detailed analysis of the effect of the parameters on different surface characteristics.
2. To study the heat-affected zone (HAZ) concerning process parameters.
3. Different types of lasers like pico-second or femto-second lasers can be used to do the research to analyze the effect of laser wavelength, and pulse on time on the responses.
4. To study the surface roughness with respect to process parameters.
5. To study with simulation using mathematical modeling for the desired response.
6. To study the physical mechanism behind titanium alloy machining for better understanding and future research.

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