# EXPERIMENTAL INVESTIGATION INTO FIBER LASER BEAM CUTTING OF TI-6AL-4V SUPERALLOY

*A thesis submitted towards partial fulfilment of the requirements for the degree of*

**MASTER OF TECHNOLOGY IN LASER TECHNOLOGY**

Course affiliated to Faculty of Engineering and Technology, Jadavpur University


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## ACKNOWLEDGEMENT

At first, I would like to express my sincere gratitude towards my supervisor ***Prof. Arunanshu Shekhar Kuar,*** Department of Production Engineering, Jadavpur University for his invaluable guidance, whole-hearted support and encouragement for accomplishing the present piece of work. His constant support, fantastic stamina, enigmatic aura and day-to-day monitoring every minute detail were a constant source of inspiration to me.

I would like to express my deep sense of gratitude towards ***Sri Dipten Misra*** for providing me the necessary environment to work in and the ***School of Laser Science and Engineering*** for giving me this opportunity to pursue my thesis work.

I would like to extend my gratitude towards my senior and co-mentor ***Mr. Dhiraj Kumar,*** PhD scholar, Department of Production Engineering, Jadavpur University, for his constant support and inspiration, helping me throughout the research work.

I would also like to thank the faculties, seniors, friends and the entire team of ***School of Laser Science and Engineering*** for supporting and helping me throughout in completion of this work.

My sincere thanks to Jadavpur University for providing with the necessary infrastructure and opportunity to pursue my research work.

I have no words to express gratitude towards my family, I shall always be grateful to them and every one for supporting me whole heartedly during accomplishing this work. Thank you everyone.

**SHOUVIK GHOSH**

***This research work is dedicated to:***

***My beloved parents,***

***My supervisor,***

***School of Laser Science and Engineering &***

***Science & Technology***

# Abstract

*Owing to the excellent combination of physical, chemical, and mechanical properties, such as high strength and stiffness at elevated temperatures, high corrosion resistance, fatigue resistance, high strength to weight ratio, and ability to withstand moderately high temperatures, TI-6AL-4V super alloy plays a significant role in the advancement of engineering in the area of advanced structures and technologies for the aerospace and power industry, medicine, automotive and mechatronics, and measurement equipment. The high chemical affinity and poor thermal conductivity of these alloys make them difficult to cut using traditional cutting techniques. Additionally, Ti-6Al-4V machining incurs higher costs due to slower cutting rates and shorter tool lives. The laser cutting technique may be a promising tool in machining titanium alloy parts like those with subsequent welding requirement: in this case, surface quality of the kerf edges is of great importance. In the present study, experimental investigations of Quasi continuous wave fiber laser cutting of 2 mm thick TI-6AL-4V super alloy are carried out based on statistical design of experiments. The relationship between the process parameters such as laser power, cutting speed, and pulse frequency with the output responses such as kerf deviation and surface roughness are established in terms of regression models. Also, the most significant process parameters and their optimum ranges are identified and their percentage contributions on output responses are calculated. It is observed that laser power and cutting speed plays the major role on cut quality characteristics. Also, laser power and cutting speed both have negative impact on surface roughness. ANOVA shows the adequacy of the developed model in terms of accuracy. Single and multi-objective desirability function based optimization technique is applied to obtain the optimum cut quality at optimal process parameter setting.*

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## List of Abbreviations

| Abbreviation | Full Form |
|---|---|
| LASER | Light Amplification by Stimulated Emission of Radiation |
| LBM | Laser Beam Machining |
| DVD | Digital Video Disc |
| MASER | Microwave Amplification by Stimulated Emission of Radiation |
| Nd:YAG | Neodymium-Doped Yttrium Aluminium Garnet |
| LIDAR | Light Detection and Ranging |
| PN | Positive and Negative |
| CW | Continuous Wave |
| QCW | Quasi-Continuous Wave |
| HSLA | High Strength Low Alloy |
| CNC | Computer Numerical Controlled |
| EDM | Electrical Discharge Machining |
| EBM | Electron Beam Machining |
| RP | Rapid Prototyping |
| CAD | Computer Aided Designing |
| CAM | Computer Aided Machining |
| DC | Direct Current |
| RF | Radio Frequency |
| HAZ | Heat-Affected Zone |
| IC | Integrated Circuit |
| 3D | Three Dimensional |
| PE | Polyethylene |
| PP | Polypropylene |
| PC | Polycarbonate |
| SEM | Scanning Electron Microscopy |
| XRD | X-ray diffraction |
| MRR | material removal rate |
| BPP | Beam Parameter Product |
| DDL | Direct Diode Lasers |
| MMC | Metal Matrix Composite |
| XPS | X-ray Photoelectron Spectroscopy |
| EDX | Energy Dispersive X-ray |
| CPU | Central Processing Unit |
| LCD | Liquid Crystal Display |
| LLC | Liabilities Limited Company |
| USB | Universal Serial Bus |
| LED | Light Emitting Diode |
| DOE | Design of Experiments |

| | |
|---|---|
| OFAT | One-Factor-At-a-Time |
| EVOP | Evolutionary Operation |
| RSM | Response Surface Methodology |
| CCD | Central Composite Design |
| ANOVA | Analysis of Variance |
| PC | Personal Computer |
| LP | Laser Power |
| PF | Pulse Frequency |
| CS | Cutting Speed |
| DFA | Desirability Function Analysis |

# List of Symbols

| Symbols | Meaning |
|---|---|
| mm | Millimetres (indicating dimension) |
| mm/s | Millimetres per second (indicating speed) |
| MW | Megawatts (indicating power) |
| Nm | Nanometres (indicating dimension) |
| eV | Electron Voltage (indicating charge of an electron) |
| kW | Kilowatts (indicating power) |
| ps | Picoseconds (indicating time span) |
| λ | Lambda (indicating Wavelength) |
| Hz | Hertz (indicating frequency) |
| Mm | Micrometre or microns (indicating dimension) |
| Bar | Unit of Pressure |
| ξ | Variable |
| F | Mathematical Function |
| ε | Error |
| η | Function response |
| β | Regression coefficients |
| i, j | Regression terms |
| x, y, z | Variables |
| α | Axial point |
| Mpa | Megapascals (indicating stress/ strength) |
| Gpa | Gigpascals (indicating stress/ strength) |
| Mpa/m | Megapascals per metre (indicating toughness) |
| Ra | Surface Roughness |
| KD | Kerf Deviation |

# Chapter 1

# Introduction

## 1.1 Introduction

Engineering materials have evolved over time, and finds applications in almost every aspect of human life. Metals, being one of the most important engineering materials, have taken a massive jump in usage in recent years. They are used in aerospace, construction, electrical, electronic, medical, packaging, processing, household products, automotive industries and many more. Their applications are seemingly endless. In recent years, non-ferrous metals have taken a significant leap in terms of usage and applications. Several alloys and light metals have been found to be extremely useful in several types of industries. With this rapid increase in demand, significantly advanced processes are required to prepare these materials, fit for end consumer usage. Until the second half of the $20^{th}$ century, most metal processing was done using conventional methods. But, advancements in material processing have brought several new techniques and technologies to easily, accurately and inexpensively produce high quality engineered products for the mankind.

Laser beam machining (LBM) is an alternative to conventional methods to process these engineering materials. This technique employs laser as a tool for processing the materials. LBM can be considered excellent alternative to conventional processes like milling, sawing, drilling, cutting, etc. While LBM can be used with different materials, however, some materials are still found to be difficult to process using lasers due to several factors. A lot of research work is being done on these materials, but scope of further work is still present.

## 1.2 Laser

LASER stands for "Light Amplification by Stimulated Emission of Radiation". This device emits an amplified beam by stimulating the emission of photons from an emitter. A laser is no ordinary light source. It is very different from a light bulb or a flashlight. A laser produces a very narrow beam of light. Lasers are not made naturally. However, mankind has found a way to artificially create this particular kind of light. A laser is a narrow beam of light in which all light waves have very similar wavelengths. Light waves from a laser have wave peaks that all cross in line or in phase. Because of this, the laser beam is very narrow, very bright, and can be focused to a very small spot. Because the laser stays focused and does not spread widely, the laser beam can travel very long distances while focusing a lot of energy in a very small area. Lasers have so many uses in everyday life. They are commonly found in precision tools and can cut materials such as diamond and thicker metals. They have been redesigned and redesigned to aid in delicate medical applications such as surgery. Lasers are the primary medium for recording and retrieving data, especially in his DVDs, Blu-rays, etc.

They are widely used in the communications industry, such as television broadcasting and internet signals. They are used in laser printers, which use a laser to charge a printing surface (usually paper) and print ink on the paper in the charged areas, and barcode scanners, in which the laser is assisted by a sensor that receives the barcode signal. You can see triggers the interpretation of information, etc. It also helps in manufacturing computer parts and peripherals and other electronics and gizmos. Lasers are also found in instruments called spectrometers that scientists use to find out what things are made of. [1]

### 1.2.1 History of Laser

Einstein laid the foundation for his laser invention in 1917 when he withheld the concept of stimulated emission. According to him, the interaction of a photon with an excited molecule or atom emits a second photon with similar frequency, phase and polarization and orientation. But it was in 1960 that Theodore Maiman of Hughes Labs developed the first practical laser, and about three months later published a paper describing how the first laser worked, published in Nature. Since then, in the United States alone he has issued a staggering 55,000 patents, which, if counted, cover lasers. Modern lasers and all their applications are the work of many respected scientists and engineers who have long been leaders in the field of optics and photonics. These names include Charles Townes at Columbia University, who developed the laser's predecessor, the maser. The first patent for laser technology was granted to Townes and Schawlow in 1960.

One of the first lasers developed by Maiman, he used a powerful energy source to excite the atoms of synthetic ruby to higher energy levels. When atoms reached a certain energy level, some began to emit particles of light known as photons. The newly generated photons interacted with other atoms in ruby, resulting in the rapid stimulated emission of more identical photons and amplified light intensity. This stimulated emission and amplification process can be continued by adding a fully reflective silver mirror at one end of the model and a partially reflective silver mirror at the other. This causes the photons to bounce back and forth between the mirrors until they reach sufficient intensity to pass through the partially silvered edge of the mirror as an intense and coherent light beam (laser). [1]

The predecessor of laser, called MASER for "microwave amplification by stimulated emission of radiation", was independently developed in 1954 by Charles Townes and Jim Gordon at Columbia University and by Nikolai Basov and Alexander Prokhorov in Russia. These were ammonia masers, with two energy level gas systems capable of continuously suppressing distribution inversions and oscillations. Nicolaas Bloembergen of Harvard University in 1956, proposed a three-level solid-state maser, which was later demonstrated by researchers at Bell Labs that same year. In fact, after the successful development of masers, Arthur Schawlow and Charles Townes began researching how to create infrared or visible light masers. In 1957, Schawlow and Townes constructed an optical cavity by holding a pair of highly reflective mirrors parallel to each other and placing a gain medium between them. The following year they published a landmark physical review paper on their discovery and applied for a patent for what they called an optical maser. [1]

Their review article generated a lot of interest from other researchers, especially experimenters trying to make their first lasers. Although the paper correctly credits Shawlow and Townes as the inventors of the laser, several others independently came up with the same "open-cavity" concept, including Columbia University graduate student Gordon Gould who was also the first to publicly use the term laser for "light amplification by stimulated emission of radiation" at the Ann Arbor Optical Pumping Conference in June 1959. After the publication of Schawlow-Townes Physical Review paper in 1958, there was an all-out race to build an effective laser. Theodore Maiman of Hughes Research Labs realized that high-gain pulsing could be achieved in ruby by optical pumping with a commercially available flashlamp, and demonstrated the first practical laser in May 1960. This laser was so easy to make that within a few weeks several other groups have replicated its output. The first widely recognized application of lasers came in his 1974 with the introduction of barcode scanners, three years before the invention of laser printers in 1971.

### 1.2.2 Laser System

Laser is a stimulated emission in which atoms in an upper energy level can be triggered (or stimulated) in phase by an incoming photon of a specific energy. The emitted photons all possess the same wavelength and vibrate in phase with the incident photons, thereby being coherent.

The components of the laser system includes:-

1. Luminescent and amplifying medium (or gain medium)
2. Pumping mechanism (or exciting mechanism)
3. Mirrors (Partially transparent and opaque)

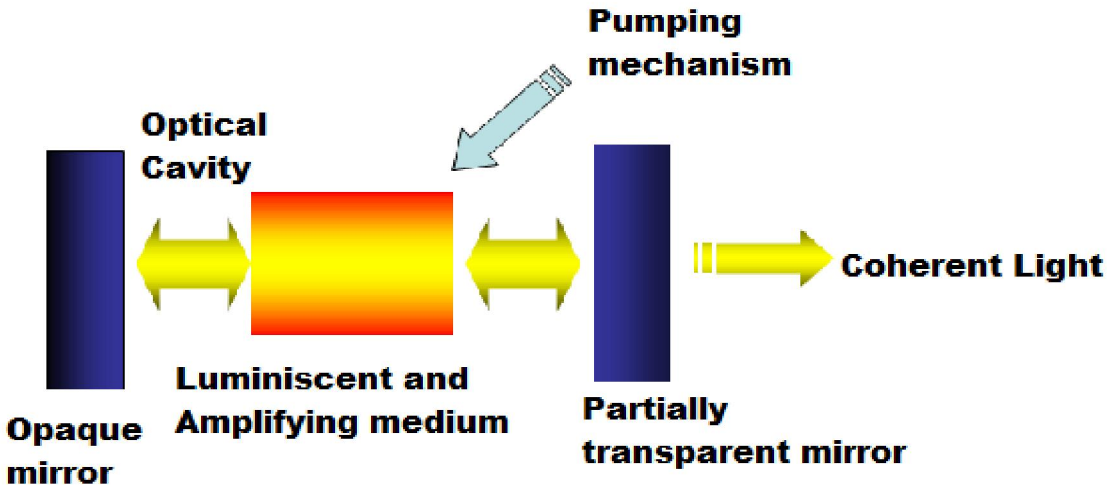



**Fig. 1.1 Laser system [6]**

### 1.2.3 Working principle of laser

The electrons in the atoms/ions/molecules of the laser material are usually at stationary low energy levels. When light energy is pumped from an excitation source into a unit of laser material, most of the unit is excited to a higher energy level. When the population of a higher level unit reaches a majority compared to the population of the level immediately below, the state reached is called population reversal of the upper level to the lower level, and is an unstable state for those units. After holding this state for a short time, it returns to its original energy state. This fallback/attenuation happens in two ways. In spontaneous emission, an entity simply falls to a ground state and emits in random directions. In stimulated emission, photons are emitted coherently. Stimulated transitions release energy in the form of photons of light. This photon propagates in phase with the same wavelength and direction as the incident photon. As shown in Fig 1.1, when the direction is parallel to the optical axis of the laser medium inside the cavity, the photons emitted inside the optical cavity travel back and forth in the laser material between the totally reflecting mirrors and the partially reflecting mirrors. The light is gradually increased until a strong beam of laser light builds up enough intensity to break through the partially reflective mirror. [2]

### 1.2.4 Properties of lasers

i. **Monochromatic**: Monochromatic refers to electromagnetic radiation of a single frequency. In reality, no source of electromagnetic radiation is purely monochromatic, even very controlled sources such as lasers operate in a range of frequencies (known as the spectral line width). In practice, filtered light, diffraction grating separated light and laser light are all routinely referred to as monochromatic.

ii. **Collimated**: They diverge or spread out very less over large distances. That is why they can concentrate the energy more or less at a single point.

iii. **Coherence**: Coherent light has a definite phase relationship. The phase difference remains either zero or constant in time. Since emission of light from a source is a random phenomenon, it is not possible to get coherent light from two different sources (Unlike sound waves). So the light from one source is bifurcated to produce two 'virtual' sources for carrying out experiments related to light. Lasers, for example are highly coherent.

iv. **Beam divergence**: Nearly all photons travel in the same direction; the light is contained in a very narrow path; laser is low in divergence mostly, leading to high intensity.

v. **High irradiance**: Since the beam is collimated and coherent, lasers subject the power on a very small spot, resulting in higher irradiance.

vi. **Elastic scattering**: Is when the scattering frequency is the same as the frequency of the incident light (e.g., Rayleigh scattering and Mie scattering).

vii. **Inelastic scattering**: Is when there is a change in the frequency.

viii. **Polarized**: mostly the energy/ beam are aligned in one direction. [2]

### 1.2.5 Types of Lasers

Lasers are classified and required for different applications. They are classified based on their gain medium into five main types:

i. **Gas Lasers**: A gas laser is a laser in which an electrical signal/current is exposed to and passed through a particular gas to produce its light through a process known as population inversion. Examples of gas lasers are carbon dioxide ($CO_2$) lasers, helium neon lasers, argon lasers, krypton lasers, and excimer lasers. Gas lasers are used in a variety of applications including holography, spectroscopy, barcode scanning, air pollution measurement, materials processing, and laser surgery. $CO_2$ lasers are probably the best known gas lasers and are primarily used for laser marking, laser cutting and laser welding.

ii. **Solid-State Lasers**: A solid-state laser is a laser that uses a solid (crystal or glass) mixed with rare earth elements as an optical gain source. Mixed elements are usually neodymium, chromium, erbium, thulium, or ytterbium. The best-known solid-state laser is the ruby laser, which was the first laser ever built. Nd:YAG (neodymium-doped yttrium aluminium garnet) lasers are also solid-state lasers commonly used in materials processing applications, laser processing, and other operations. Solid-state lasers are used not only for LIDAR technology, but also for various medical applications such as tattooing, hair removal, tissue ablation, and kidney stone removal.

iii. **Fiber Laser**: A fiber laser is a special type of solid-state laser. In fiber lasers, the gain medium is optical fiber (silica glass), as opposed to crystal or glass in the case of conventional solid-state lasers. The rare earth elements are mixed as in the solids. This type of laser is very different from other lasers due to the light guiding properties of optical fibers due to total internal reflection. The laser beam is straighter and smaller than other types of lasers, making it more precise. Fiber lasers are known for their small footprint, fairly high electrical efficiency, and low maintenance and operating costs. Fiber lasers are widely used in a variety of applications, including material processing (laser cleaning, texturing, cutting, welding, marking), medical, and defense systems such as directed energy weapons. Examples of fiber lasers used for these applications include ytterbium and erbium doped fiber lasers.

iv. **Liquid/ Dye Lasers**: Liquid lasers use a liquid organic dye as the gain medium. Also known as dye lasers, they are used in medical applications, spectroscopy, bruise removal, and isotope separation. One of the main advantages of dye lasers is their ability to generate a much wider range of wavelengths. This means that the wavelength can be controlled on-the-fly.

v. **Diode Lasers**: Laser diodes, also called diode lasers or semiconductor lasers, are similar to regular diodes in that they have positive and negative (PN) charge junctions. The only difference is that laser diodes have an intrinsic layer of material at the PN junction that produces spontaneous emission. The intrinsic layer is polished so that the generated photons are amplified and finally the electrical current is converted into laser light. Most semiconductor lasers are diode lasers, but very few are. This is because there are semiconductor lasers that do not use a diode structure, such as quantum cascade lasers and optically pumped semiconductor lasers. Like fiber lasers, laser diodes can also be classified as solid-state lasers. This is because its gain medium is a solid. However, PN junctions exist, so they are a separate category. Laser diodes are often used as energy sources to excite other lasers. These lasers are called diode-pumped lasers. In such cases, the laser diode is usually positioned to pump more energy. Laser diodes are widely used in everyday applications. It is used in barcode readers, laser pointers, laser printers, laser scanners, etc. [2]

Another classification of laser is based on the type of pulse operation:

i. **Continuous Wave (CW) laser**: a CW laser is a laser in which the laser beam is continuous in nature, i.e., the laser light is always on. It emits beams continuously without any break.
ii. **Pulsed laser**: a pulsed laser is a laser, in which the light beam is emitted intermittently, i.e., the laser goes on and off, emitting very short flash of light at a certain pulse width and frequency.
iii. **Quasi-Continuous Wave (QCW) laser**: it is also a pulsed laser but the pulse duration is longer than pulsed laser, i.e., a QCW laser emits long pulses, while a pulsed laser emits nanosecond or even shorter pulses.

## 1.3 Engineering Materials

Engineering materials are a group of materials that are used by engineers in the construction of manmade structures and components. The main function of an engineering material is to withstand applied load efficiently without breaking and without exhibiting excessive deflection. The major classifications of engineering materials include metals, polymers, ceramics, and composites. [3]

### 1.3.1 Metals

Metals are the most commonly used class of engineering material. Almost every engineering feat, construction, component, consist of metal as one of the key ingredient. Even though metals have their own set of advantages and uses, but they have their drawbacks too. For example, iron is an excellent metal for construction, but it oxidizes pretty easily if subjected to damp or wet/ moist conditions. This results in formation of iron oxides or commonly called rust. This rust affects the mechanical properties of iron, hence using iron directly in complicated or extremely responsible structures like bridges, puts them in a higher level of risk position. Hence to overcome these drawbacks and to improve thermo-mechanical, electro-mechanical or to simply improve strength, toughness, ductility, etc metal alloys are developed.

Metal alloys are formed by combining a base metal with one or more other metallic and/or non-metallic materials. This combination usually occurs through a process of melting, mixing, and cooling. The goal of alloying is to improve the properties of the base material, as mentioned above, in some desirable way. Metal alloy compositions are described in terms of the percentages of the various elements in the alloy, where the percentages are measured by weight. [3]

### 1.3.2 Alloys

#### 1.3.2.1 Ferrous Alloys

Ferrous alloys have iron as the base element/metal. These alloys include steel and cast iron. Iron alloys are the most commonly used metal alloys because they are rich in iron, easy to manufacture, and highly versatile of materials. The main drawback of many iron alloys is their poor corrosion resistance. Carbon is an important alloying element in iron alloys. Higher levels of carbon generally increase strength and hardness, but reduce the ductility and weldability of the alloy. Different types of Ferrous alloys are:-

- **Carbon Steel**: They are basically just mixtures of iron and carbon. They may contain small amounts of other elements as well, but carbon remains the primary alloying material. The effect of adding carbon is an increase in strength and hardness of the alloy. They are mainly of 3 types:-
    - **Low Carbon Steel**: As the name suggests, this alloy contains low amount of carbon. It has less than about 0.30% carbon. It is characterized by low strength but high ductility. Even though some strengthening can be achieved through cold working, but it does not respond well to heat treatment. Low-carbon steel is very weldable and is inexpensive to produce. Applications for low-carbon steel include wire, structural shapes, machine parts, and sheet metal.
    - **Medium Carbon Steel**: This particular alloy contains medium amount of carbon. It contains between 0.30% to 0.70% carbon. Unlike low carbon steel, this can be heat treated to increase strength, especially with the higher carbon contents. Medium-carbon steel is frequently used for axles, gears, shafts, and machine parts.
    - **High Carbon Steel**: This alloy contains between about 0.70% to 1.40% carbon. It is attributed with high strength but low ductility. It is commonly used in drills, cutting tools, knives, and springs.
- **Low Alloy Steel**: Also commonly referred to as alloy steel, it contains less than about 8% of all alloying elements. Low alloy steels are generally stronger and more corrosion resistant than carbon steels. Some low alloy steels are called high strength low alloy steels (HSLA). This means that they are designed to achieve specific mechanical properties rather than meeting a specific chemical composition.
- **Tool Steel**: As the name suggest, tool steels are primarily used to make tooling for use in manufacturing processes, like cutting tools, drill bits, punches, dies, and chisels. Alloying elements are typically chosen to optimize hardness, wear resistance, and toughness. One of the most common tool steel is High Speed Steel, mainly used as cutting tools in turning, milling, drilling operations.

- **Stainless Steel**: Stainless steel is good corrosion resistant steel, mainly due to the addition of chromium as an alloying element. Chromium content in stainless steel is at least 11%. A phenomenon called passivation occurs at chromium levels above 12% and forms an inert protective film of chromium oxide on top of the material to prevent oxidation. The corrosion resistance of stainless steel is the result of this particular passivation phenomenon. They are of the following types:-
    - **Austenitic Stainless Steel**: Austenitic stainless steel is the most common form of stainless steel. It has the highest general corrosion resistance of any stainless steel. This is also the best stainless steel for welding due to its low carbon content. Its strength can only be increased by cold working. Austenitic stainless steels are generally more expensive than other stainless steels due to their nickel content. Austenitic stainless steels are not magnetic, but ferritic and martensitic stainless steels are. Common applications are fasteners, pressure vessels and piping.
    - **Ferritic Stainless Steel**: Ferritic stainless steels are high in chromium and moderate in carbon. It has better corrosion resistance than strength. Its moderate carbon content makes it less weldable compared to austenite. Generally, it cannot be strengthened by heat treatment and can only be strengthened by cold working.
    - **Martensitic Stainless Steel**: Martensitic stainless steels are high in carbon (up to 2%) and low in chromium. This higher carbon content is the main difference between ferritic and martensitic stainless steels. It is difficult to weld due to its high carbon content. It can be strengthened by heat treatment. Common applications are cutlery and surgical instruments.
    - **Duplex Stainless Steel**: Duplex stainless steels contain both austenite and ferrite phases. Up to twice as strong as austenitic stainless steel. It also has high toughness, high corrosion resistance, and excellent wear resistance. Duplex stainless steels are generally as weldable as austenitic steels, but have temperature limitations.
    - **Precipitation Hardenable Stainless Steel**: This special stainless steel can be strengthened by precipitation hardening, a hardening process. These materials are strong, corrosion and heat resistant.
- **Cast Iron**: Cast iron is a ferrous alloy containing high levels of carbon, usually greater than 2%. The carbon present in the cast iron can take the form of graphite or carbide. Cast irons usually have a low melting temperature which makes them well suited to casting, hence the name cast iron. They are of following types:-
    - **Grey Cast Iron**: Gray cast iron is the most common type of cast iron. The carbon is in the form of graphite flakes. Gray cast iron is a brittle material, and its compressive strength is much higher than its tensile strength. The fracture surface of gray cast iron has a gray color, which is how it got its name.
    - **Ductile Cast Iron**: Adding magnesium to gray cast iron improves the ductility of the material. The resulting material is called nodular cast iron because the magnesium causes the graphite flakes to form into spherical nodules. It is also called ductile cast iron. Nodular cast iron has good strength, ductility, and

machinability. Common uses include crankshafts, gears, pump bodies, valves, and machine parts.

- **White Cast Iron**: White cast iron has carbon in the form of carbide, which makes the material hard, brittle, and difficult to machine. White cast iron is primarily used for wear-resisting components as well as for the production of malleable cast iron.
- **Malleable Cast Iron**: Malleable cast iron is produced by heat treating white cast iron. The heat treatment improves the ductility of the material while maintaining its high strength. [3]

### 1.3.2.2 Non-Ferrous Alloys

- **Aluminium Alloys**: Pure aluminium is soft and weak, but alloying it can increase its strength. Pure aluminium has excellent corrosion resistance due to the oxide layer that forms on top of the material and prevents it from oxidizing. Alloying aluminium tends to reduce corrosion resistance. Aluminium is a widely used material especially in the aerospace industry due to its light weight and corrosion resistance. Aluminium alloys are generally not as strong as steel, but they have a good strength-to-weight ratio. All 2000, 6000, and 7000 series aluminium alloys can be heat treated for maximum strength. Other alloys can be strengthened by cold working.
- **Nickel Alloys**: Nickel alloys have high temperature and corrosion resistance. Common alloying ingredients include copper, chromium, and iron. Common nickel alloys include Monel, K-Monel, Inconel, and Hastelloy.
- **Copper Alloys:** Copper alloys are generally considered to be electrically conductive, highly corrosion resistant, and relatively easy to form and cast. Copper alloys are useful engineering materials, but they are also very attractive and commonly used in decorative applications. Copper alloys are mainly composed of brass and bronze. Zinc is the most important alloying element in brass. Tin is the main alloying element in most bronzes. Bronze may also contain aluminium, nickel, zinc, silicon and other elements. Bronze is generally stronger than brass, but retains excellent corrosion resistance. Aluminium bronze alloys are very hard and have good wear resistance, so they are often used in bearing applications. Beryllium-copper alloys have excellent strength and fatigue properties, as well as excellent wear resistance when properly lubricated. Beryllium copper is commonly used in springs, bearings and bushings.
- **Titanium Alloys**: Titanium alloy is light, strong and has excellent corrosion resistance. It has a much lower density than steel and a better strength-to-weight ratio. For this reason, titanium alloys are very widely used, especially in the aerospace industry. The main drawbacks of titanium alloys are their high cost and brittleness. There are three categories of titanium alloys: alpha alloys, beta alloys, and alpha-beta alloys. Alpha alloys do not react to heat treatment and are instead strengthened by a solid solution strengthening process. Beta and alpha-beta alloys can be strengthened by heat treatment, mainly by precipitation hardening. [3]

### 1.3.3 Non Metals

- **Polymers**: Polymers are materials that consist of molecules formed by long chains/ arrays of repeating units. They may be natural or synthetic. Many useful day-to-day engineering materials are polymers, such as plastics, rubbers, fibers, adhesives, and coatings. Polymers are classified as:-
    - **Thermoplastic Polymers**: The classification of thermoplastics and thermosets is based on their thermal behavior. When heat is applied to thermoplastics, they soften and melt. When cooled, it returns to its original solid state. Thermoplastics can be repeatedly heated and cooled without undergoing a chemical change (unless the temperature is hot enough to break molecular bonds). Therefore, it is very suitable for injection molding.
    - **Thermosetting Polymers**: Thermosets are typically heated during initial processing, after which they become permanently hard. Thermosets do not melt when reheated. However, if the heat applied becomes extreme, the thermoset will degrade due to the breaking of molecular bonds. Thermosets are typically harder and stronger than thermoplastics. They also typically have better dimensional stability than thermoplastics and excellent at maintaining original dimensions when exposed to temperature and humidity changes.
    - **Elastomers**: Elastomers are highly elastic polymers with rubber-like mechanical properties. Elastomers are widely used in seals, adhesives, hoses, belts and other flexible parts. The strength and stiffness of rubber can be increased through a process called vulcanization. Vulcanization is the addition of sulfur and subjecting the material to high temperature and pressure. This process forms crosslinks between polymer chains.
- **Ceramics**: Ceramics are solid compounds that may consist of metallic or nonmetallic elements. Ceramics generally have excellent corrosion and wear resistance, high melting temperature, high stiffness, and low electrical and thermal conductivity. Ceramics are also very brittle materials. The primary classifications of ceramics include:-
    - **Glass**: Glass is a common material and is used for applications such as windows, lenses, and containers. Glass is amorphous, while other ceramics are predominantly crystalline. The main advantages of glass include clarity and ease of manufacture. The basic element of most glasses is silica, and other ingredients can be added to modify its properties. Common processes used to form glass include:
        - Heating until melting, then pouring into molds to cast into useful shapes.
        - Heating until soft, and then rolling.
        - Heating until soft, and then blowing into desired shapes.
    - **Cements**: Cement is a material that hardens into a paste when mixed with water. This property allows pasty cement to be molded into useful shapes before hardening into a solid structure. Gypsum is one of the common

cements. The most common cement is called Portland cement, which is a mixture of clay and limestone that is fired at high temperatures. Portland cement is a raw material for concrete made by mixing sand, gravel and water. One can also make a mortar by mixing sand and water. Like other ceramics, cement is low stress but highly compressible. Cement is very cheap to produce and is widely used in the construction of buildings, bridges and other large structures.

    - **Clay Products**: Clay is a common ceramic material. It can be molded by mixing with water and cured by heating at high temperature. His two main classifications of clay products include structural clay products and white goods. Structural clay products are used for bricks, tiles, plumbing, etc. Whiteware is found in uses such as pottery and plumbing fixtures.
    - **Refractories**: Refractory ceramics can withstand high temperatures and extreme environments. They can also provide thermal insulation. Brick is the most common refractory ceramic.
    - **Abrasives**: Abrasive ceramics are hard materials that are used to cut, grind, and wear away other softer materials. Typical properties of abrasives include high hardness, wear resistance, and temperature resistance. Abrasives can either be bonded to a surface (e.g., grinding wheels and sandpaper), or can be used as loose grains (e.g., sand blasting). Common abrasives include cemented carbide, silicon carbide, tungsten carbide, aluminium oxide, and silica sand. Diamond is also an excellent abrasive, but it is expensive.

- **Composites**: A composite material is a material in which one or more mutually insoluble materials are mixed or bonded together. The primary classes of composites are particulate composites, fibrous composites, and laminated composites. Different types of composites are:
    - **Particulate Composites**: Particulate composites are created by adding particles of one material to a matrix (the filler material). The particles would typically account for less than 15% of the total material volume. The particles are added to improve upon some shortcoming of the matrix material.
    - **Fibrous Composites**: A fibrous composite is a material in which fibers of one material are embedded within a matrix. The fibers carry most of the stress, and the matrix serves to hold the fibers in place and to transmit stress between the fibers. The fibers can be short and randomly oriented, or they can be long and continuous.
    - **Laminated Composites**: Laminated composites are created by combining layers of composite materials. The layers will typically differ in the orientation of the fibers, or they will differ in the material itself. *Sandwich* materials are common, in which a lightweight material (such as foam or a honeycomb) will be placed in between layers of a strong, stiff material. [3]

## 1.4 Machining of Engineering Materials

**Machining** is a process in which an engineering material is cut/ chipped to a desired final shape and size by a controlled material-removal process. These processes are collectively called **subtractive manufacturing**, which utilizes machine tools and/ or other methods to remove material from the workpiece.

### 1.4.1 Conventional Machining Processes

A conventional machining process is a process in which machining is done in a conventional manner, without using complicated methods. Therefore, this processing method is also called traditional processing. This technique involves the use of sharp cutting tools that are stronger than the workpiece. Friction and tool wear occur as the cutting tool comes into direct contact with the workpiece. To remove material, use the cutting tool against a rotating or stationary workpiece.

Conventional machining methods are known to produce poor quality products due to abrasive enhancement and uneven structure. Examples of conventional machining include lathes, mills, vertical drills, grinders, etc. Moldings with contoured channels are difficult to manufacture with conventional methods. Channels are milled and drilled to be as close as possible to the matched system, ensuring fast and smooth cooling, but also benefiting from short cycle times and excellent plastic part quality. However, since the drilled channels are straight and it is very difficult to achieve perfect curvature, the surface of the mold is uneven and the numbers of channels need to be reduced due to geometric limitations; it is expected that there will be some decrease in cooling performance for the same mold volume. The channels created represent the first step towards a "pure" cooling system. This is only conceivable in this form with advanced manufacturing technology. [4]

Various types of conventional machining processes are:

- **Turning**: Turning is a machining method in which the workpiece is spun as cutting tools traverses across its surface on a lathe. To make cuts with exact depth and width, the cutting tools move along two axes of motion. Traditional manual lathes and automated computer numerical controlled (CNC) lathes are the two types of lathes available.
- **Grinding**: Grinding is the technique of removing small amounts of material from flat or cylindrical surfaces. He has three types of grinders. A surface grinder that feeds the workpiece from the table to the grindstone in a reciprocating motion. A cylindrical grinder that rotates the workpiece while the circumference of the rotating grindstone is in contact with the workpiece, and a centerless grinding technology that mass-produces small parts in which the grinding surface is not connected to other surfaces.
- **Milling**: In contrast to turning processes, where the tool does not spin, milling removes material using revolving cutters. The workpieces are placed on moving tables in traditional milling machines. The cutting tools are stationary in these

machines, while the table moves the material to make the desired cuts. Tables and cutting tools are both moveable components on other milling machines however.

- **Shaper/ Planer**: Planning is typically used to mill large flat surfaces, especially those that will be scraped, such as machine tool paths. The only difference being, in shaper the tool moves over the fixed workpiece while the tool is fixed and the workpiece transverses in case of a planer.
- **Drilling**: Drilling is the process of drilling a cylindrical hole in a solid material using a tool called a drill. This is one of the most important machining techniques. The holes created are typically used when assembling parts. Drilling can be done on a drill press or lathe. Drilling is a preliminary process in most manufacturing processes to create a threaded hole or to create a finished hole by tapping, reaming, drilling, etc. to achieve acceptable tolerances in the hole dimensions. [4]

### 1.4.2 Non-Conventional Machining

Non-conventional processing, also called "non-traditional processing" or "modern processing methods", is processing using unconventional/conventional media such as electricity, heat, light, electrochemical energy, chemical energy, acoustic energy, etc. More specifically, in contrast to drilling, boring, cutting, milling, turning, and other conventional machining operations, mechanical energy is required for removal, deformation, property alteration of plate material. It is usually performed at the cutting edge using conventional machining tools. These traditional machining methods form the basis of the machining process, but are becoming obsolete as technology and time advance.

Various types of Non-Conventional Machining are:

- **Electrical Discharge Machining**: EDM, or electrical discharge machining, is a non-traditional machining technique for etching conductive materials using electrochemical machining caused by a pulsed electrical discharge between two poles immersed in a machining fluid. The basic equipment for this process is an electrical discharge machine. It is used for machining complex shaped holes and cavities in molds and parts. A variety of hard and brittle materials such as hard alloys and hardened steels are machinable. Machining of fine deep holes, curved holes, deep grooves, narrow slits, thin plates, etc is done using EDM. Cutting and measuring equipment such as cutting tools, templates, and thread ring gauges are machined on EDM.
- **Electrochemical Machining**: The workpiece is shaped and sized with the help of a shaped cathode according to the principle of anodic dissolution in an electrolytic process. Electrochemical machining offers great advantages for difficult-to-machine materials, complex shapes, and thin-walled products. Gun barrels, blades, integral wheels, dies, profile holes and parts, chamfering and deburring are all examples of electrochemical machining. Electrochemical machining technology has played an important, if not irreplaceable, role in the processing of many products.

- **Laser Machining**: To achieve processing, lasers use light energy to achieve high energy density at the focal point after being focused through a lens to melt or vaporize material and remove it in a very short time. Laser processing offers the advantages of reduced material waste, measurable cost efficiency in high volume production and high flexibility of the workpiece to be cut. Laser technology is mainly used in Europe to weld unique materials such as high quality car bodies and bases, airplane wings and spacecraft hulls. Laser welding, laser cutting, surface modification, laser marking, laser drilling, micromachining and photochemical vapor deposition; stereolithography, laser etching, and other laser processing methods are the most commonly used applications.
- **Electron Beam Machining**: The processing of materials using the thermal or ionizing effect of high-energy focused electron beams is known as electron beam machining (EBM). High energy density, strong penetration, wide unique melt depth, large weld width ratio, high welding speed, small heat affected zone and low operating deformation are all advantages. There are a wide variety of processing materials for electron beam processing, and the cutting area is extremely small. Machining accuracy can be measured in nanometers, allowing molecular or atomic machining. Greater productivity; less environmental pollution from processing, but higher cost of processing equipment. It can be used to create microscopic holes, tiny slits and other complex shapes. It can also be used for fine lithography and welding. A major application of e-beam processing in the automotive industry is the vacuum e-beam welded bridge shell technology.
- **Ion Beam Machining**: Under vacuum, ion beam processing is performed by accelerating the ion current generated from the ion source and concentrating it on the workpiece surface. Precise tuning of ion flux density and ion energy enables perfect tuning of processing effects, enabling ultra-precision processing at nanometer, molecular and atomic levels. Ion beam processing produces less contamination, less stress and strain, and is more flexible in the materials being processed, but it comes at a significant cost. Ion beam machining can be used in two phases; etching and coating:
    - **Etching machining**: Ion etching is used to machine gyroscope air bearings and hydrodynamic motor grooves with high resolution, accuracy and repeatability. Etching of precision graphics such as Integrated circuits, optoelectronic devices, and optical integrated devices are another application of ion milling. Ion milling is also used to thin materials to prepare specimens for transmission electron microscopy.
    - **Ion beam coating machining**: There are two types of ion beam coating machining: sputtering deposition and ion plating. Metal or non-metal films can be plated on metal or non-metal surfaces, and various alloys, compounds, or certain synthetic materials, semiconductor materials, and high-melting-point materials can also be plated with the ionic coating. Coating lubricating film, heat-resistant film, wear-resistant film, decorative film, and electrical film with ion beam coating technique is possible.

- **Plasma Arc Machining**: Plasma arc machining is a non-traditional machining technique that uses the thermal energy of a plasma arc to cut, weld, and spray metals or non-metals. It is possible to weld foils and thin plates, and has a keyhole effect that enables single-sided welding and double-sided free molding. Plasma arcs have high energy density, high arc column temperature, and high penetration. For 10-12 mm thick steel, no chamfer is required and full weld penetration and double sided forming can be achieved in one step with high welding speed, high productivity and minimal stress deformation. Due to the complexity of the equipment and high gas consumption, it is only suitable for indoor welding. It is widely used in industrial production, especially in the welding of copper and copper alloys, titanium and titanium alloys, alloy steels, stainless steels, molybdenum in military applications, and titanium alloy rocket shells and some aircraft with thin walls. It is used in advanced industrial technology such as aerospace thin-walled containers.
- **Ultrasonic Machining**: By using ultrasonic frequency as a tool to make small amplitude vibrations and punching the treated surface by free abrasive grains in the liquid between the processing surface and the workpiece, ultrasonic machining causes the surface of the workpiece to gradually cut. Punching, cutting, welding, nesting, and polishing are common applications of ultrasonic processing. It can machine any material, but is especially suited for cutting a wide variety of hard, brittle, non-conductive materials with high precision and excellent surface quality at low speeds. Perforations (round holes, shaped holes, curved holes, etc.), cutting, slitting, nesting, engraving, deburring batches of small parts for various hard and brittle materials such as glass, quartz, ceramics, silicon, germanium, ferrite, gemstones, and jade. Polishing of mold surfaces and dressing of grinding wheels are examples of ultrasonic processing.
- **Chemical Machining**: To obtain the desired shape, size, or finish of the workpiece, chemical machining uses acid, alkali, or salt solutions to erode or dissolve the material of the part. This machining method is great for thinning large areas or drilling complex holes in thin-walled objects. It is suitable for mass processing and can process many parts at once, handles all machinable metal materials with no hardness or strength, no pulling, no cracking, no burrs and easy handling. However, it cannot be used to machine narrow slits or holes, and is not suitable for removing defects such as surface roughness and scratches.
- **Rapid Prototyping**: Rapid Prototyping technology is developed and integrated by making full use of advanced CAD/CAM technology, laser technology, computer numerical control technology, precision servo drive technology, and new material technology. Due to the different molding materials, several types of rapid prototyping systems differ in molding principle and system properties. But the underlying technology remains the same: “build layer by layer, build layer by layer.” It is similar to the integral method in mathematics. Visually, rapid prototyping technology resembles a "3D printer". Receive product design (CAD) data directly and quickly create new product samples, molds, or models without the need for dies, cutters, or fixtures. As a result, the widespread adoption and deployment of RP technology significantly reduces new product development time, reduces development costs, and

improves development quality. This is the revolutionary importance of RP technology in manufacturing, from traditional 'removal techniques' to current 'growth methods', from mold making to mold-free manufacturing. Rapid prototyping technology can be used in a variety of industries including aerospace, automotive, communications, medical, electronics, consumer electronics, toys, military equipment, industrial modeling (sculpting), architectural models, and engineering.

- **Abrasive Jet/ Water Jet Machining/ Abrasive Water Jet Machining**: Abrasive jet machining is the process of impinging the high-speed stream of abrasive particles by high-pressure gas or air on the work surface through a nozzle and metal removal occurs due to erosion caused by high-speed abrasive particles. Abrasive Water Jet Machining is similar to abrasive jet machining, the only difference being that, water is mixed with abrasive materials which is subjected to the workpiece for material removal. And if abrasives are absent, then it is water jet machining where only water is subjected to the workpiece for material removal. [5]

## 1.5 Laser Beam Machining

Laser beam machining (LBM) is a type of machining that uses heat generated by a laser beam. This process uses thermal energy to remove material from metallic or non-metallic surfaces. The high-frequency monochromatic light that hits the surface heats, melts, and vaporizes the workpiece material due to the impingement of photons. LBM is most commonly attributed to brittle and poorly conductive materials, but is safe to use in most engineering materials. In fact, LBM can even run on glass without actually melting the surface. For photosensitive glasses, the laser changes the chemical structure of the glass and selectively etches it. This particular type of glass is often known as photoprocessable glass. The advantages of this glass are the ability to generate precise vertical walls and the native glass being suitable for many biological applications, such as substrates for genetic analysis. Lasers are used for welding, plating, marking, surface treatment, drilling, cutting, etc. Laser is used for precision machining of complex parts in the automotive, shipbuilding, aerospace, steel, electronics and medical industries.

Laser welding has the advantage of being able to weld at speeds of up to 100 mm/s and to weld dissimilar metals. Laser cladding is used to coat cheap or weak parts with a harder material to improve surface quality. Laser drilling and cutting has the advantage of little or no wear on the cutting tool as there is no damaging contact. Laser milling is his three-dimensional process that requires two lasers, but significantly reduces the cost of machining parts. A laser can be used to modify the surface properties of a workpiece. Applications for laser processing vary by industry. In light industry, machines are used for engraving and drilling other metals. In the electronics industry, laser processing is used for stripping and stripping circuit boards. [6, 7]

### 1.5.1.1 Advantages of LBM:

- Since the rays of a laser beam are monochromatic and parallel, it can be focused to a small diameter and can produce as much as 100 MW of power for a square millimeter of area.
- Laser beam machining has the ability to engrave or cut nearly all materials, where traditional cutting methods may fall short.
- There are several types of lasers, and each has different uses.
- The cost of maintaining lasers is moderately low due to the low rate of wear and tear, as there is no physical contact between the tool and the workpiece.
- The machining provided by laser beams is high precision, and most of these processes do not require additional finishing.
- Laser beams can be paired with gases to help the cutting process be more efficient, help minimize oxidization of surfaces, and/or keep the workpiece surface free from melted or vaporized material.

### 1.5.1.2 Disadvantages of LBM:

- The initial cost of acquiring a laser beam is moderately high. There are many accessories that aid in the machining process, and as most of these accessories are as important as the laser beam itself the startup cost of machining is raised further.
- Handling and maintaining the machining requires highly trained individuals. Operating the laser beam is comparatively technical, and services from an expert may be required.
- Laser beams are not designed to produce mass metal processes.
- Laser beam machining consumes a lot of energy.
- Deep cuts are difficult with workpieces with high melting points and usually cause a taper. [6, 7]

## 1.6 Laser Cutting

Laser cutting is a type of LBM that uses a laser to vaporize material and produce a cut edge. In laser cutting, the output of high power lasers is most commonly routed through optics. Laser optics and his CNC (Computer Numerical Control) are used to direct the laser beam onto the material. Commercial lasers for cutting materials use motion control systems to follow the CNC or G-code of the pattern cut into the material. A focused laser beam is directed at the material, which is then melted, burned, vaporized, or blown away by a jet of gas to create an edge with a high-quality surface finish. There are three main types of lasers used in laser cutting. $CO_2$ lasers are suitable for cutting, drilling and engraving. Laser Neodymium (Nd) and Neodymium-Yttrium-Aluminium-Garnet (Nd:YAG) have the same structure, differing only in their applications. Nd is used for drilling and where high energy and low repetition rates are required. Nd:YAG lasers are used for drilling and engraving as well as where very high power is required. Both $CO_2$ and Nd:YAG lasers can be used for welding. The $CO_2$ laser is typically "pumped" by passing an electric current through the gas mixture (DC excitation) or using radio frequency energy (RF excitation). RF methods are new and growing in popularity. Since DC designs require electrodes within the cavity, electrode erosion and plating of electrode material on glassware and optics can occur. Since RF resonators have external electrodes, these problems do not occur. $CO_2$ lasers are used for industrial cutting of many materials, including titanium, stainless steel, mild steel, aluminium, plastics, wood, engineered wood, wax, fabric, and paper. Nd:YAG lasers are primarily used for cutting and scribing metals and ceramics. In addition to the power supply, the type of gas flow can also affect performance. Common variations of $CO_2$ lasers are fast axial, slow axial, cross flow, and slab. In a high-speed axial resonator, a mixture of carbon dioxide, helium, and nitrogen is circulated at high speed through a turbine or fan. Cross-flow lasers circulate the gas mixture at a slower speed and require a simpler fan. Plate or diffusion cooled resonators have a static gas field that does not require pressurization or glassware, saving spare turbines and glassware. The laser generator and external optics (including the focus lens) require cooling. Depending on system size and configuration, waste heat is transferred through coolant or directly to the air. Water is a commonly used coolant, typically circulating through radiators or heat transfer systems.

A laser microjet is a water jet guided laser in which a pulsed laser beam is coupled into a low pressure water jet. It is used to perform the laser cutting function and the waterjet is used to guide the laser beam by total internal reflection similar to that of an optical fiber. The advantage of this is that the water removes dirt and cools the material. Additional advantages over traditional "dry" laser cutting are high speed cutting, parallel kerf and omnidirectional cutting. The fiber laser is one of the fastest growing solid-state lasers in the metal cutting industry. Unlike $CO_2$, fiber technology uses a solid gain medium rather than a gas or liquid. A "seed laser" produces a laser beam that is amplified by a glass fiber. With a wavelength of just 1064 nanometers, fiber lasers produce extremely small spot sizes (up to 100 times smaller than $CO_2$), making them ideal for cutting reflective metallic materials. This is one of the main advantages of fiber laser over $CO_2$. [6, 7, 8]

### 1.6.1 Advantages of Laser Cutting Process

- Rapid processing time
- Reduced energy consumption & bills – due to greater efficiency.
- Greater reliability and performance - no optics to adjust or align and no lamps to replace
- Minimal maintenance.
- The ability to process highly reflective materials such as copper and brass.
- Higher productivity - lower operational costs offer a greater return on investments.

### 1.6.2 Methods for Laser Cutting

There are many different methods in cutting using lasers, with different types used to cut different materials. The methods are:

- **Vaporization Cutting**: In vaporization cutting a focused beam heats the surface of the material to its flashpoint, creating a keyhole. The keyhole sharply increases absorption and rapidly deepens the hole. As the hole deepens and the material boils, the steam produced erodes and blows off the molten walls, further expanding the hole. Non-melting materials such as wood, carbon and thermosets are commonly cut in this manner.
- **Melt & Blow**: Melt and blow or fusion cutting uses high pressure gas to blow molten material away from the cutting area, greatly reducing energy requirements. First, the material is heated to its melting point, and then a jet of gas blows the molten material away from the kerf, preventing the material from increasing its temperature any further. Materials cut in this process are typically metals.
- **Thermal Stress Cracking**: Brittle materials are particularly susceptible to thermal fracture, a feature exploited in thermal stress cracking. The beam is focused on the surface, causing localized heating and thermal expansion. This creates a crack, allowing the beam to move and guide. Cracks can be displaced on the order of m/s. usually used when cutting glass.
- **Wafer Dicing/ Stealth Dicing of Silicon Wafers**: Separation of microelectronic chips, such as those produced in semiconductor device manufacturing, from silicon wafers can be performed by the so-called stealth dicing method with a pulsed Nd:YAG laser. The electronics are silicon bandgap (1.11 eV or 1117 nm).
- **Reactive Cutting**: Also called "burning stabilized laser gas cutting", "flame cutting". Reactive cutting is similar to oxyfuel cutting, but uses a laser beam as the ignition source. Mainly used for cutting carbon steel with a thickness of 1 mm or more. This process allows very thick steel plates to be cut at relatively low laser power. [7, 8]

### 1.6.3 Components of Laser Cutting System

- Optical unit (reflecting mirrors, focusing optical lens, etc.).
- Power supply
- Worktable
- Arrangement for scrap removal.
- Supply of assist gas at required pressure.
- Control and CNC unit with servo motors

The fig. 1.2 given below depicts a typical laser cutting system. Fig. 1.2 shows all the components typically associated with laser cutting.

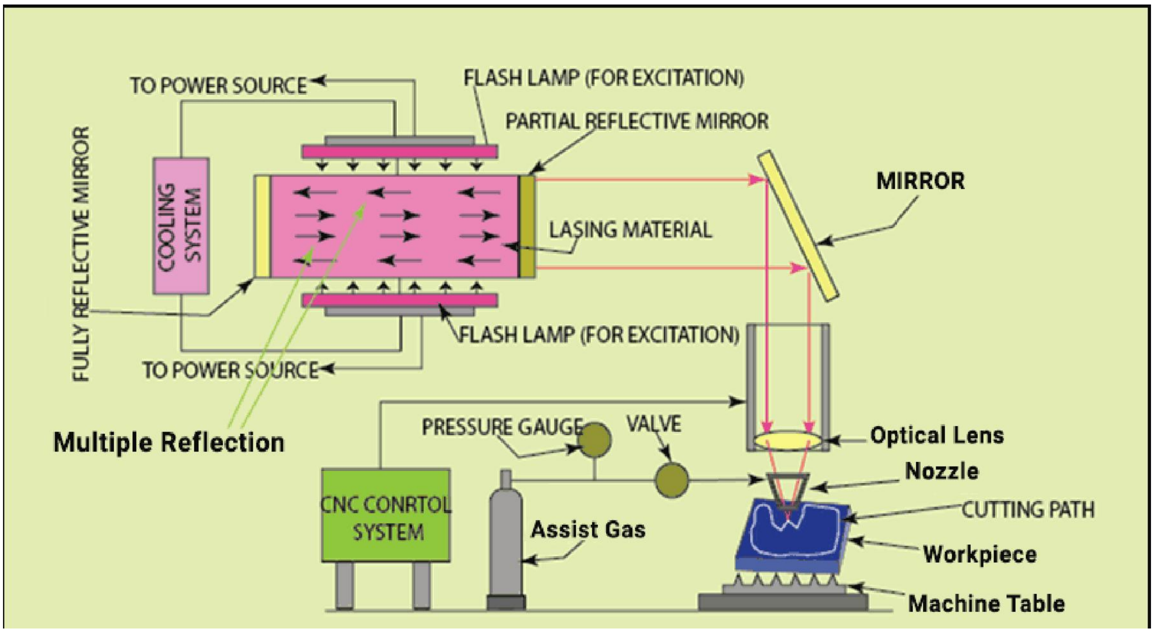



**Fig. 1.2 Laser Cutting System [42]**

### 1.5.2.4 Applications of Laser Cutting

- For cutting precision micro holes and complex profiles including sharp corners on metal or non-metal sheets, tubes, or open sections; the laser beam can be moved very easily as per the program in the CNC and cutting is fast and accurate especially for thin sheets.
- For cutting of highly brittle or fragile materials since there is no necessity of clamping the workpiece in the Laser cutting machine (there are no physical forces between the cutting tool (laser) and the workpiece); brittle or fragile materials tend to break or crack during clamping.
- Materials cut by Laser normally do not need an additional operation and can be directly used for the next operation like forming, pressing, or welding and this makes the process faster and cheaper.
- For welding of two or more materials with or without filler material; an inert gas like argon is used as the shield. The Laser beam of solid lasing material can be carried over a distance using fiber optics cable, for welding.
- The laser beam can be used to clean the rust on a metal surface. However, the surface must not contain inflammable oil or grease.
- For cutting different profiles in paper and cardboard to create beautiful invitation and greeting cards.
- For etching designs, logos, and advertising on acrylic sheets for display.
- For marking of sheets, pipes, or other sections.
- In the production of cloth.
- For texturing of steel and aluminium sheets used in the automobile industry. [6, 7, 8]

### 1.5.2.5 Benefits of Laser Cutting of Engineering Materials

- The laser cutting process produces a very fine edge (when the material thickness is less, like 10/12 mm in mild steel and less than 6 mm in stainless steel) without burrs and can be directly used for further processing. This saves time and money.
- A Laser cutting machine can cut any shape with any complexity with ease; it is very efficient for cutting micro holes and complex profiles in thin sheets, pipes, box sections and open channels.
- Laser cutting machine does contactless cutting with quality, precision, speed, and a high level of repeatability; it is a versatile process with great flexibility and easy automation.
- When the material and thickness range is the same, Laser cutting machine can go on cutting without any change in set-up.
- The Laser cutting has high cutting accuracy of ± 0.1 mm (for lower thickness material) which is not possible in other cutting; also the cutting is fast even for very complex profiles. When one needs high cutting accuracy like in the aerospace industry, Laser is the first choice.
- Compared to other thermal cutting processes for plates, the heat-affected zone (HAZ) in a Laser cutting is very small.
- The Laser cutting machine can cut any material, metallic or nonmetallic, from paper to wood to plastic to metals like mild steel, stainless steel, brass, aluminium, etc.
- One can use Laser cutting for small as well as big production runs with equal ease since there are no complex tool set-ups. One needs to simply program the cutting profile in the CNC and is ready to start.
- A Laser cutting machine has very few moving parts and this gives the advantage of low downtime in maintenance and also low maintenance cost.
- The CNC of Laser cutting machine makes a perfect cutting plan leading to a high percentage utilization of the material and low wastage. This helps to control the material cost-effectively.
- The work material does not need any clamping in Laser cutting since there are no physical cutting forces. Laser cutting does not warp or bend the material (even when the material is thin). This is a huge advantage when cutting brittle or fragile material which is prone to crack during clamping.
- The power consumed by a Laser cutting machine is comparatively less. One 10 kW Laser cutting machine may be able to do all kinds of cutting including fairly thick and reflective surface materials like aluminium.
- The width of cut (kerf) of the Laser cutting (0.1 to 1 mm) is less compared to other thermal cutting processes.
- With the help of a fiber optics cable, one can carry the laser beam from the machine to the difficult-to-reach areas for cutting and welding. [6, 7, 8]

### 1.5.2.6 Drawbacks of Laser Cutting of Engineering Materials

- The Laser cutting is accurate for cutting lower thickness of material up to mild steel-10/12 mm or stainless steel 6 mm. beyond this thickness, laser cutting accuracy deteriorates and the cutting may have a taper, roughness, and burrs. You can minimize this problem to some extent by using a higher power Laser and lower cutting speed.
- The initial cost of your Laser cutting is very high when compared to abrasive water jet cutting, or plasma cutting. Also, the room where you install this machine needs a very high level of ventilation to exhaust the toxic fumes produced during the process.
- The Laser cutting is not suitable for cutting dual materials like mild steel sheet clad with stainless steel or wood sandwiched with plastic etc.
- Laser cannot cut a blind hole accurately.
- Laser can cut all materials, however, the process may emit toxic gasses/fumes, specifically when cutting non-metals like plastic; the Laser operator needs to wear safety gears like a face mask and goggles.
- Laser cutter is not efficient for cutting material with high reflective surfaces like aluminium and copper, since a percentage of the laser beam gets reflected and goes as waste. [6, 7, 8]

In this particular work, LBM has been deployed to perform laser cutting operation, a significant part of LBM, on Titanium alloy Ti-6Al-4V to investigate the process, the responses acquired and above all, to study the effects of process parameters on the responses, and to optimize the process parameters for the best results possible. Aim of this work: performing experimental investigation, developing empirical models based on experimental works, relating process parameters with responses, checking the adequacy of the developed model, optimizing the process parameters for laser beam machining.

# Chapter 2

# Literature Review and Research Objectives

## 2.1 Review of Past Research Work

**Yamaguchi et al** [9] conducted an experimental study using a nitrogen laser-pumped dye laser to laser cut an aluminium laser stripe on an IC chip. In the aperture projection process, a laser pulse with a relatively flat power density distribution is irradiated to the optimum stripe area, so that the stripe can be removed cleanly without damaging the underlying layer. The basic properties of the ablated aluminium films and strips are revealed considering the defocus distance, laser power density, SiOz underlayer thickness, and aperture image size. They found that complex structured strips can be easily removed using this method.

**Niziev et al** [10] published his 3D theory of laser cutting. They estimated the splitting efficiency at different polarization types determined by the final parameters. When cutting metals with a large thickness-to-cut width ratio, the laser cutting efficiency for radially polarized beams is 1.5-2 times higher than that for plane P-polarized and circularly polarized beams.

**Slocombe et al** [11] conducted experiments to ablate highly reflective metal using polymer powder, by subjecting laser on the polymer powder, placed on metal surface, resulting in metal ablation. According to the author, laser machining of high temperature and highly reflective metallic materials can be performed with significantly lower laser powers to those required to machine the solid materials. Also Argon jet not just acts as an assist gas, but also prevents ignition and burning of polymer vaporised gas.

**Griffith et al** [12] demonstrated by understanding the migration kinetics and de-lamination of the resulting channel morphology, complex geometries can also be fabricated in stainless steel. A key factor for creating clean features is choosing a suitable layer reduction that allows the ionized species to escape from the channel.

**Li et al** [13] report a new technique aimed at minimizing the heat-affected zone while improving material removal efficiency. In their work, they used a relatively environmentally benign saline solution in contact with the point of interaction between the beam and the material, enabling material removal based on a laser-activated thermo-chemical mechanism. Not only can they remove layers that are deformed during processing, they can increase material removal rates by up to 300% on 316 stainless steel workpieces.

**Kaldos et al** [14] shows an investigation of surface quality, material removal during machining with a combination of high-speed milling and laser machining for roughing and finishing. The research includes machining a variety of difficult-to-machine metallic and non-metallic materials used in the tool and die industry. Centralized processing on a milling machine, which combines the advantages of both milling and laser processing, is especially effective for processing complex shapes. The aim of the current research program is to determine the process window for laser ablation of several materials. This allows us to find the optimal process parameters for maximum ablation rate.

**Caiazzo et al** [15] conducted laser cutting of three thermoplastic polymers, polyethylene (PE), polypropylene (PP) and polycarbonate (PC) with different thicknesses from 2 to 10 mm. For all three of his polymers used, the cutting speed was very interesting and proved to be significantly faster than ferrous and non-ferrous metals. We also found that in many cases there was no need to use a powerful $CO_2$ laser source. Sometimes a few hundred watts are enough. Surface roughnesses (Ra) measured on cut surfaces (PP, PE, PC) were very low compared to those observed for similar thicknesses of typical mild steels. We also observed that the edge and face quality obtained was much better with PP than with PE. The cut surface of the PC leaves tiny droplets of re-solidified molten material.

**Forsman et al** [16] developed a pulse format that enhances processing speed through efficient ablation and extends the ability to percussion drill small, high-aspect-ratio holes in certain materials by reducing the rate of hole blockage.

**Rao et al** [17] aimed to study the dynamic behavior of melt ejection during laser cutting of titanium sheet and achieve dross-free cutting with minimal heat affected zone (HAZ). $CO_2$ laser cutting of titanium sheets was performed using continuous wave (CW) and pulsed laser operation with different shear gases, namely argon, helium and nitrogen. Laser cutting at high frequency and low duty cycle pulsed mode operation produced dross-free cuts with no discernible HAZ. Helium produced narrow HAZ and low dross laser cutting compared to those produced using argon as shear gas due to its high thermal convection and ability to generate high shear stress.

**Dausinger et al** [18] conducted experiments to find the optimal laser parameters for laser ablation and found two drawbacks. With strong deformation of the laser beam near the focal point, the thermal nature of ablation is also present in femto-second lasers. To minimize thermal damage on the one hand and avoid destructive nonlinear effects on the other, pulse widths close to 5–10 ps are considered optimal. When drilling with high aspect ratios, a vacuum atmosphere allows you to avoid errors while applying higher energy density values.

**Knowles et al** [19] suggest that laser micromachining is a fundamental technology that facilitates miniaturization and performance improvement of parts. It is used in many industries including semiconductor, electronics, medical, automotive, aerospace, instrumentation and telecommunications. Laser ablation of metals, ceramics and polymers is a complex process and the exact nature of the interaction is specific to the materials used and laser processing parameters.

An experimental study was conducted by **Yilbas et al** [20] to observe the laser melting of thick mild steel plates and to investigate the effect of cutting parameters on the percentage of cut width variation. Cutting parameters were laser power, cutting speed, and assist gas pressure. A factorial analysis is performed to identify interactions between main effects and parameters. Formulate the thermal efficiency of cutting and the thickness of the liquid layer. Perform optical microscopy and scanning electron microscopy (SEM) to examine cutting errors and changes in kerf size. Laser power and oxygen gas pressure were found to have a significant effect on the kerf width variability.

**Avanish et al** [21] uses the Taguchi quality loss function to optimize two cut qualities, such as cut deviation and cut width, when cutting aluminium alloy sheets with a pulsed Nd:YAG laser beam, which is a very difficult material to laser cut. They determined the optimal process parameter conditions to minimize kerf deviation and width. They also found that pulse frequency and assist gas pressure also had a significant impact on kerf quality.

**Arif et al** [22] carried out Cutting thick mild steel plate with a laser. The temperature and stress fields of the cut surface were modeled using the finite element method. Residual stresses induced on the cut surface are determined using X-ray diffraction (XRD) techniques and compared to predictions. Structural and morphological changes in the sections are examined using light microscopy and scanning electron microscopy (SEM). They found that temperature and von Mises stress increase sharply in the cut region, especially in the direction perpendicular to the cut direction. Residual stresses near the cut remain high.

Fiber lasers offer distinct advantages over established laser systems in terms of power efficiency, beam guidance, and beam quality. **Mahrle et al** [23] suggest that the shorter wavelength of the fiber laser in combination with its high focusability is advantageous for thin sheet metal cutting whereas the $CO_2$ laser is probably still capable of cutting thicker materials more efficiently.

**Genna et al** [24] investigated the effect of process parameters on material removal rate (MRR) and surface roughness in engraving operations using C45 carbon steel and a Q-switched 20 W Yb:YAG fiber laser with fundamental wavelength $\lambda$ = 1070 nm. We investigated pulse frequency, beam velocity, distance between linear patterns of two successive laser scans, number of geometric pattern repetitions, and scanning method (horizontal lines only or both horizontal and vertical lines). Experimental results show that a Yb:YAG fiber laser can be used to machine C45 steel to obtain a three-dimensional engraving shape with MRR and roughness that are strictly dependent on the process parameters.

The effect of processing parameters was investigated by **Riviero et al** [25] to determine the optimum conditions for $CO_2$ laser cutting of aluminium-copper alloy (2024-T3). Cutting speed and cutting quality were evaluated. They observed that superior cutting quality was achieved when processing in CW mode compared to pulsed mode. The results obtained confirm that the 2024-T3 Al alloy can be successfully cut under optimized processing conditions with the necessary precautions taken to avoid back reflections of the laser beam.

A quantitative experimental study was conducted by **Reviero et al** [26] to determine the effect of machining parameters on cutting speed and quality criteria in machining using an off-axis supersonic nozzle. Cutting tests were performed in pulse mode and the results were interpreted using melt removal mechanisms. Experiments conducted show that the cutting speed is reduced compared to processing in continuous wave (CW) mode and that there are two processing regimes as a function of pulse frequency. Best results are obtained in high pulse rate mode.

A detailed study was conducted by **Reveiro et al** [27] on the effects of different auxiliary gases on the laser cutting efficiency and cutting quality of Al-Cu alloys. Results show that the formation of oxides and nitrides alters cutting quality and cutting speed. Oxygen, nitrogen, and compressed air react to a greater or lesser extent with the molten material, producing large amounts of oxides and/or nitrides that affect cutting speed and the quality of the resulting section. Argon, on the other hand, proved to be a more efficient assisting gas for the highest quality results and a highly efficient treatment of Al-Cu alloys.

**JK Park et al** [28] presented a new approach to improve metal laser processing quality by vibrating an optical objective lens at a frequency (500 Hz) and different displacements (0–16.5 μm) during the femto-second laser processing process. The wall finish and aspect ratio of the machined structures were found to be superior to the non-vibration assisted process.

**Pawan et al** [29] aimed to develop a numerical simulation model for predicting temperature and residual stress during laser cutting of an aluminium alloy (Al-2024). It is known that there is a high temperature gradient at the laser irradiation site, and high thermal stress is generated across the cut surface. We also know that the maximum temperature obtained during laser cutting decreases as the laser scanning speed increases. The stress distribution results show that the stress at the laser irradiation site reaches a low value due to the decrease of the thermal expansion coefficient with increasing temperature.

Al1050 sheet cutting experiments were performed by **Dorsch et al** [30] using a fiber laser and nitrogen as auxiliary gas. Decreasing the auxiliary gas pressure or increasing the cutting speed will reduce the cut quality. If the focal position is set within the thickness of the surface or sheet, maximum irradiance is reached in this state and reliable cutting results are obtained. The results showed that CW processing using fiber lasers improved cutting speed and produced cut quality comparable to the results obtained with $CO_2$ and Nd:YAG lasers.

A lamp-pumped and pulsed Nd:YAG laser source was used by **Astarita et al** [31] to cut Al2024-T3 aluminium alloy sheets coated with commercial pure titanium by cold gas dynamic spray technique. We found that we could cut the sample with a low power laser. The shape of the kerf is affected by all investigated parameters. In particular, the top kerf increases when the laser beams hits his Ti face, and the bottom kerf increases when the pulse duration and cutting speed increase. Slag height is affected by side and duration and increases proportionally. The absolute value of the cone angle is very small. However, it is subject to all controlling factors. Regardless of which side the laser hits, the underlying material is covered with a thin layer of the overlying material. This property can be used to create a protective layer inside the kerf.

Laser cutting tests of aluminium alloy 6061-T6 sheet were performed by **Leone et al** [32] using a multimode, pulsed, low power Nd:YAG laser to investigate the effect of process parameters on kerf geometry. We found that the cutting speed increased with increasing pulse duration as the laser beam moved along the minor axis of the elliptical focal footprint. The direction of jet travel has been found to affect both kerf width and draft. Pulse duration affects kerf, cone angle, and slag height. From a practical point of view, a nearly vertical notch ($Ta < 4°$) can be obtained by assuming a long pulse width. In this state, the dross height is less than 40 μm.

Laser cutting of aluminium alloy was performed by **Keles et al** [33]. Cut quality was assessed by measuring cut width and morphological examination of the cut. Large cracks and cavities on the laser cut part. There is no side burn on the front of the laser cut part. However, a localized sideburn is observed at the rear of the cut section, mainly due to the slow laser cutting speed. A striped pattern can be seen on the kerf surface. The slower the cutting speed, the deeper the fringes were found. The kerf width changes before and after the cut surface. In this case, the kerf width increases at the rear. Close examination of the kerf surface reveals the formation of several microcracks, especially at low cutting speeds and high laser powers.

Copper and copper-based alloys are difficult materials to laser cut due to their high thermal conductivity, high reflectivity, and tendency to lose zinc in the zone adjacent to cutting. **Previtali et al** [34] performed laser cutting of copper 110 and brass C464 highly reflective materials treated with a high power, ultra-low BPP direct diode laser source. The results show that it is possible to obtain high quality cuts in brass and copper alloys using nitrogen and oxygen assist gases. In cutting brass alloys, productivity is higher than that of pure copper, and conditions for easy cutting can be obtained. Smooth, homogeneous surfaces and burr-free edges can be achieved using a DDL source and HAZ less than 300 microns.

**Lutey et al** [35] performed laser cutting experiments using inert and active assist gases by varying the peak power, pulse energy, pulse frequency, and cutting speed on 1 mm and 4 mm thick steel samples. They achieved the lowest minimum laser cutting power and highest cutting efficiency, maximum peak power and minimum allowable pulse overlap for continuous cutting. Under these conditions, thermal conduction losses are significantly reduced with nitrogen support than with oxygen. In both cases the average edge temperature calculated is well below the melting temperature of the steel. However, with the oxygen assist gas, minimal slag adhesion and minimal surface roughness of the cut edge are achieved, resulting in both the lowest minimum average cutting performance and the highest cut quality.

**Cui et al** [36] experimented laser processing in the nanosecond range aims to produce hydrophobic 17-4 PH stainless steel surfaces with structures in the micron and submicron range. Four surface structures with microscale channels and pillars of uniform or varying heights were designed. During fabrication, high-power laser beams created sub-micron features in addition to micro-scale features, resulting in hierarchical and multi-scale surface structures. A detailed wettability analysis was performed on the manufactured samples. The static contact angle of water measured on these uncoated surfaces is over 130 degrees compared to 70 degrees on the pristine steel surface before laser processing. A slightly lower contact angle hysteresis was also observed on the laser-processed surface. Overall, these results are consistent with a simple Cassie-Baxter model of wetting that assumes only a fraction of the surface contact between droplet and surface.

**Gabdrakhmanov et al** [37] carried out experimental studies on laser cutting of copper and its alloys and found that an oxygen-containing medium (air, oxygen) is required. When the copper is exposed to laser irradiations, a thin and highly heat absorbing oxide layer is formed over the surface that absorbs the radiation, causing heating and ablation of the material. They confirm this in experiments using nitrogen and carbon dioxide as working gases. It is known that even at maximum power all laser radiation is reflected from the surface. Using oxygen as the assist gas reduces the power and increases the speed of laser irradiation.

**Marimuthu et al** [38] conducted laser cutting of a 2 mm thick aluminium metal matrix reinforced with aluminium oxide fibers (Al MMC). Experimental results showed that the laser cutting mechanism of fiber-reinforced MMC is very different from that observed for laser cutting of monolithic metals and alloys. His $Al_2O_3$ fibers in the MMC do not evaporate and are removed along with the molten low-melting matrix material. A thin, uniform layer of Al2O3 is deposited on the cut surface, useful for applications involving the transfer of gases or liquids.

**Parmar et al** [39] studied laser machining of titanium alloy (Ti-6Al-4V) and stainless steel (SS316L) and found that despite the higher melting temperature of Ti-6Al-4V, Ti-6Al-4V can be machined at higher cutting speeds and lower laser power than SS316L. The main methods of material separation for both materials were melting and blow cutting. However, the secondary treatment methods examined by XPS, XRD, and EDX confirmed significant conversion of the Ti6Al4V component to oxides despite the use of argon gas for shielding. Significant expansion and deformation stresses were present in Ti6Al4V, but thermo-elastic, plastic and deformation stresses were relatively comparable for both materials. They hypothesized that laser processing of Ti-6Al-4V, but not SS316L, was facilitated by major chemical transformations.

**Kang et al** [40] proposes a new laser processing apparatus for ultrasonic vibration-assisted lenses that improves the quality of laser processing and maintains the degree of freedom in laser processing by applying ultrasonic vibrations to lenses. Finite element analysis is used to optimize the design results, and the prototype's resonant frequency and ultrasonic vibration amplitude are calibrated on a test rig. Based on this study, we propose a processing mechanism for ultrasonic vibration-assisted laser processing of lenses, modifying the laser energy density on the workpiece by adjusting the spot diameter. Moreover, the first experimental validation of the device shows that ultrasonic vibration of the lens is of great importance for improving the surface quality of laser polishing and reducing the taper angle of laser drilling. This is mainly caused by changes in laser energy density.

High-energy $CO_2$ laser cutting of titanium alloy sheets was performed by **Aoud et al** [41] with the aim of estimating the effect of various laser cutting parameters such as laser power, cutting speed and assist gas pressure on the integrity of the cut area. Microcracks and poor surface quality were the result of nitrogen. Laser power and cutting speed have an important and significant effect on surface roughness. The main effects plot shows that pressure also affects roughness. The highest surface quality is achieved by combining high laser power with high cutting speeds.

## 2.2 Objective of the present research work

The present work aims to laser machine Ti-6Al-4V alloy and record the responses. Three process parameters: laser power, pulse frequency and cutting speed are independent variables that define the cutting process. Two responses for all the combination of the parameters are recorded: surface roughness and kerf deviation. The present work also aims at establishing the effects of process parameters on the responses. This work also aims to optimize the process parameters for laser cutting this alloy.

The objectives of this research work are as follows:

1. To perform the laser cutting of 2 mm thick TI-6AL-4V super alloy using 500 watt QCW fiber laser.
2. To study the effect of laser cutting parameters on cut quality characteristics of TI6AL4V super alloy
3. To design the experiment based on central composite design using response surface method
4. To develop the empirical relationship between key process parameters and machining quality characteristics
5. To check accuracy and quality of machined surface using optical microscope
6. To optimize the process parameters in order to obtain optimum response using desirability function analysis technique.

## Chapter 3

# Experimental Setup

## 3.1 Experimental Setup

This investigative study work was performed on a QCW fiber laser metal cutting machine manufactured by Mehta India Cad-Cams Limited.


**Fig. 3.1 Photographic view of the QCW Fiber laser metal cutting machine workstation**

The above picture shows the full view of the workstation used in this particular investigative work. The workstation consists of the laser system as shown above, fixtures, controls console and indicator lamps.

### 3.1.1 Schematic Diagram of the QCW Fiber Laser Metal Cutting Machine

The schematic diagram of the QCW Fiber Laser Metal Cutting Machine depicts all the components and layout of the system. All the parts such as the laser head, servo motors, pressure gauge, assist gas system, chiller system, control console, laser system and work table are shown.

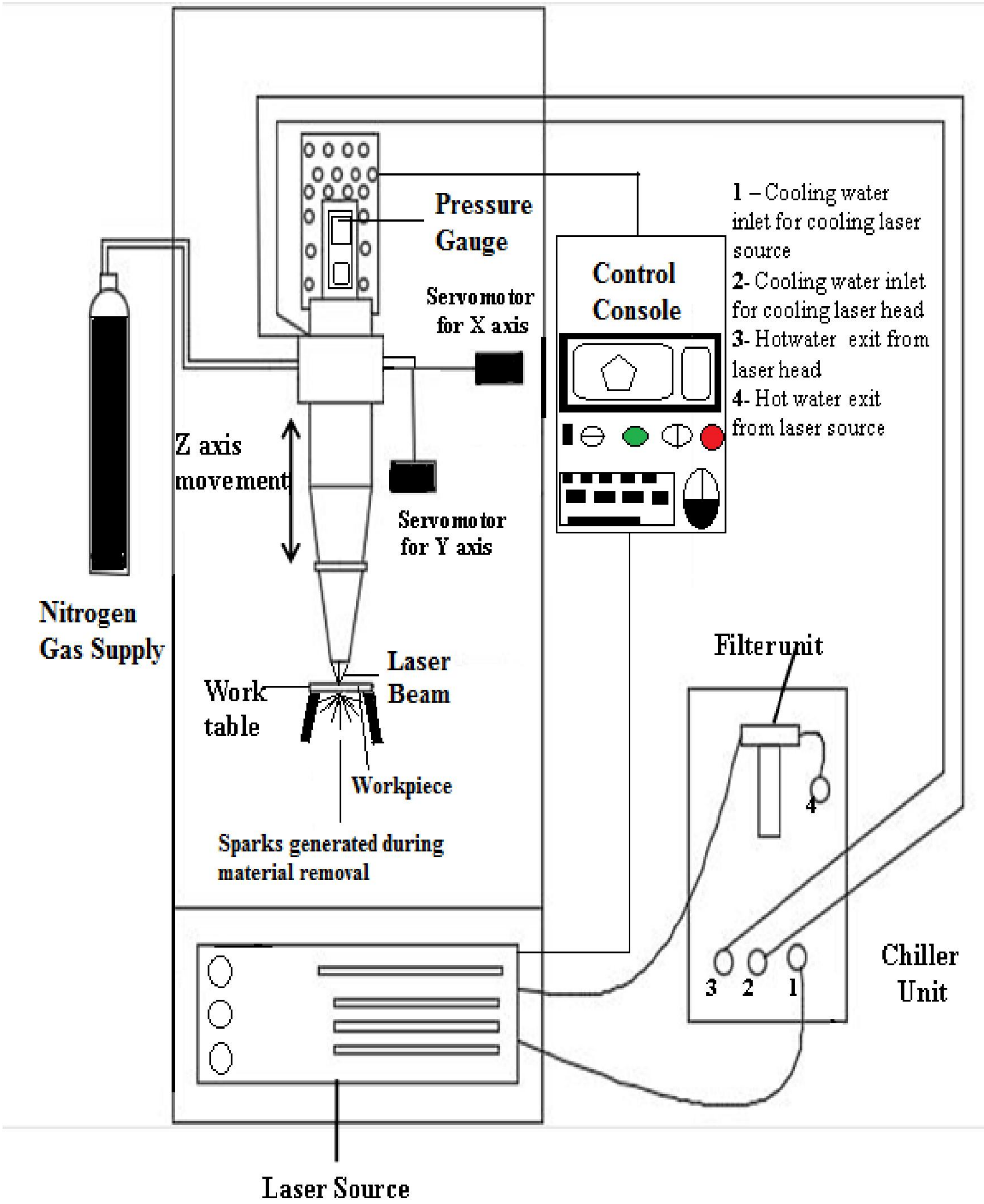



**Fig. 3.2 Schematic diagram of the fiber laser metal cutting machine**

## 3.2 Laser System

The above mentioned laser cutting machine employs a fiber laser to perform the required function of cutting. The laser system produces a bright, coherent, quasi-static or quasi-continuous wave (QCW) laser beam that when subjected on a workpiece, produces cut on the surface of the given workpiece. The laser is produced in the laser system enclosed within the workstation. The laser is then transported to the working space in the workstation via a fiber, hence the name fiber laser. The laser then works through a focusing lens and finally reaches the workpiece surface through the laser head. The laser is moved over the workpiece using a pair of servo-motors that are placed perpendicular to each other. The system consists of a nozzle too, that aids and controls the flow of assist gas during the cutting process. Being a quasi-static laser system, it can produce a huge range of laser frequencies, although the duty cycle cannot be changed and the pulses are not ultra-short.

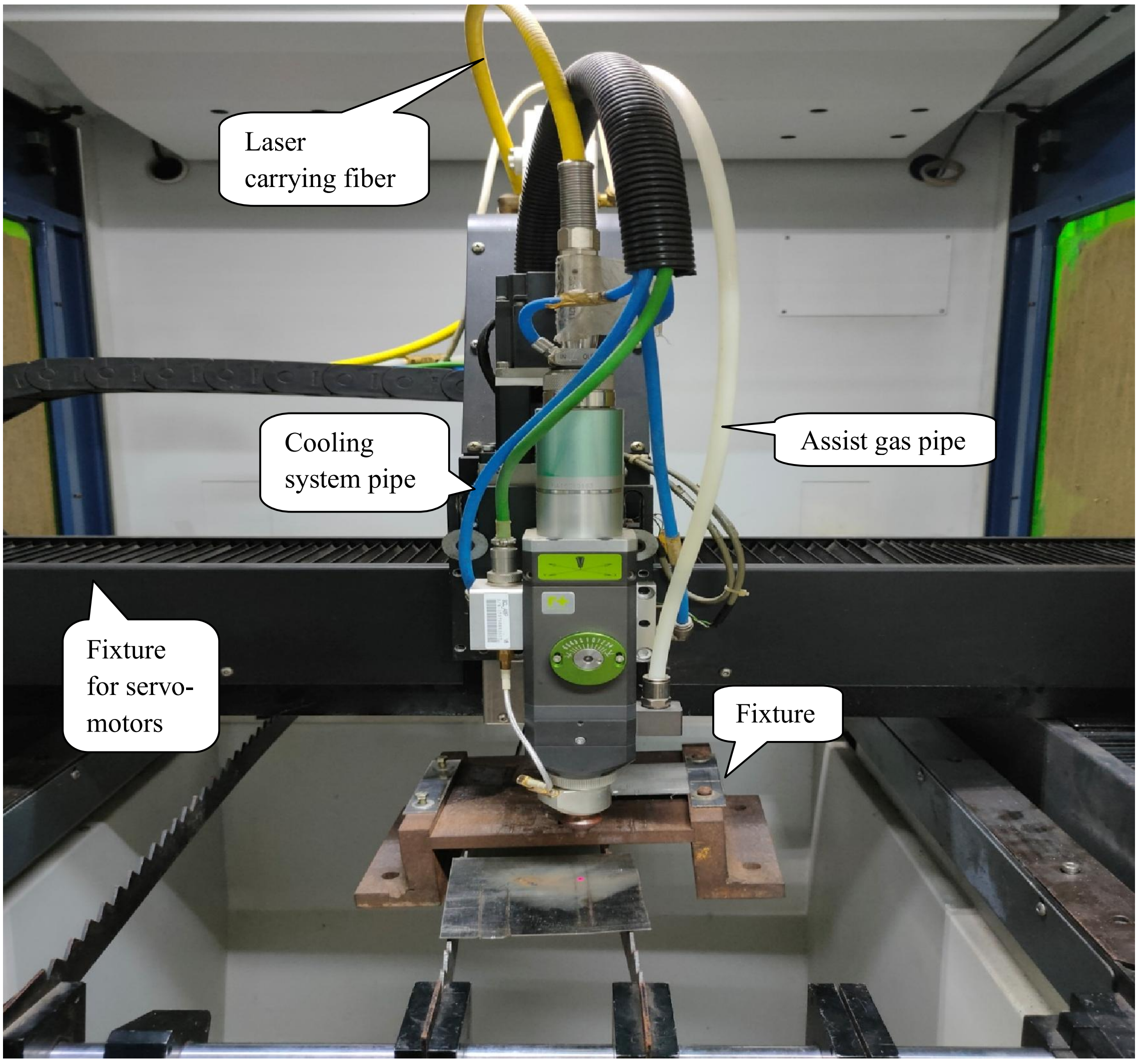



**Fig. 3.3 the laser system: comprising of the laser head, nozzle, fiber, assist gas pipe, fixture, workpiece and cooling system pipes**

The laser workstation consists of a laser spot LED that shows a red mark on the place where the laser would actually fall if the cutting process is initiated. There's a top mounted pressure dsiplay that views the current assist gas pressure in the system when operating.

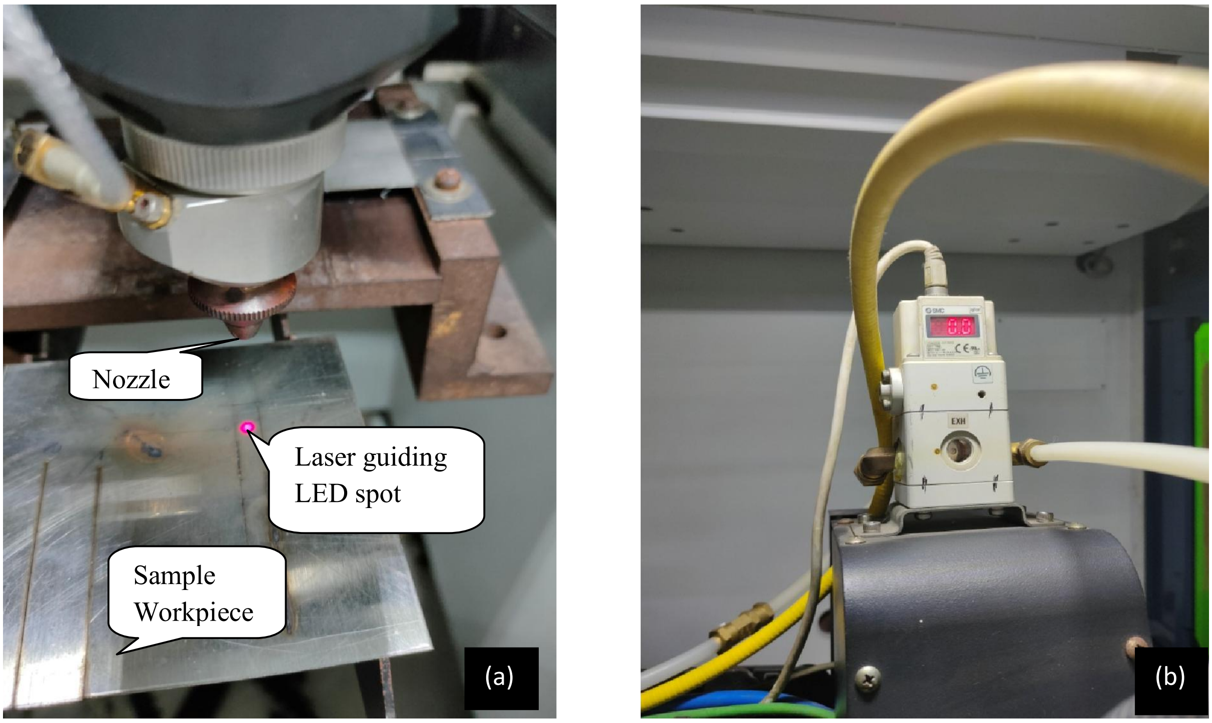



**Fig. 3.4 (a) photographic view of nozzle, laser shutter and workpiece, (b) photographic view of assist gas pressure display.**

### 3.2.1 Laser System Specification

**Table 3.1 Specification of the laser system**

| | |
|---|---|
| Laser Type | :Solid state Fiber laser |
| Max Avg Power | :500W |
| Spot Dia | :50 microns |
| Wavelength | :1064nm |
| Frequency of Laser | :1Hz – 50kHz |
| Cutting Speed range | :0.1mm/s – 500mm/s |
| Cutting Height Range | :0.6mm – 8mm |

### 3.2.2 Facility Requirements

**Table 3.2 Electrical Supply Requirement**

| | |
|---|---|
| Electrical Supply | :2 phases and earth/ earth, neutral and phase |
| Operating Voltage | :220/380V |
| Operating Current Frequency | :50/60 Hz |
| Power Consumption | :9kW |

**Fig. 3.5 Power Unit/ Stabilizer**

The fig. 3.5 shows the power unit or stabilizer that is used alongside this machine to control the power supplied to the system. In the fig. 3.5, it depicts 233V supply is being available to the system.

## 3.3 Laser Head Motion System

In a laser cutting process, it is important that the laser moves over the surface of the workpiece efficiently so that the cutting operation takes place perfectly. Some laser cutting machines have movable workpiece holder along with a fixed laser head, and some have movable laser head with fixed workpiece. The cutting machine used for this work has a movable laser system and the workpiece is mounted on a stationary fixture. The laser is aligned and programmed with the compatible software to make the necessary movements of the laser head to get the desired result, i.e., cutting.

The QCW fiber laser cutting system comes with a pair of servo-motors that are held perpendicular to each other, leading to bidirectional movement, that is, the laser head can move in two axes. This movement helps in cutting not just straight lines, but any shape that can be drawn on a two-dimensional plane. The cutting speed has a good range, thereby helping to cut different materials, with different thickness easily.

## 3.4 Assist Gas System

Like every other laser metal cutting machine, this machine too, comes with an assist gas system to aid the cutting process. The assist gas has two major applications. At first, it helps in cooling down the workpiece surface, preventing it from burning, or developing some thermal damages. Thermal damages may cause changes in the workpiece material to different physical or mechanical properties. These changes may not be desirable. The second role of assist gas is to blow away the debris produced during the cutting process. This debris often causes blockages to the nozzle or laser lens. Thereby it is advisable to blow this debris.

**Table 3.3 Specification of the gas supply**

| | |
|---|---|
| Gas Type | :Nitrogen |
| Maximum Gas Pressure Available | :150 bar |
| Maximum Permissible Gas Pressure | :10-12 bar |

The current fiber laser metal cutting machine being discussed uses a gas cylinder to supply the assist gas to the nozzle through an assist gas pipe. The cylinder comes mounted with two pressure gauges that indicate the available pressure in the cylinder and the supply pipe.

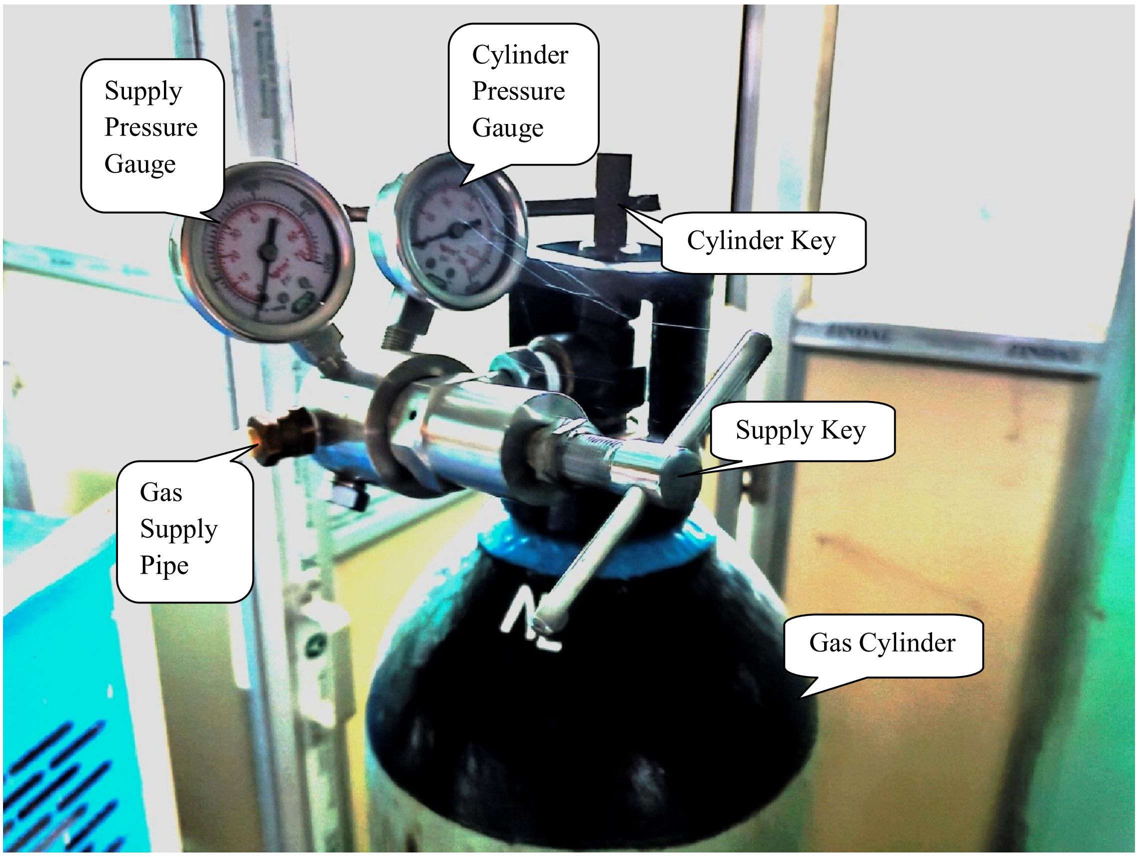



**Fig. 3.6 Photographic view of gas cylinder with keys, supply pipe and pressure gauges mounted**

From fig. 3.6, it can be seen that the gas cylinder comes mounted with several equipments. At first, the cylinder consists of two keys. The one labelled cylinder key is used to open and control the gas flow from the cylinder to the pressure gauges. The second key, labelled as supply key, is used to open and control of the gas to the assist gas pipe and then to the main workspace. Two pressure gauges in fig. 3.6 are labelled as cylinder pressure gauge and supply pressure gauge. The cylinder pressure gauge indicates the total available pressure of the gas from the cylinder at a given time. As the gas is being consumed during the cutting process, the cylinder pressure gauge shows that the pressure in the cylinder to be reducing with consumption of the gas. The second pressure gauge, labelled as supply pressure gauge, indicates the gas pressure currently available in the assist gas pipe that is being carried to the workspace.

## 3.5 Machine Cooling System

Laser is often associated with heat. It is a well known fact that any machining process requires and generates some amount of heat. This heat however may damage the system components leading to loss of property and damage to the infrastructure. Many machining systems come equipped with a cooling system to overcome these problems and to extend the lifespan of the machine and its components.

The laser cutting machine involved in this particular investigative work too comes equipped with a cooling system. A chiller has been used with this machine that helps to cool down the system components. This chiller supplies water through a pair of water supply pipes. The first pipes supplies cold water to the periphery of the different components of the cutting machine. Water, being well known to have good heat capacity, carries heat from the components through the second pipe to the chiller. The chiller then cools down the water using an air cooled heat exchanger. The heat exchanger reduces the temperature of the water, which then turns cold again. This cold water is supplied again to the workspace components and the cycle repeats.


**Fig. 3.7 Photographic view of the chiller unit**

Fig. 3.7 depicts the frontal view of the chiller unit that shows the display and has the controls for the temperature management. The display also shows a timer, which indicates the time countdown for initializing the chiller unit operation, and supplied voltage.

## 3.6 Laser Cutting Machine Control System

Every machine requires to be controlled by the operator to ensure smooth and efficient functioning. The laser cutting machine used in this work too requires to be controlled by an operator. Most of the controls of the machine are done using a computer. The computer consists of a Central Processing Unit (CPU), a monitor, a keyboard and a mouse. The CPU is enclosed in the workspace, which controls all the electronic and electrical components. The mouse and keyboard are for inputting the commands, and the display monitor views the operation using the compatible software.


**Fig. 3.8 Photographic view of the control console**

**Table 3.4 Specification of the control console**

| | |
|---|---|
| Display Type | :LCD |
| Manufacturer | :AOC Limited |
| Display Resolution | :1366x768 |
| Input Interface Type | :Wireless input/output, USB receiver |
| Manufacturer | :Logitech LLC |
| Other Controls | :Emergency stop (Red), Key, LED switch, Machine Start/Stop (Green) |

## 3.7 User Control System

Although the machine comes with all the controls and a console, the fiber laser metal cutting machine requires compatible software for its operation, wherein the user can input the commands, the machine works accordingly and the user can keep a view on the operation using the software. The machine is based on FSCUT interface. And software with the compatible interface is required for its operation.

**Table 3.5 Specification of the user control system**

| | |
|---|---|
| Operating System | :Windows 7; 64-bit |
| Machine Interface | :FSCUT 2.0 |
| Software | :CypCut Laser Cutting Machine Software |

CypCut laser cutting machine software based on FSCUT 2.0 interface is used with the machine to operate the machine. The software has a CAD – like interface where the user can draw any shape (compatible with the two-dimensional plane/ axes), input the machining parameters, set the position of the laser head, check for the frame, that is, the square/ rectangular area over which the operation will be performed, puff the assist gas to clean the surface of the workpiece, switch on/off the laser shutter or mark, the laser and start, pause, stop and monitor the operation. CypCut allows the user to vary the cutting speed, cutting height of the laser head or stand-off distance, laser power and laser current (in percentages), laser delay time, laser – off delay time, laser frequency, assist gas pressure, number of passes and many more options within the interface.

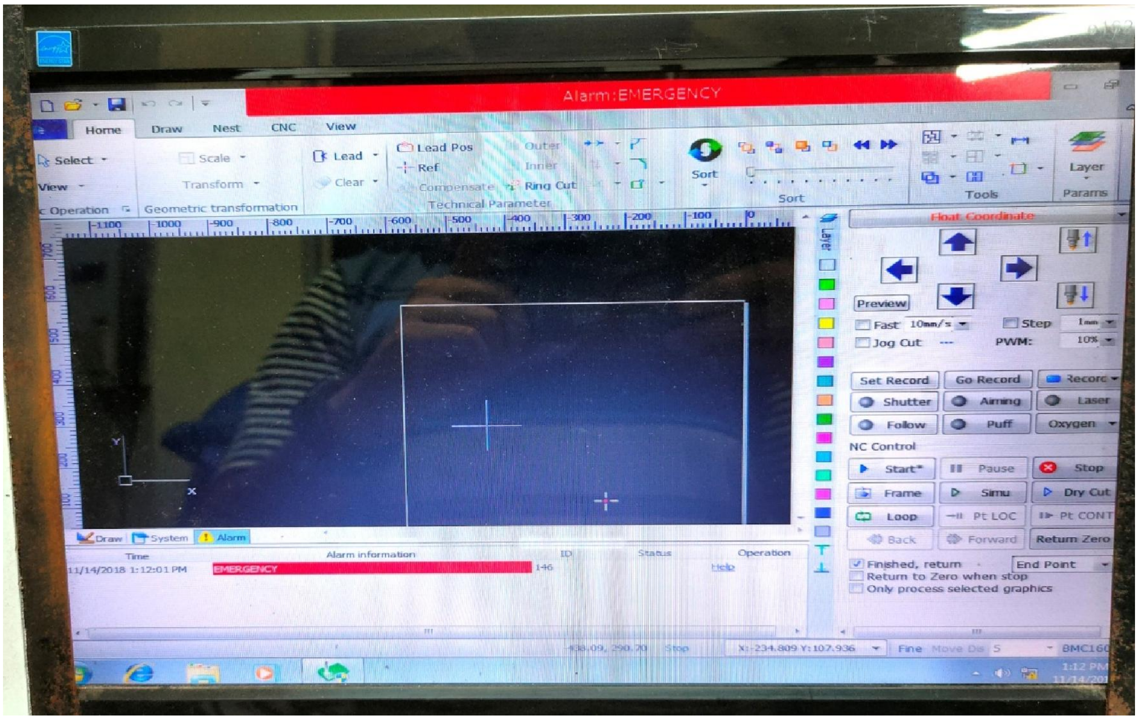



**Fig. 3.9 User Interface of the CypCut Software**

## 3.8 Indicators System

The fiber laser cutting machine comes equipped with indictor lamps mounted on the top of the workspace. The lamps have three colour LED system with distinct functions.

- Red – the red lamp glows when the machine is either initializing before being ready to use, or if the machine has encountered any error during the operation.
- Yellow – the yellow lamp glows when the machine is getting ready to be used.
- Green – the green lamp glows when the machine is either ready for operating or is running the operation without any error.

**Fig. 3.10 Indictor lamps mounted on the top of the workspace, currently glowing in green symbolizing the machine is ready for operation**

## Chapter 4

# Research Methodology

## 4.1 Design of Experiments (DOE)

Every investigative experimental research work requires a method to plan the experiments. For doing so, Design of Experiments (DOE) is implemented. Design of Experiments (DOE) is defined as the branch of applied statistics concerned with the design, conduct, analysis, and interpretation of controlled tests to assess factors that control the value of a parameter or group of parameters. DOE is a powerful data acquisition and analysis tool that can be used in a wide variety of experimental situations.

One can manipulate multiple input elements to determine their impact on the desired output (response). By manipulating multiple inputs simultaneously, DOE can identify important interactions that may be missed when he experiments one factor at a time. You can explore all possible combinations (complete factorial) or only some of the possible combinations (fractional factorial). Strategically designed and conducted experiments can provide a great deal of information about the influence of one or more factors on a response variable. Many experiments keep certain factors constant while varying the values of other variables. However, this one-factor-at-a-time (OFAT) approach to processing knowledge is inefficient compared to simultaneous changes in factor levels. Many of the current statistical approaches to designed experiments are the work of R.A. Fisher in the first half of the 20th century. Fisher showed how taking the time to seriously consider experimental design and conduct before attempting an experiment can help avoid common analytical problems. Key concepts in developing experimental designs include blocking, randomization, and replication.

There are several types of DOEs, namely:

- Full Factorials
- Fractional Factorials
- Screening Experiments
- Response Surface Methodology
- EVOP
- Mixture Experiments

This experimental work has been performed using Response Surface Methodology or RSM.

## 4.2 Response Surface Methodology (RSM)

Engineers often want to determine the value of the process input parameter at which the response reaches an optimum, which is either the minimum or maximum value of a particular function related to the process input parameter. The Response Surface Method is one of the widely used modelling and optimization techniques currently used to describe the performance of welding processes and to find the optimum value of the response of interest. RSM is a collection of mathematical and statistical methods that help model and analyze problems where the answer of interest is affected by several variable factors and the goal is to optimize the response.

The field of RSM consists of:

i. Developing the experimental strategy for exploring the space of the process or independent variables.
ii. Empirical statistical modeling to develop an appropriate approximating relationship between the yield and the process variables ,and
iii. Optimization of process for finding the values of the process variables that produce desirable values of the response.

($\xi_1$, $\xi_2$, ……, $\xi_k$) are considered as independent variables which are measurable, controllable and continuous with the experiments. They are considered to be nearly error free. In such a condition, the response surface y can be computed as:

$$y=f(\xi_1, \xi_2, \ldots\ldots, \xi_k)+ \varepsilon \qquad \ldots\ldots(4.1)$$

Where, f is an unknown and complicated response function,

ε is an unanticipated error that occurred during measurement, vibration in the system or some unaccounted noise or variability.

In most cases, ε is considered as a statistical error, with mean zero and variation $\sigma^2$. For such a condition, the response expected can be written as:

$$E(y) =\eta = E[f(\xi_1, \xi_2, \ldots\ldots, \xi_k)]+E(\varepsilon) = f(\xi_1,\xi_2,\ldots\ldots,\xi_k) \qquad \ldots\ldots(4.2)$$

The variables mentioned in Eq. 4.1 and 4.2, $\xi_1,\xi_2,\ldots\ldots,\xi_k$, are natural variables with units like Celsius, mm/s, degree, Hz, mm, mm/s$^2$, etc. however, for the sake of simplicity, they can be coded into variables such as x ,y, z, etc in RSM. This allows the variables to be dimensionless, with zero mean and same standard deviation. Using these coded variables, the response in Eq. 4.2 can be rewritten as:

$$\eta= f(x_1, x_2, \ldots\ldots\ldots\ldots, x_k) \qquad \ldots\ldots(4.3)$$

Practical applications of RSM require the development of an approximate model of the true reaction surface. Fitted models are based on observed data from processes or systems and are empirical models. Multiple regressions are a set of statistical methods that help build the type of empirical model required in RSM. RSM typically uses quadratic polynomials:

$$\eta = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j \qquad \ldots\ldots(4.4)$$

In Eq. 4.4, $\beta_{i,j}$=0,1,…..k are regression coefficients.

## 4.3 Response Surface Designs

RSM comprises of mainly two types of design methodologies, namely, Box-Behnken Design and Central Composite Design (CCD).

### 4.3.1 Box-Behnken Design

- Have a specific arrangement of design points and combine the $2^k$ Factorial with incomplete block scheme.
- Have 3 levels for each factors
- It is created using estimation of quadratic model.
- It provides strong estimates near the center of the design space (where there are hypothetical optimal values), but weaker estimates in the corners of the cube (where there are no design points).
- If the experimenter misses a run, the accuracy of the remaining runs is critical to the reliability of the model. The central composite plan initially has runs, which makes it very resilient to problems.

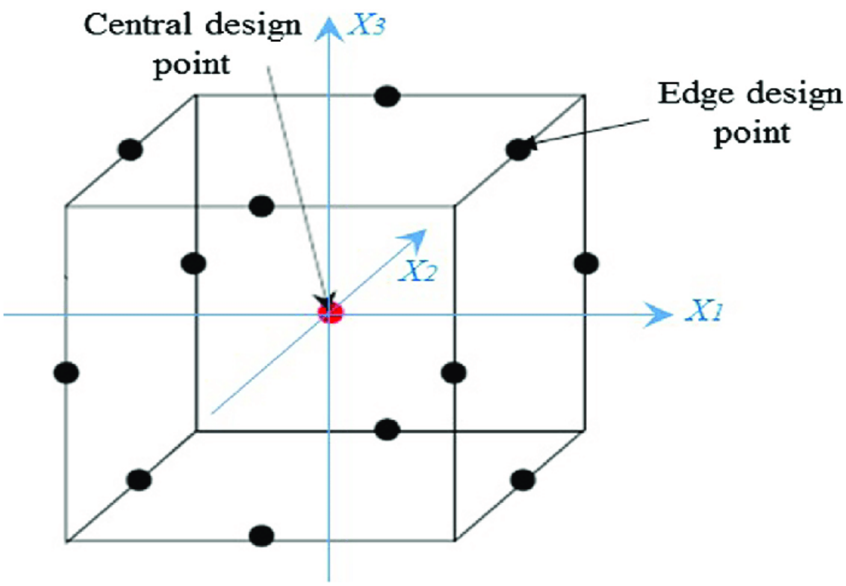



**Fig. 4.1 Box-Behnken design point for k=3 in design space** [43]

### 4.3.2 Central Composite Design

- Created from $2^k$ Factorial points extended by multiple centerpoints.
- The designs must specify two parameters. The distance α of the axis string from the design center and the number of centers.
- A typical central composite design has 5 levels for each factor, but this can be changed by choosing α =1.0 (CCD centered on the face). Face-centric designs have only 3 levels of per factor however.

- A second model, created to estimate the second order model. $2^k$ Factorial points were used to fit the first-order model. This model shows a lack of fitting. Axial runs are then added to the model to allow quadratic terms to be included in the model.
- Very sensitive to missing data.
- Replicated centers provide good predictive power near the center of the design space (where the assumed optimum is).

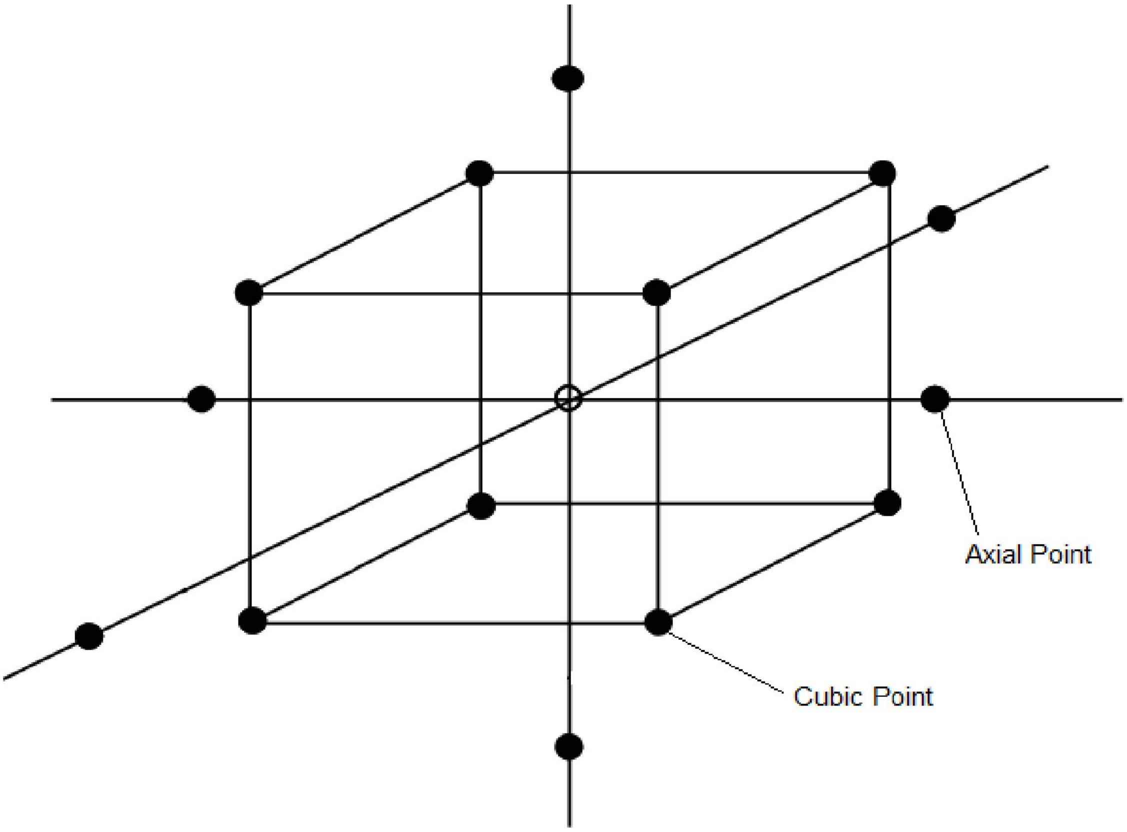



**Fig. 4.2 CCD design points for k=3 in design space** [44]

The value of α depends on the number of experimental runs in the factorial part of the central composite design:

$\alpha = [\text{number of factorial runs}]^{1/4} = [2^k]^{1/4}$ …………………………………………………...(4.5)

**Table 4.1 CCD design points and values of α**

| | | | | | |
|---|---|---|---|---|---|
| No of Continuous factors | 2 | 3 | 4 | 5 | 6 |
| Factorial Points | 4 | 8 | 16 | 32 | 64 |
| Axial Points | 4 | 6 | 8 | 10 | 12 |
| α | 1.414 | 1.682 | 2 | 2.378 | 2.828 |
| Center Points | 5 | 6 | 7 | 10 | 15 |

# Chapter 5

# Experimental Investigation

## 5.1 About Experimental Investigation

This chapter provides detailed information about the workpiece material and the experimental procedure used in the current study. This chapter begins with a brief description of the experimental planning, followed by a brief description of the Ti-6Al-4V samples used in the experiment. Next, the experimental details consisted of selecting process parameters, finding process parameter limits, and developing a design matrix. The following section details the laboratory and testing facilities and the procedures used for the experimental studies.

## 5.2 Experimental Planning

This investigative work has been done under the following plan of experiments.

- Preparing the Ti-6Al-4V alloy sample. The Ti-6Al-4V sample is prepared into dimensions of 50mm x 50 mm x 2mm. The surface of the sample is cleaned from any foreign particles present, making it ready for Laser Cutting.
- The experimental setup is arranged to perform the laser cutting operation.
- Some trial experimental runs are performed on the sample to figure out the range of process parameters that would be suitable for the cutting process.
- Preparing the design of experiments using central composite design matrix.
- Performing the laser cutting operation on the Ti-6Al-4V sample by varying process parameters: laser power, laser pulse frequency and cutting speed based on the DOE
- Taking down observations of the responses: Surface Roughness and Kerf Deviation.
- Developing empirical models, establishing relationships between factors and responses, and verifying using ANOVA.
- Optimizing the process for optimum value of the responses.

## 5.3 Workpiece Material Selection

This investigative experimental work has been performed on Ti-6Al-4V alloy workpiece. Ti-6Al-4V (UNS designation R56400), sometimes referred to as TC4, Ti64 or ASTM Grade 5, is an alpha-beta titanium alloy with high specific strength and excellent corrosion resistance. It has been selected as the workpiece material in this work as it is one of the most commonly used titanium alloys and is used in a variety of applications: jet engines in Aerospace industry, marine engines, airframe components, and biomechanical applications (implants and prostheses) where low density and good corrosion resistance are required. This alloy is very hard, has excellent strength to weight ratio, very high resistance to fatigue. It has excellent strength, low modulus, high corrosion resistance, good weldability, and can be heat treated. Adding aluminium and vanadium increases the hardness of the material in the alloy matrix and improves its physical and mechanical properties.

The chemical composition of Ti-6Al-4V is nearly 90% titanium, 6% aluminium, 4% vanadium, 0.25% (max) iron and 0.2% (max) oxygen. Although these are general composition value, the workpiece may be subjected to extremely slight variation in its composition; however the properties of the material are anticipated to be nearly same as in general.

**Table 5.1 Workpiece Material Specification**

| | |
|---|---|
| Workpiece Material | :Ti-6Al-4V |
| Sample Appearance | :Lustrous shiny metallic sheet |
| Length | :50mm |
| Width | :50mm |
| Thickness | :2mm |

Ti-6Al-4V titanium alloys usually exist in alpha phase with hcp crystal structure and beta phase with bcc crystal structure. The mechanical properties are a function of the alloy's heat treatment conditions and vary according to properties, but typical property ranges for properly treated Ti-6Al-4V are given below. Aluminium stabilizes the alpha phase and vanadium stabilizes the beta phase.

**Table 5.2 Mechanical properties of Ti-6Al-4V**

| | |
|---|---|
| Brinell Hardness Number | :379 |
| Knoop Hardness Number | :414 |
| Rockwell C Hardness Number | :49 |
| Vickers Hardness Number | :396 |
| Ultimate Tensile Strength | :1170 MPa |
| Yield Tensile Strength | :1100 Mpa |
| Elongation at break | :10% |
| Modulus of Elasticity | :114 |
| Compressive Yield Strength | :1070 MPa |
| Notched Tensile Strength | :1550 MPa |
| Ultimate Bearing Strength | :2140 Mpa |
| Yield Bearing Strength | :1790 Mpa |
| Poisson’s Ratio | :0.33 |
| Charpy Impact | :23 J |
| Minimum Fatigue Strength | :160 MPa |
| Maximum Fatigue Strength | :700 MPa |
| Fracture Toughness | :43 MPa/m |
| Shear Modulus | :44 GPa |
| Shear Strength | :760 MPa |

Although Ti-6Al-4V is a very useful material, however it is very to machine. Some conventional machining processes may be employed, but the results are often disappointing. From past literature surveys, it has been found that machining Ti-6Al-4V is rather difficult due several reasons.

At first, it is very hard, it requires a harder cutting tool to operate, which is expensive in most cases. Secondly it's very brittle and experiences brittle fractures when machined by conventional processes. Since both the tool and the alloy are hard, a lot of cutting force is generated at the tool-workpiece interface. This leads to a lot of tool wear and also a lot of surface roughness on the specimen. Since there's a lot of friction between tool and workpiece, there's a lot of heat generation. This excessive heat produced at the tool-workpiece interface causes thermal damage to both the tool and the workpiece. It has been found that the resultant Heat Affected Zone (HAZ) in conventional machining of Ti-6Al-4V is very high. The cut surface often experience burns on them. Such processes mostly require post processing to get the desired shape and size. Laser cutting on the other hand, is a non-contact process. There is no tool wear. Laser cutting can be performed on brittle materials with ease, as laser cutting does not cause brittle fractures in the specimen often. Laser machining is often attributed with excellent surface finish, low thermal damage, lesser distortions, burrs, and burns and is way more efficient compared to other machining processes. These are reason why laser cutting of Ti-6Al-4V is considered in this present work.

## 5.4 Experimental Details

### 5.4.1 Process Parameters Selection

The current investigative work has been carried out by varying three input parameters: Laser Power, Laser Pulse Frequency and Cutting Speed. The parameters have been chosen keeping the machine limitation, trial experiments and literature survey data in mind.

### 5.4.2 Finding limits of the process parameters

Once the variables/ parameters for the operation are selected, they are required to be limited to a specific range for the process. For doing so, trial experiments are conducted where one of the parameters are varied, keeping the other two factors or parameters constant. The limits of the parameters are decided based on three factors. At first, the machine limitation is considered. Secondly, the experiences of trial experiments are considered and finally data suggestions from literature survey are taken into account. Using Central Composite Design matrix from Response Surface Methodology for three continuous factors, the design matrix for the present work is determined using statistical tool Minitab v18.
The detailed process parameters and their levels are given in the following table.

**Table 5.3 Process parameters with their units, notations and limits**

| **Parameters** | **Units** | **Notations** | **Limits** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **-1.682** | **-1** | **0** | **+1** | **+1.682** |
| Laser Power | Watts | LP | 349.43 | 375 | 412.5 | 450 | 475.57 |
| Laser Frequency | Hertz | PF | 7.39 | 50 | 112.5 | 175 | 217.61 |
| Cutting Speed | mm/s | CS | 1.32 | 2 | 3 | 4 | 4.68 |

### 5.4.3 Design Matrix Preparation

The design matrix for three continuous factors in unblocked design is developed using central composite design matrix with five levels of three independent variables taken into consideration. A total of 20 set of experiments' design matrix is obtained. There are 8 cubic points, 6 cubic center points and 6 axial points. The cubic points are -1 and +1, and axial points are +1.682 and -1.682 respectively. The design matrix is prepared using statistical tool Minitab v18.

**Table 5.4 the design matrix with both coded and Actual values**

| Run Order | Coded Values | | | Actual Values | | |
|---|---|---|---|---|---|---|
| | LP (Watts) | PF (Hz) | CS (mm/s) | LP (Watts) | PF (Hz) | CS (mm/s) |
| 1 | -1 | -1 | -1 | 375 | 50 | 2 |
| 2 | 1 | -1 | -1 | 450 | 50 | 2 |
| 3 | -1 | 1 | -1 | 375 | 175 | 2 |
| 4 | 1 | 1 | -1 | 450 | 175 | 2 |
| 5 | -1 | -1 | 1 | 375 | 50 | 4 |
| 6 | 1 | -1 | 1 | 450 | 50 | 4 |
| 7 | -1 | 1 | 1 | 375 | 175 | 4 |
| 8 | 1 | 1 | 1 | 450 | 175 | 4 |
| 9 | -1.682 | 0 | 0 | 349.43 | 112.5 | 3 |
| 10 | 1.682 | 0 | 0 | 475.57 | 112.5 | 3 |
| 11 | 0 | -1.682 | 0 | 412.5 | 7.39 | 3 |
| 12 | 0 | 1.682 | 0 | 412.5 | 217.61 | 3 |
| 13 | 0 | 0 | -1.682 | 412.5 | 112.5 | 1.32 |
| 14 | 0 | 0 | 1.682 | 412.5 | 112.5 | 4.68 |
| 15 | 0 | 0 | 0 | 412.5 | 112.5 | 3 |
| 16 | 0 | 0 | 0 | 412.5 | 112.5 | 3 |
| 17 | 0 | 0 | 0 | 412.5 | 112.5 | 3 |
| 18 | 0 | 0 | 0 | 412.5 | 112.5 | 3 |
| 19 | 0 | 0 | 0 | 412.5 | 112.5 | 3 |
| 20 | 0 | 0 | 0 | 412.5 | 112.5 | 3 |

From the matrix, axial point $\alpha$=1.682.

## 5.5 Experimental Procedure

Since the design matrix is now prepared, the experimentation are performed based on it. The procedure of the experiments is as follows:

1. The sample is first prepared and made into the required dimension of 50mm x 50mm x 2mm.
2. The surface of the sample is cleaned using acetone.
3. Then the fiber laser metal cutting machine is started.
4. Once the machine is ready for the operation, the workpiece material is placed on the fixture.
5. The fiber laser metal cutting machine works with a FSCUT 2.0 based compatible software: CypCut Laser Cutting Machine Software.
6. The software enables the user to control the parameters, move and align the laser head, draw the specific shape that is eventually the path the laser follows to cut.
7. After the parameters are set with the CypCut software, the frame of run is checked to confirm cutting in the required position.
8. The safety door of the workstation is then closed, the laser is fired, and the operation is started.
9. The assist gas flow starts by default as soon as the operation starts.
10. The machine stops and gives an audio feedback (usually a beep) when the cutting operation is complete.
11. This is repeated for all the parameter combinations as per the design matrix.
12. After all the cutting operations are done, the samples are then tested using a Measuring Microscope and Surface Roughness Tester.

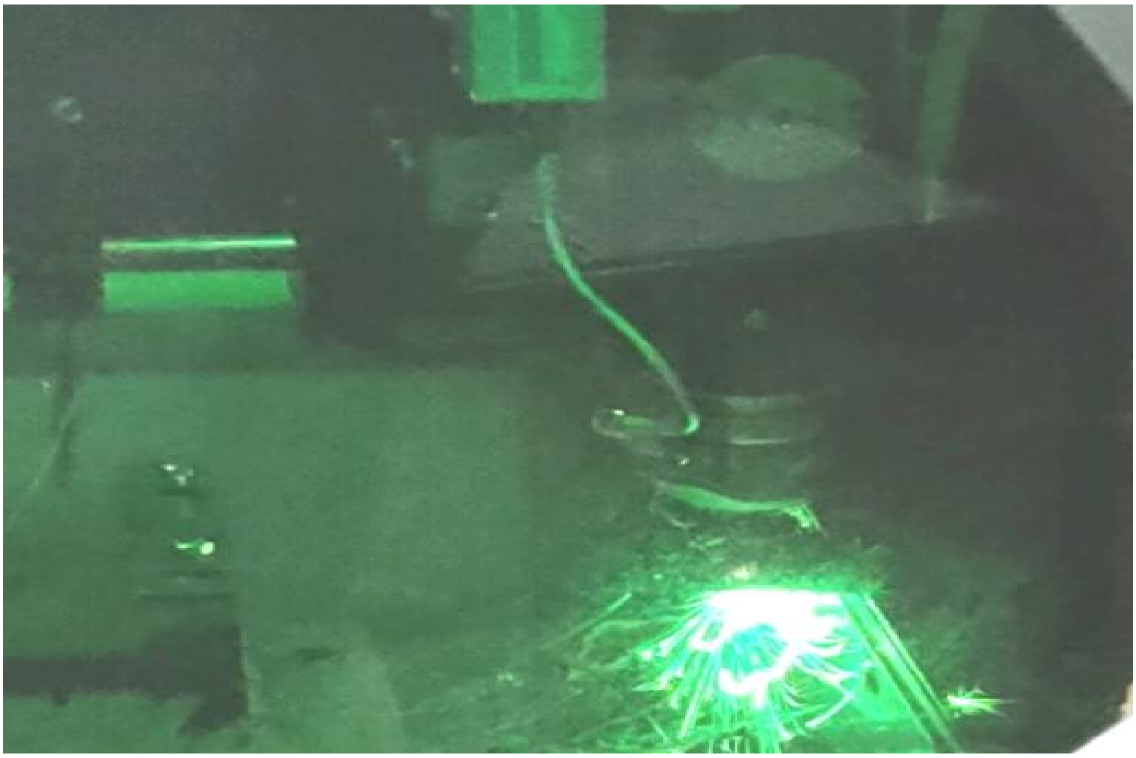


**Fig. 5.1 Photographic view of laser cutting operation in progress**

Fig. 5.1 depicts the laser cutting operation on a specimen. The laser head can be seen aligned to the workpiece material, traversing over the cutting path. The sparks indicate the material removal in the cutting operation.

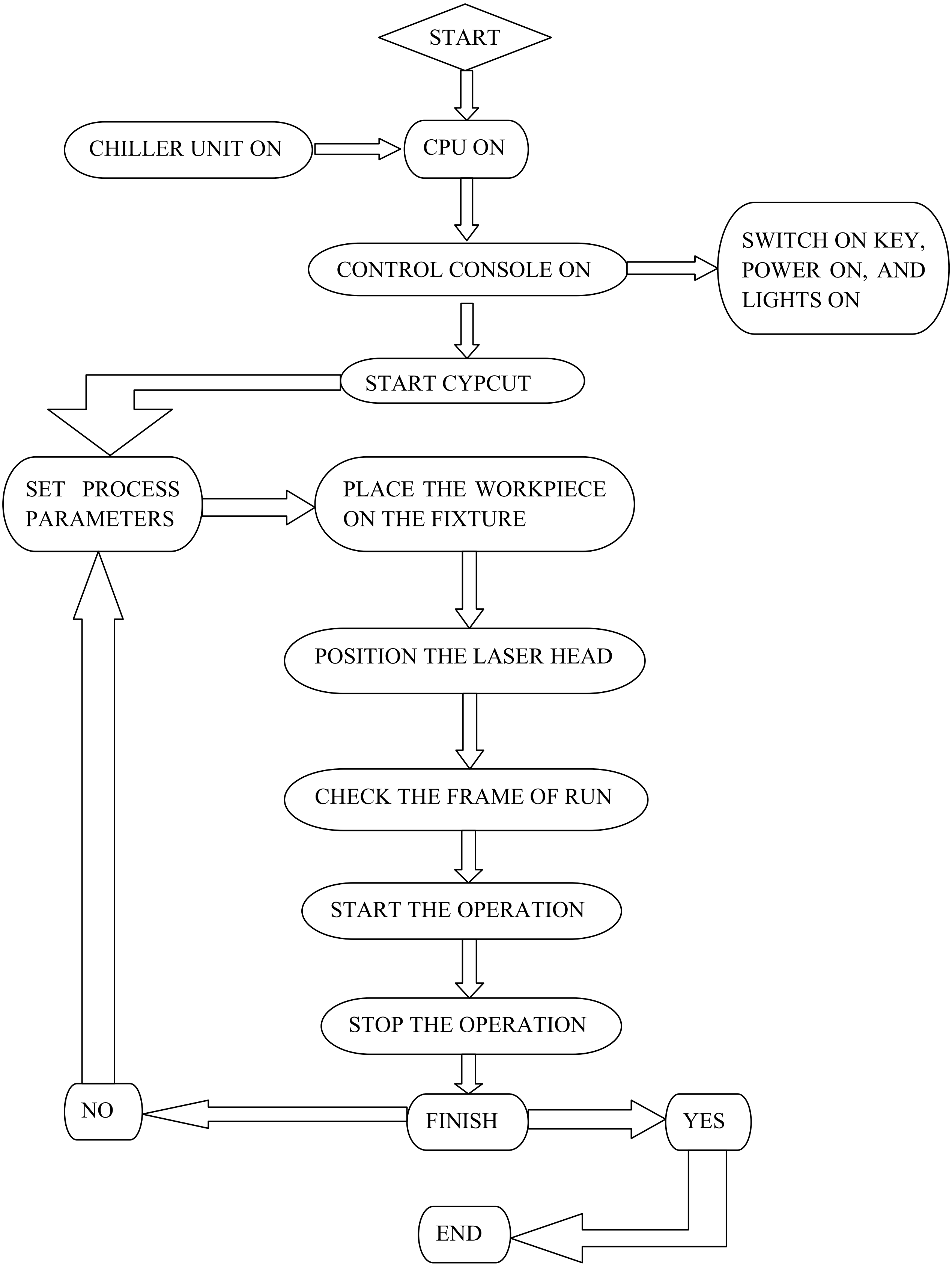



**Fig. 5.2 Flowchart of the laser cutting operation**


**Fig. 5.3 Photographic view of the workpiece cut with laser**

Fig. 5.3 depicts two specimens of Ti-6Al-4V cut with laser. Fig. 5.3 (a) shows a laser cut specimen keeping both the cut pieces against each other. Fig. 5.3 (b) shows a laser cut specimen with only one side of the cut piece shown. This image also depicts the inside of the kerf.

## 5.6 Specimen Testing Equipments

After the machining process is concluded, the specimens are required to be tested for observation data. In this present work, two responses have been taken into account: Surface Roughness (Ra) and Kerf Deviation (KD). The measurements of these responses have been recorded using specific testing equipments.

### 5.6.1 Measuring Microscope

Kerf deviation is one the major factors associated with laser cutting. In this present work, kerf deviation has been measured with an Olympus branded STM 6 model measuring optical microscope. The STM 6 measuring microscope offers high performance three axis measurements of parts, with submicron precision (0.1 μm). Inbuilt LED illuminator is used for rejected coaxial illumination during measurements. This microscope comes with an USB interface for easy connection with a PC. The measured data can be recorded using the PC and the acquired data can be then processed for the analytical part.

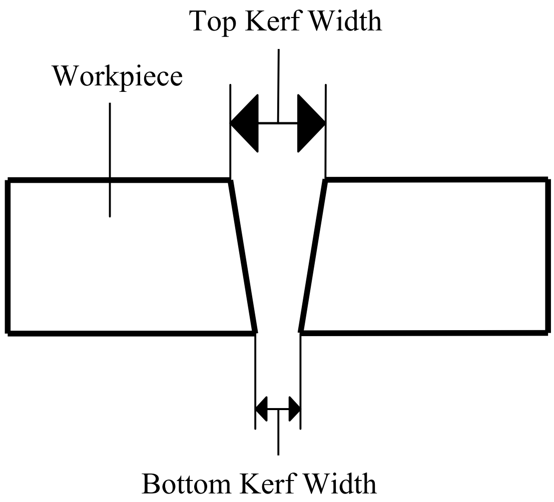
### 5.6.2 Surface Roughness Tester

Any machining process involves damage to the workpiece material. The damages can be of several types. One of the major damages encountered with machining is surface finish.

In this present work, surface roughness has been counted as one of the responses. Hence it is necessary to measure this. A Mitutoyo branded surface roughness tester has been utilized to do the same. The tester comes with a diamond mounted stylus head that helps in determining the surface roughness.

## 5.7 Procedure for testing

### 5.7.1 Kerf Deviation Measurement




**Kerf Deviation = Top Kerf Width – Bottom Kerf Width**

**Fig 5.4 Kerf Deviation**

Fig. 5.4 depicts the schematics of kerf deviation of a specimen cut with laser. Upon laser cutting, the measured kerf widths of the top surface and the bottom surface are not same. There exists some difference between the two resulting in a taper. The difference between the top and bottom kerf widths is referred to as kerf deviation.

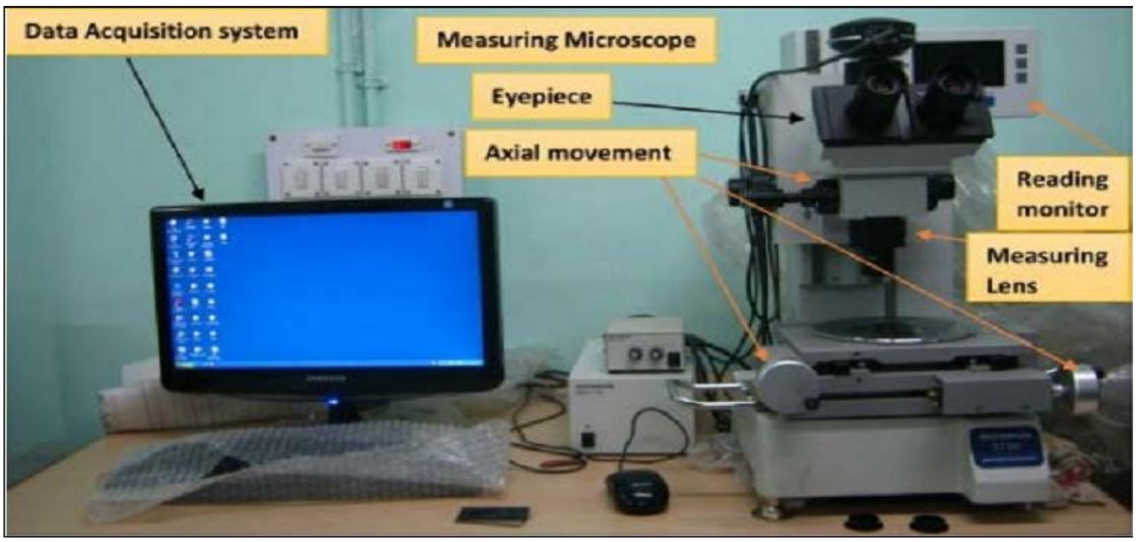
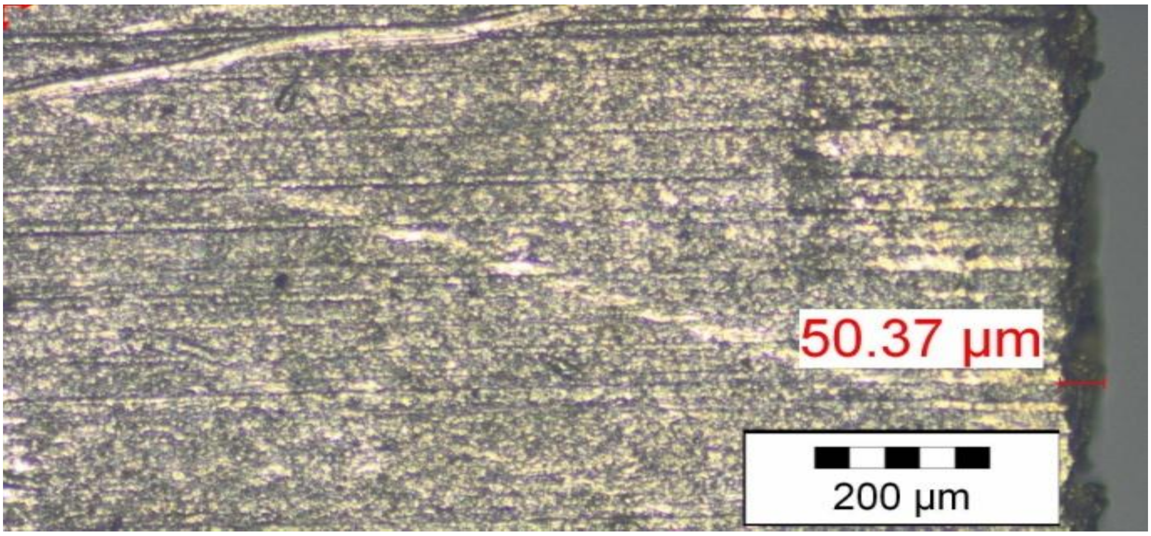



**Fig. 5.5 Photographic view of the Olympus STM 6 measuring microscope with labeled parts**

The Olympus STM 6 optical metallurgical measurement microscope has been used in this present work to measure kerf deviation of the cut edge. The microscope offers high performance three axis measurements of parts, with sub-micron precision. Inbuilt LED illuminator is used for reflected coaxial illumination during measurements. The average of three results of kerf deviation has been calculated. At first the laser cut specimen is placed under the microscope lens. Then the pointer of eyepiece is set at extreme end of the cut edge on the right side. Then only the x-axis of the reading monitor is set to zero. Then the pointer is moved along the negative x-axis i.e to the left with the help of axial movement. The pointer is set to left edge of the cut premises and reading taken from reading monitor. This is the kerf deviation in mm. The pointer is then moved along y-axis along the length of the work piece and another measurement is taken. Similarly a total of 3 different measurements taken and they are averaged to get the average value of kerf deviation. The measured data can be stored in the computer interface.



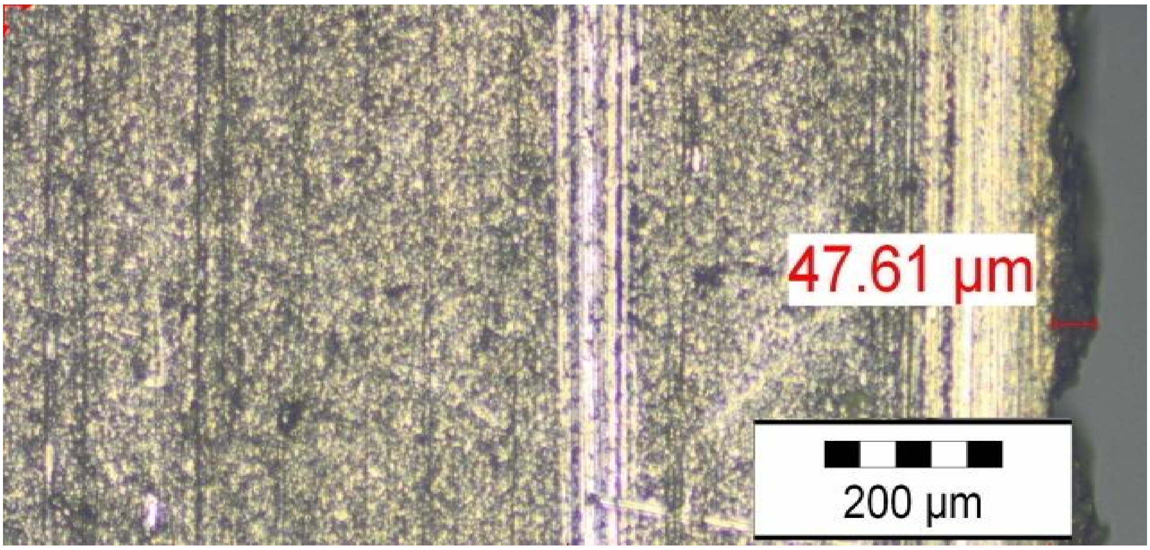




**Fig. 5.6 Microscopic view of two Specimen**

Fig. 5.5 depicts the kerf deviation in two different specimens. The images also show the scale factors as well as the kerf deviation measurements.

## 5.7.2 Surface Roughness Measurement

A Mitutoyo branded surface micrometer has been employed in this present work to determine the surface roughness of the specimen. At first, the specimen is placed on a stationary surface. The micrometer comes with a LCD display which shows a red bar on the top line of display. When the stylus is touched on the surface of the specimen, and the pressure on the stylus is perfect, that is, when the stylus does not experience extremely light or heavy pressure, the red bar turns blue which indicates it is ready for operating. The start button is subsequently pressed and the stylus starts traversing over the specimen kerf surface, while the stylus head mounted with diamond, remains in touch constantly. It is advisable that the micrometer or the specimen do not experience any vibration during operation as it may lead to error in data. Once the stylus is done traversing over the specimen, it comes back to its original position. The display shows the measured Ra, Rq and Rsm values. The value of Ra is only taken into consideration in this study though. The Ra values are recorded thrice for each specimen at different kerf positions and the average Ra value is calculated and taken into account for subsequent analytical work.

Chapter 6

# Results and Discussion

## 6.1 About Results and Discussion

This chapter presents experimental observations or experimental results on the effects of process parameters on cut quality and experimental studies, which also provide a technical database on laser cutting of Ti-6Al-4V alloy. Experimental investigations on laser cutting of Ti-6Al-4V using lasers have been carried out. The purpose of this work is to relate the most important cut quality attributes namely, kerf deviation (KD) and surface roughness (Ra), to the process parameters considered in this study to determine the optimum cutting conditions. Experimental designs are used to achieve better quality cut within existing resources. Empirical models have been developed to establish relationships between process parameters and cut quality characteristics. The developed empirical model is used to find the optimal cutting conditions for the desired optimization criteria with the desired values for the quality characteristics. The effect of each parameter on cut quality characteristics is determined and the optimum cutting conditions are found.

## 6.2 Experimental Responses

Description of the use of Minitab v18 software to select appropriate process parameters, finding their limits, and developing the experimental Design matrix is already done in previous chapters. Cutting is performed to the appropriate combination of input process parameters designed by RSM's Central Composite Design. The experiments were performed and measurements were observed. The average of the 3 kerf deviation and surface roughness results were calculated and are as follows:

**Table 6.1 Design Matrix and the experimental responses**

| Run Order | LP (Watts) | PF (Hz) | CS (mm/s) | Ra(µm) | KD(µm) |
|---|---|---|---|---|---|
| 1 | 375 | 50 | 2 | 7.634 | 49.56 |
| 2 | 450 | 50 | 2 | 6.508 | 57.17 |
| 3 | 375 | 175 | 2 | 6.396 | 49.27 |
| 4 | 450 | 175 | 2 | 6.856 | 53.31 |
| 5 | 375 | 50 | 4 | 5.313 | 45.03 |
| 6 | 450 | 50 | 4 | 4.278 | 47.43 |
| 7 | 375 | 175 | 4 | 4.231 | 47.96 |
| 8 | 450 | 175 | 4 | 4.793 | 49.73 |
| 9 | 349.43 | 112.5 | 3 | 5.342 | 55.83 |
| 10 | 475.57 | 112.5 | 3 | 4.857 | 59.75 |

| | | | | | |
|---|---|---|---|---|---|
| 11 | 412.5 | 7.39 | 3 | 6.439 | 45.54 |
| 12 | 412.5 | 217.61 | 3 | 5.843 | 46.61 |
| 13 | 412.5 | 112.5 | 1.32 | 7.804 | 50.41 |
| 14 | 412.5 | 112.5 | 4.68 | 4.184 | 43.85 |
| 15 | 412.5 | 112.5 | 3 | 5.817 | 50.27 |
| 16 | 412.5 | 112.5 | 3 | 5.865 | 50.75 |
| 17 | 412.5 | 112.5 | 3 | 5.859 | 50.37 |
| 18 | 412.5 | 112.5 | 3 | 5.857 | 48.78 |
| 19 | 412.5 | 112.5 | 3 | 5.867 | 48.61 |
| 20 | 412.5 | 112.5 | 3 | 5.817 | 50.54 |

## 6.3 Empirical Modeling

Planned experiments and subsequent analyzes are performed to develop mathematical models to study the effects of process parameters on the recorded responses. The validity of the developed model is tested using sequential F-test, lack of fit test, and analysis of variance (ANOVA) techniques. Analysis of the measured response variables and determination of the best-fit mathematical model were done using Minitab v18 software. Based on the developed mathematical model, the effect of each cutting parameter on cutting responses is studied.

### 6.3.1 Analysis of Surface Roughness

The final mathematical model for surface roughness (Ra) determined by Minitab software in terms of actual factors:

**$Ra$ =-10.919 + 0.12865 LP - 0.08098 PF - 1.7543 CS - 0.000186 LP x LP + 0.000027 PF x PF + 0.05461 CS x CS + 0.000170 LP x PF + 0.000643 LP x CS + 0.000646 PF x CS..(6.1)**

**Table 6.2 Analysis of Variance (ANOVA) for surface roughness (Ra)**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 9 | 19.5028 | 2.1670 | 4464.21 | 0.000 |
| Linear | 3 | 16.9072 | 5.6357 | 11610.26 | 0.000 |
| LP | 1 | 0.2798 | 0.2798 | 576.35 | 0.000 |
| FS | 1 | 0.4429 | 0.4429 | 912.39 | 0.000 |
| CS | 1 | 16.1846 | 16.1846 | 33342.03 | 0.000 |
| Square | 3 | 1.3114 | 0.4371 | 900.56 | 0.000 |
| LP*LP | 1 | 0.9866 | 0.9866 | 2032.45 | 0.000 |
| PF*PF | 1 | 0.1637 | 0.1637 | 337.25 | 0.000 |
| CS*CS | 1 | 0.0430 | 0.0430 | 88.53 | 0.000 |

| | | | | | |
|---|---|---|---|---|---|
| 2-Way Interaction | 3 | 1.2841 | 0.4280 | 881.82 | 0.000 |
| LP*PF | 1 | 1.2664 | 1.2664 | 2609.00 | 0.000 |
| LP*CS | 1 | 0.0047 | 0.0047 | 9.59 | 0.011 |
| PF*CS | 1 | 0.0130 | 0.0130 | 26.87 | 0.000 |
| Error | 10 | 0.0049 | 0.0005 | | |
| Lack-of-Fit | 5 | 0.0021 | 0.0004 | 0.75 | 0.618 |
| Pure Error | 5 | 0.0028 | 0.0006 | | |
| Total | 19 | 19.5076 | | | |

**Table 6.3 Model summary for Surface Roughness (Ra)**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.0220320 | 99.98% | 99.95% | 99.90% |

For surface roughness, the fit summary recommends a quadratic model. In this model, all the process parameters are significant and the model is not aliased. Table 6.2 shows the ANOVA table for the model. The Analysis of Variance (ANOVA) has been performed with 95% level of confidence, which means a maximum of 5% of error is allowed. The results of ANOVA show that laser power (LP), laser frequency (PF), and cutting speed (CS) along with their interactions of power and frequency, power and speed, and speed and frequency are inevitable terms related with surface roughness. From the ANOVA table, it is evident that cutting speed is the most dominant process parameter, followed by pulse frequency and laser power for surface roughness. This is confirmed by their F-Values. Other Validity Measures $R^2$, adjusted $R^2$ and predicted $R^2$ are in reasonable agreement and close to 1 indicating a good model. An adequate precision ratio value indicates the adequacy of the model. A lack of fit F-value of 0.75 means that the lack of fit is not significant compared to the pure error.

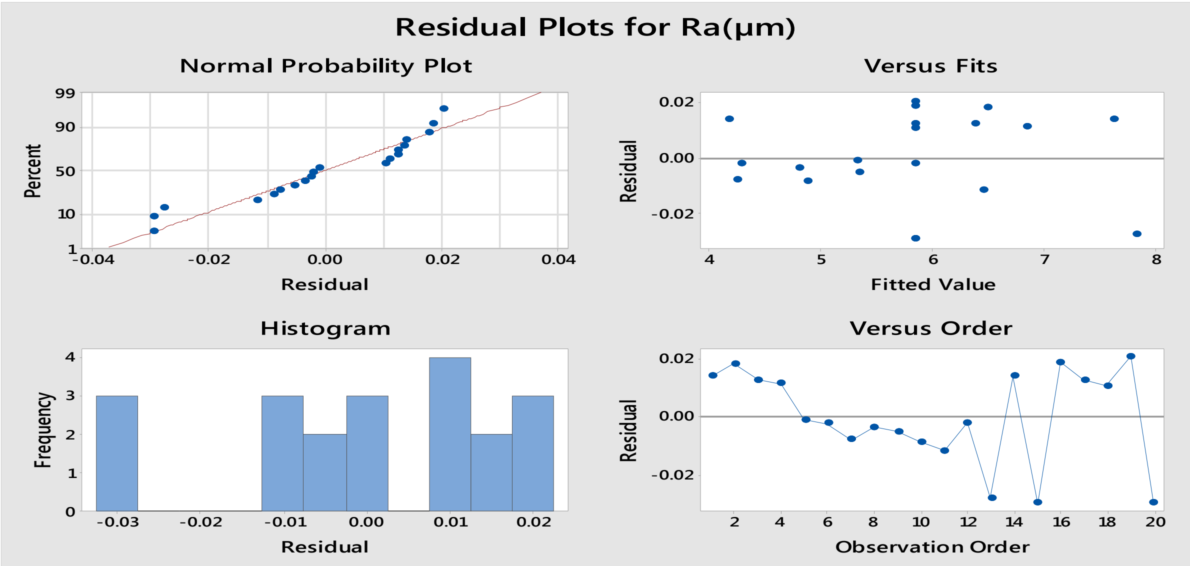



**Fig. 6.1 – Residual plot for Surface Roughness (Ra)**

Fig. 6.1 depicts the residual plots based on the ANOVA for the model developed using Minitab v18. From the normal probability and histogram plots, it is evident that the recorded responses are consistent. The plot is found to be very slightly skewed, indicating that the data holds validity as the points are very close to the normal. The versus fit and versus order plots are also a bit skewed, but the fit is still on order and close to normal, suggesting the adequacy of the model developed.

### 6.3.2 Analysis of Kerf Deviation

The final mathematical model for kerf deviation (KD) determined by Minitab software in terms of actual factors:

$$\boldsymbol{KD} = 316.2 - 1.443\ LP + 0.1223\ PF + 12.35\ CS + 0.001923\ LP \times LP - 0.000368\ PF \times PF - 1.065\ CS \times CS - 0.000224\ LP \times PF - 0.02493\ LP \times CS + 0.01876\ PF \times CS \quad \ldots\ldots\ldots\ (6.2)$$

**Table 6.4 Analysis of Variance (ANOVA) for kerf deviation (KD)**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 9 | 292.493 | 32.499 | 36.03 | 0.000 |
| Linear | 3 | 104.139 | 34.713 | 38.49 | 0.000 |
| LP | 1 | 36.782 | 36.782 | 40.78 | 0.000 |
| PF | 1 | 0.607 | 0.607 | 0.67 | 0.431 |
| CS | 1 | 66.750 | 66.750 | 74.01 | 0.000 |
| Square | 3 | 168.157 | 56.052 | 62.15 | 0.000 |
| LP*LP | 1 | 105.395 | 105.395 | 116.85 | 0.000 |
| PF*PF | 1 | 29.782 | 29.782 | 33.02 | 0.000 |
| CS*CS | 1 | 16.332 | 16.332 | 18.11 | 0.002 |
| 2-Way Interaction | 3 | 20.197 | 6.732 | 7.46 | 0.007 |
| LP*PF | 1 | 2.205 | 2.205 | 2.44 | 0.149 |
| LP*CS | 1 | 6.994 | 6.994 | 7.75 | 0.019 |
| PF*CS | 1 | 10.998 | 10.998 | 12.19 | 0.006 |
| Error | 10 | 9.020 | 0.902 | | |
| Lack-of-Fit | 5 | 4.612 | 0.922 | 1.05 | 0.481 |
| Pure Error | 5 | 4.407 | 0.881 | | |
| Total | 19 | 301.512 | | | |

**Table 6.5 Model summary for Kerf Deviation (KD)**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.949711 | 97.01% | 94.32% | 85.72% |

The kerf deviation fit summary proposes a quadratic model in which all the parameters are not significant; however the model is not aliased. The ANOVA table for the model is shown in Table 6.4. Analysis of Variance (ANOVA) suggests that for the developed model for Kerf Deviation, cutting speed is the most dominant factor, followed by laser power. Pulse frequency is found to be very less significant compared to the other two parameters. A p-value of more than 0.05 associated with the pulse frequency indicates the same. Main effect of laser power (LP), cutting speed (CS), and their interaction effects are statistically significant as depicted in Table 6.4. Other adequacy measures: mean $R^2$, adjusted $R^2$ and predicted $R^2$ are in reasonable agreement, with close to 1, indicating the validity of the model. The lack of fit F-value of 1.05 means that the lack of fit is not significant compared to the pure error. So it is acceptable.

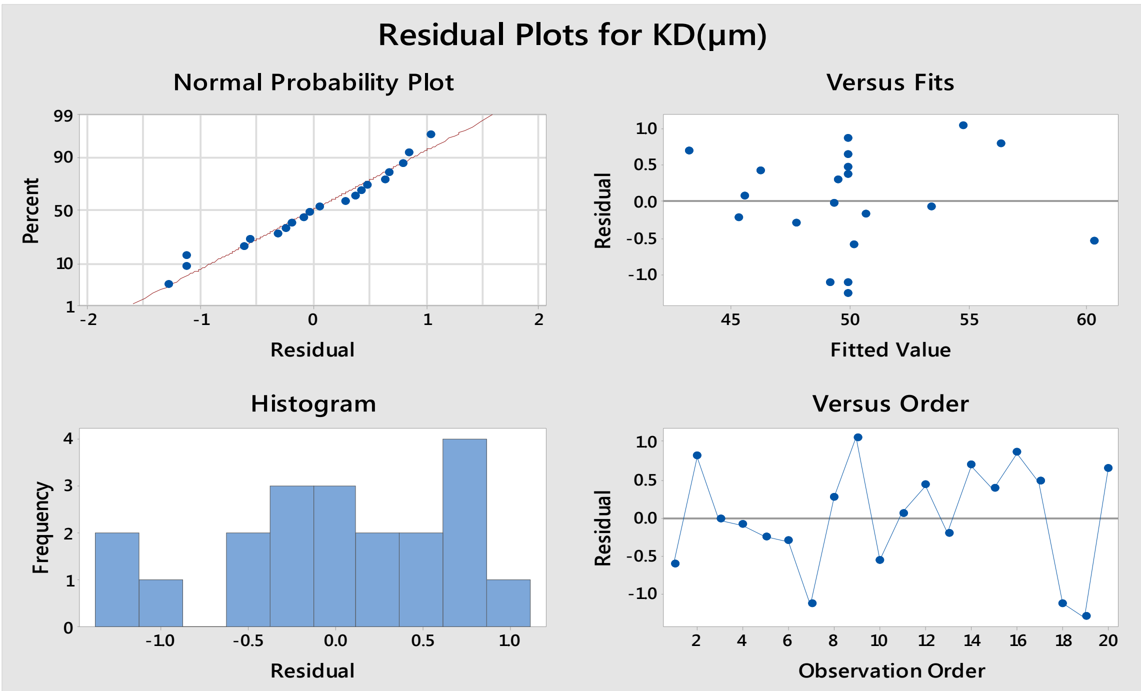



**Fig. 6.2 Residual Plot for Kerf Deviation (KD)**

The residual plots for kerf deviation in fig. 6.2 depicts that the model is consistent. The normal probability and histogram plots show that the model is very consistent and there is hardly any skew, suggesting that the model is valid. The versus-fit and versus-order plots depict fit to be reasonably in order, suggesting consistency in fitted values. So the model holds adequacy.

## 6.4 Effects of process parameters on the responses

The effects of process parameters on the kerf deviation and surface roughness of laser cut sample are investigated and discussed here for the specified material within the limits of the parameters considered in this study. Surface plots and contour plots are used to display the results in graphical formats. All significant interaction terms associated with the kerf deviation and surface roughness are graphically displayed and factorial effect trends are detailed.

### 6.4.1 Effects of process parameters on Kerf Deviation (KD)

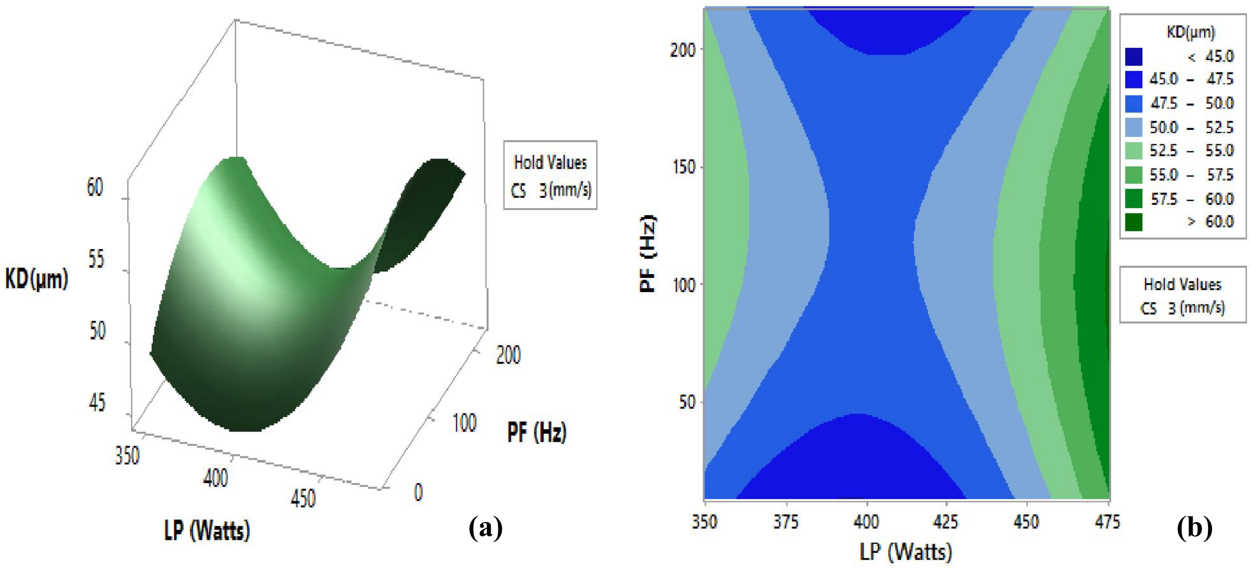



**Fig. 6.3 (a) Surface and (b) Contour plots showing the interaction effect of laser power (LP) and pulse frequency (PF) on kerf deviation (KD) at cutting speed (CS) of 3 mm/s**

From the plots, it is evident that laser power significantly affects the kerf deviation. As laser power increases, the kerf deviation decreases at first and then increases after medium laser power level, maintaining a linear relationship from thereon. This happens because at lower laser power, the material may not receive enough heat to break or cut, resulting in uneven cut surface. And also when the laser power is high, it overheats and causes thermal damage, resulting in higher Kerf Deviation. The plot suggests that pulse frequency has less impact on kerf deviation compared to laser power. Kerf deviation is found to be minimum at lower or higher pulse frequency. The pulse frequency increase leads to the increment of the number of pulses (overlapping rate). When there is continuous increment in over lapping rate an unevenness will appear at the top kerf width throughout the length of arc due to the fact that there will be more rapid interaction between the material and the laser beam for very less time. Proper time is required for interaction with laser for absorption of the laser light to process the material.

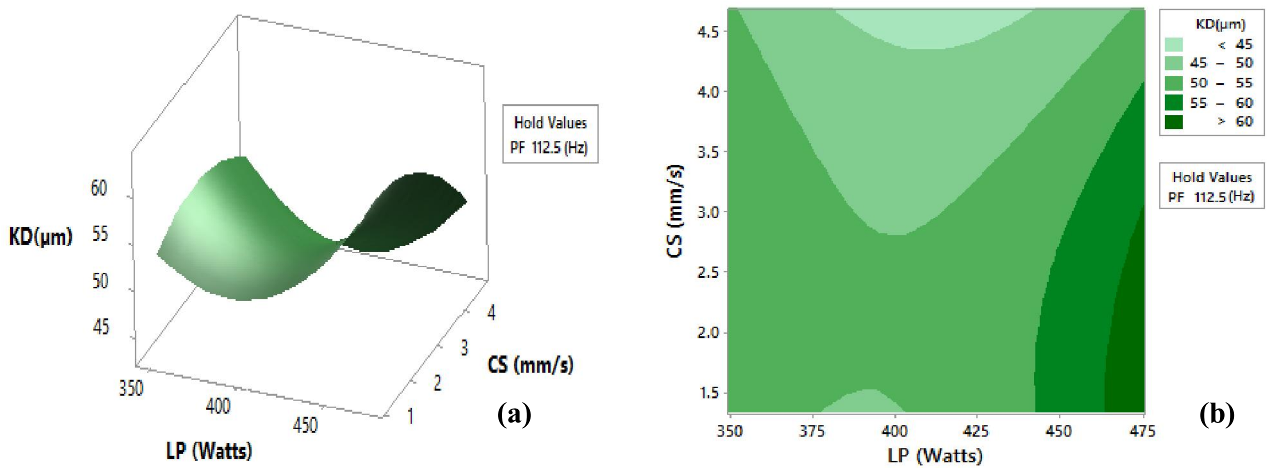



**Fig. 6.4 (a) Surface and (b) Contour plots showing the interaction effect of laser power (LP) and cutting speed (CS) on kerf deviation (KD) at pulse frequency (PF) of 112.5 Hz**

Fig. 6.4 suggests that with increase in cutting speed, kerf deviation significantly reduces. They share an inversely proportionate relationship. This is mainly because of the fact that, as cutting speed increases, the laser interaction time with the material decreases. The lower the interaction time, the lesser is the heat dissipated, and subsequently decreases the thermal damage, leading to lower kerf deviation. It is also evident that as laser power increases, the kerf deviation decreases at first and then increases after medium laser power level, maintaining a linear relationship from thereon. This happens because at lower laser power, the material may not receive enough heat to break or cut, resulting in uneven cut surface. And also when the laser power is high, it overheats and causes thermal damage, resulting in higher kerf deviation. One can conclude that with higher cutting speed and medium laser power, kerf deviation can be kept significantly low. This is because of lower interaction time and sufficient laser power enabling efficient cutting of the material.

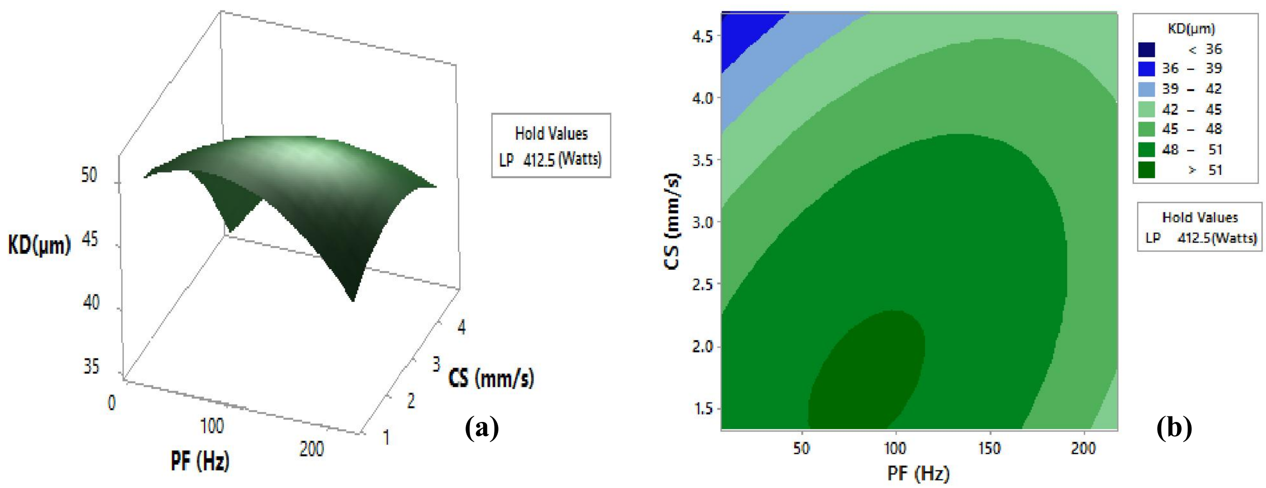



**Fig. 6.5 (a) Surface and (b) Contour plots showing the interaction effect of pulse frequency (PF) and cutting speed (CS) on kerf deviation (KD) at laser power (LP) of 412.5 Watts**

It can be seen from fig. 6.5 that higher cutting speed leads to lower kerf deviation. This can be attributed to the fact that as cutting speed increases, the laser interaction time with the material decreases. The lower the interaction time, the lesser is the heat dissipated, and subsequently decreases the thermal damage, leading to lower kerf deviation. Kerf deviation is found to be minimum at lower or higher pulse frequency. The pulse frequency increase leads to the increment of the number of pulses (overlapping rate). When there is continuous increment in over lapping rate an unevenness will appear at the top kerf width throughout the length of arc due to the fact that there will be more rapid interaction between the material and the laser beam for very less time. Proper time is required for interaction with laser for absorption of the laser light to process the material.

### 6.4.2 Effects of process parameters on Surface Roughness (Ra)

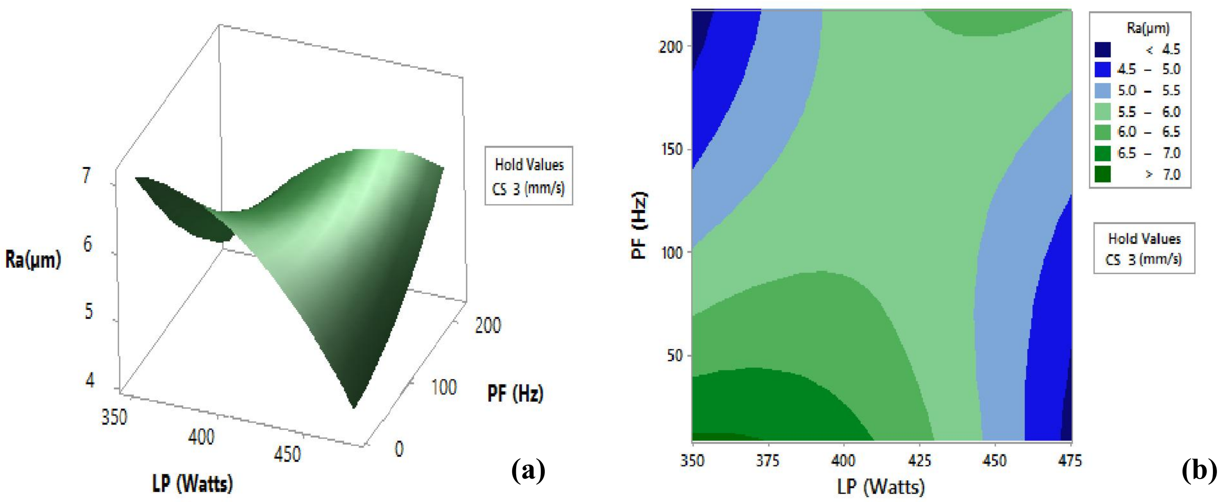



**Fig. 6.6 (a) Surface and (b) Contour plots showing the interaction effect of pulse frequency (PF) and laser power (LP) on surface roughness (Ra) at cutting speed (CS) of 3 mm/s**

Fig. 6.6 depicts that both frequency and laser power have significant effect on surface roughness. It is evident from fig. 6.6 that with increase in laser power, surface roughness significantly reduces. This can attributed to the fact that as laser power increases, the heat energy received by the material also increases. At higher laser power, the material surface receives enough heat to perform efficient cutting, resulting in finer edge with low surface roughness. Surface roughness is found to be lower at lower and higher pulse frequency. The pulse frequency increase leads to the increment of the number of pulses (overlapping rate). When there is continuous increment in over lapping rate an unevenness will appear at the kerf surface throughout the length of arc due to the fact that there will be more rapid interaction time between the material and the laser beam. Proper time is required for interaction with laser for absorption of the laser light to process the material. Hence, at medium frequency, the interaction time is insufficient, causing uneven cutting and leading to higher surface roughness.

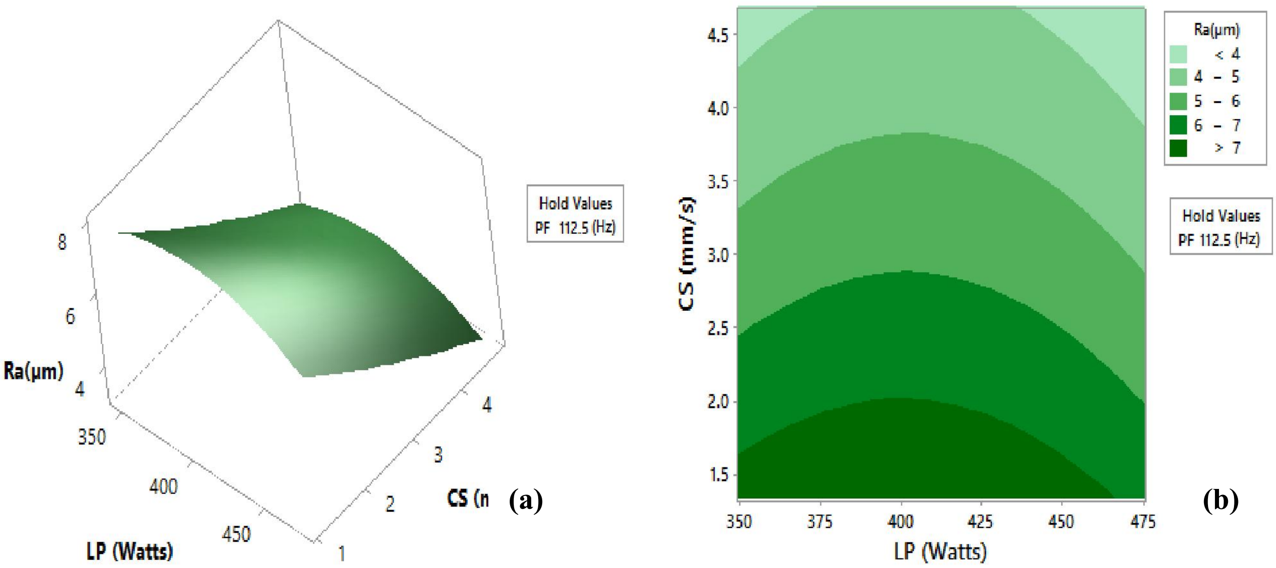



**Fig. 6.7 (a) Surface and (b) Contour plots showing the interaction effect of laser power (LP) and cutting speed (CS) on surface roughness (Ra) at pulse frequency (PF) of 112.5 Hz**

Fig. 6.7 indicates that increase in the cutting speed decreases the surface roughness; therefore they are inversely proportional to each other. This is mainly due to lesser laser interaction time with the material surface at higher cutting speed. Lower interaction time leads to lower heat dissipation causing lesser surface roughness. It is also evident that as laser power increases, the surface roughness increases at first and then decreases after medium laser power level, maintaining a linear relationship from thereon. This happens because at lower laser power, the material receives enough heat to break or cut, resulting in even cut surface. And also when the laser power is high, it overheats and melts the kerf surface resulting in finer edge, causing lower surface roughness.

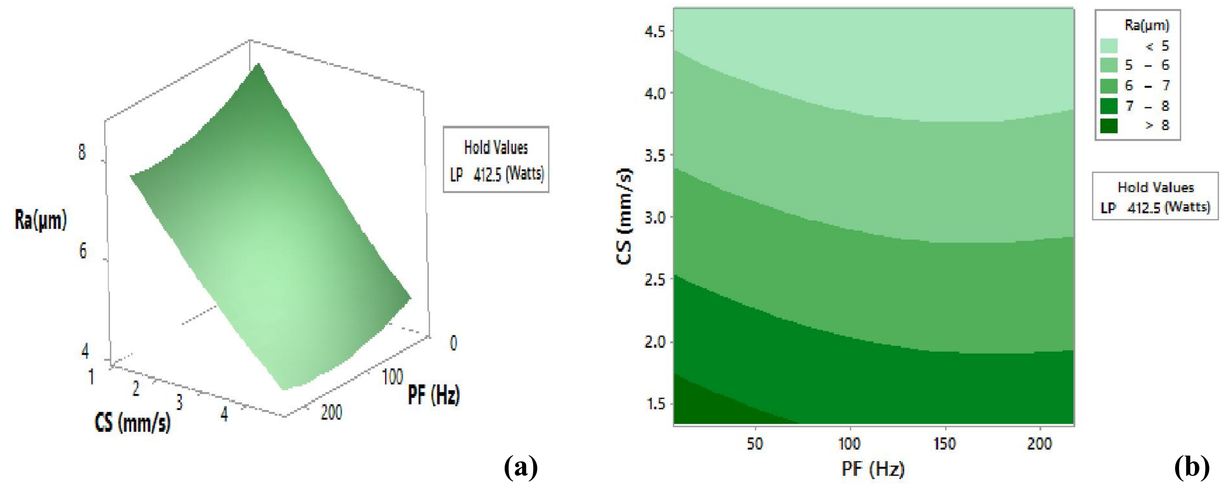



**Fig. 6.8 (a) Surface and (b) Contour plots showing the interaction effect of pulse frequency (PF) and cutting speed (CS) on surface roughness (Ra) at laser power (LP) of 412.5 Watts**

From the fig. 6.8, both cutting speed and pulse frequency have been found to be inversely proportional to surface roughness. This can be attributed to the fact that higher cutting speed and higher frequency results in lower laser interaction time, leading to lower line energy, causing lower thermal damage subsequently resulting in better surface finish. Surface roughness is found to be lower at higher pulse frequency. The pulse frequency increase leads to the increment of the number of pulses (overlapping rate). When there is continuous increment in over lapping rate, there happens to be more rapid interaction time between the material and the laser beam. Hence, at lower frequency, the interaction time is higher, causing higher heat dissipation to the workpiece material, causing uneven cutting and leading to higher surface roughness.

## 6.5 Optimization of the process parameters using Desirability Function Analysis (DFA)

With the responses and process parameters related, it is important the optimum machining conditions are established simultaneously. This work also includes optimization of the process parameters. In this work, both single objective optimization with kerf deviation and surface roughness have been carried out keeping the other factor non-optimized, and a multi objective optimization has also been performed optimizing both the responses using Desirability Function Analysis based optimization using Minitab v18. Desirable Function Analysis (DFA) is one of the most widely used optimization techniques in Multi-response characteristics. Desirability is the objective function ranging from zero outside the range to 1 on the target. DFA optimization finds the point that minimizes the desirability function in this work. One can change the properties of goals by simply adjusting their weights and importance. If there are multiple responses and factors, all goals are combined into a single desirability function.

### 6.5.1 Single Objective Optimization of Kerf Deviation

At first, a single objective optimization has been performed for minimum kerf deviation using Minitab v18. The process parameters and other responses are left with no constraints. This returns the ideal condition for laser cutting the specimen with lowest possible kerf deviation while other factors are considered insignificant. This optimization result is returned using Eq. 6.2, that is, the regression equation for Kerf Deviation (KD). The criterions for single objective optimization of Kerf Deviation:

**Table 6.6 Criteria for single objective optimization of Kerf Deviation**

| Response | Goal | Lower | Target | Upper | Weight | Importance |
|---|---|---|---|---|---|---|
| KD(µm) | Minimum | | 43.85 | 59.75 | 1 | 1 |

In this optimization, the target or the presumed optimal is expected to be 43.85µm, while every other parameter and response are left unconstrained. The solution for optimizing kerf deviation for the above criteria as returned by Minitab v18 using DFA optimization:

**Table 6.7 Solution for single objective optimization of Kerf Deviation**

| Solution | LP (Watts) | PF (Hz) | CS (mm/s) | KD(µm) Fit | Composite Desirability |
|---|---|---|---|---|---|
| 1 | 405.493 | 7.38795 | 4.68179 | 35.3509 | 1 |

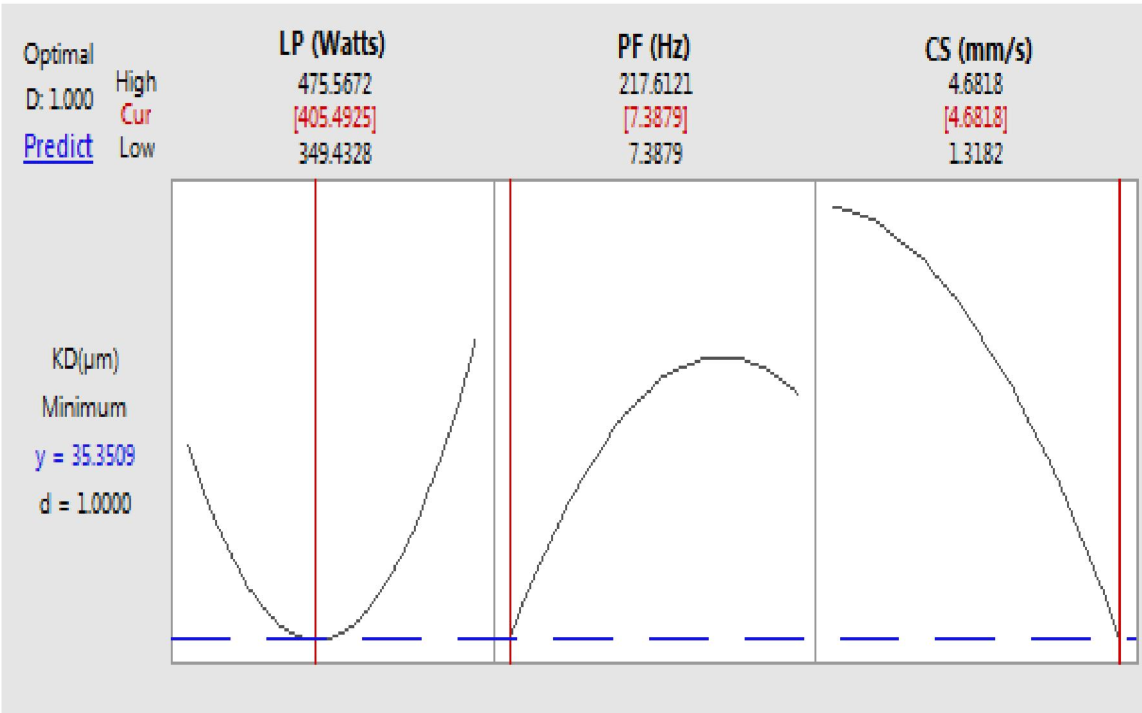



**Fig. 6.9 Single Objective Optimization results for Kerf Deviation**

Minitab v18 performed the DFA optimization and returned the results as shown in table 6.7 and fig. 6.9. It is observed that the fitted or optimal Kerf Deviation returned after optimization is 35.3509µm, which is significantly lesser than the target value. This condition is achieved for power of 405.493W, frequency of 7.38795Hz and cutting speed of 4.68179mm/s.

## 6.5.2 Single Objective Optimization of Surface Roughness

A single objective optimization was performed in this study to optimize another response: surface roughness using Minitab v18. In this case, the goal is to only optimize or minimise surface roughness of the specimen while the process parameters and other response are left unconstrained. The solution is returned using the Eq. 6.1 which is the regression equation for surface roughness (Ra). The criterions for single objective optimization of surface roughness:

**Table 6.8 Criteria for single objective optimization of surface roughness (Ra)**

| Response | Goal | Lower | Target | Upper | Weight | Importance |
|---|---|---|---|---|---|---|
| Ra(µm) | Minimum | | 4.184 | 7.804 | 1 | 1 |

The target or presumed optimal for surface roughness is expected to be 4.184µm for this optimization process. The solution for optimizing surface roughness at the given criteria as given by Minitab v18 based on DFA optimization is:

**Table 6.9 Solution for single objective optimization of surface roughness (Ra)**

| Solution | LP (Watts) | PF (Hz) | CS (mm/s) | Ra(µm) Fit | Composite Desirability |
|---|---|---|---|---|---|
| 1 | 349.433 | 217.612 | 4.68179 | 2.59008 | 1 |

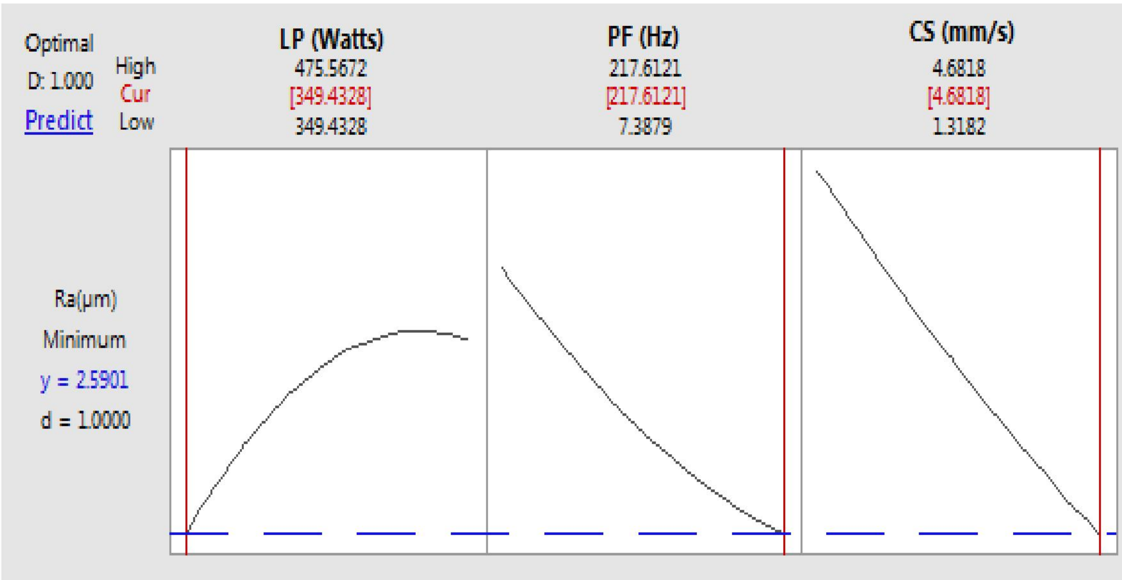



**Fig. 6.10 Optimization result for surface roughness**

Minitab v18 returned the DFA optimization solution in table 6.9 and fig 6.10. It is found that the fitted or optimal value of Ra achieved is 2.59008, which is significantly lower than the target value. This condition is achieved when power is 349.433W, frequency is 217.612Hz and cutting speed is 4.68179mm/s.

### 6.5.3 Multi Objective Optimization

Single objective optimization for both the responses has been successfully done. So a multi objective optimization is being performed to achieve the minimum or optimal of both the responses, while the process parameters are unconstrained. Both Eq. 6.1 and 6.2 are required to frame the solution for this optimization process. Minitab v18 has been used to return the optimization results using DFA. The criterions for this multi objective optimization are:

**Table 6.10 Criteria for multi objective optimization**

| Response | Goal | Lower | Target | Upper | Weight | Importance |
|---|---|---|---|---|---|---|
| KD(µm) | Minimum | | 43.850 | 59.750 | 1 | 1 |
| Ra(µm) | Minimum | | 4.184 | 7.804 | 1 | 1 |

The goal is to reach the minimum possible targets of both the responses. The targets are 43.85µm and 4.184µm for KD and Ra respectively. Their weights and importance are kept at 1, that is, both the responses are equally important in this optimization. Minitab v18 returns the solution for this multi objective optimization using DFA:

**Table 6.11 Solution for multi objective optimization**

| Solution | LP (Watts) | PF (Hz) | CS (mm/s) | KD(µm) Fit | Ra(µm) Fit | Composite Desirability |
|---|---|---|---|---|---|---|
| 1 | 394.026 | 217.612 | 4.68179 | 43.8337 | 3.94038 | 1 |

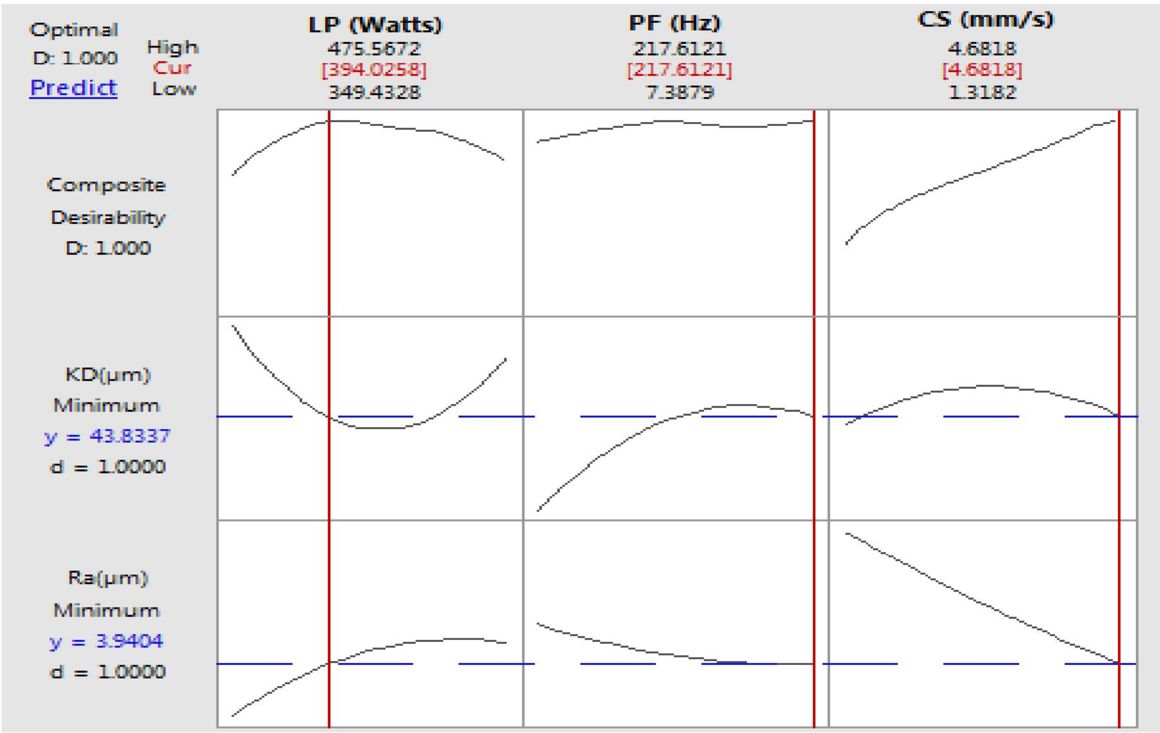



**Fig. 6.11 Multi objective optimization result**

Minitab v18 returns the solution and result for multi objective optimization by using DFA optimization in table 6.11 and fig 6.11. The returned optimal value of KD is 43.8337 µm, and Ra is 3.9404 µm; both the obtained optimal values are lesser than the target values. This means that the responses have been successfully optimized. The optimum condition is achieved with laser power of 394.0258 W, frequency of 217.6121 Hz and cutting speed of 4.6818 mm/s.

## Chapter 7

# Conclusions and Future Scope of Work

## 7.1 Conclusions

In the present study, laser cutting of 2 mm thick TI-6AL-4V super alloy is carried out using Quasi continuous wave (QCW) fiber laser at different cutting conditions to understand the effect of process parameters on cut quality characteristics i.e. kerf deviation and surface roughness. Response surface methodology of statistical DOE with ANOVA is carried out to identify the most significant process parameters and their percentage contribution on output responses. A regression equation is modeled to plot their individual and combined effect. Finally, the optimization of the process parameters is carried out to minimize the kerf deviation and surface roughness for improving the cut quality. The following points can be drawn from research work:

1. Laser cutting of 2 mm thick TI-6AL-4V super alloy using 500 watt QCW fiber laser has been carried out successfully with superior cut quality and excellent surface finish.
2. A mathematical model has been developed using central composite design response surface method based on experimental study and also investigation has been conducted to evaluate the effect of laser cutting parameters on cut quality characteristics of Ti-6Al-4V super alloy.
3. ANOVA for kerf deviation suggested that cutting speed is the most dominant factor, followed by laser power. Pulse frequency is found to be less significant compared to the other two factors.
4. ANOVA for surface roughness suggested that cutting speed is the most dominant factor, followed by pulse frequency and then laser power and all the parameters are significant.
5. Cutting speed shows the inversely relationship with both surface roughness and kerf deviation.
6. Lower kerf deviation is achieved with medium laser power. However, higher laser power is found to be more suitable for obtaining lower surface roughness.
7. Pulse frequency is also found to be inversely proportional to both surface roughness and kerf deviation.
8. The optimal kerf deviation of 35.35 µm is achieved at laser power of 405.49 W, pulse frequency of 7.38 Hz and cutting speed of 4.68 mm/s using single objective DFA technique.
9. The optimal surface roughness of 2.59µm is achieved at laser power of 349.43 W, pulse frequency of 217.61 Hz and cutting speed of 4.681 mm/s using single objective DFA technique.

10. The optimal value of kerf deviation of 43.83 μm and surface roughness of 3.94 μm have been achieved at laser power of 394 W, pulse frequency of 217.61 Hz and cutting speed of 4.68 mm/s using multi-objective DFA technique.

## 7.2 Future Scope of Work

The present investigative study performed reveals a lot about the laser cutting of Ti-6Al-4V alloy. With three independent variable process parameters with five levels, the study could successfully correlate process parameters with responses: surface roughness and kerf deviation. Single and multi objective optimization were also successfully done. However, some more process parameters and responses could be a part of the study. So the future scope of this work would be to discover several more possibilities in terms of different parameters, responses and even their ranges.

Several parameters like assist gas type assist gas pressure, water microjet assist as well as higher and lower ranges of the present parameters and possible parameter levels can be exploited.

Some responses like material removal rate, heat affected zone, heat dissipation, thermal damage, material deformation and damage, can be recorded for better understanding the laser cutting of Ti-6Al-4V alloy.

As most of the machines in use are CNC machines, taking the main controlling process parameters considered in the research, an Adoptive control system by optimization may be designed as it will help the CNC controller to use optimized parameters and controlled machine tool operation for higher production.

# References

1. Convissar, R. A. (2015). *Principles and Practice of Laser Dentistry-E-Book*. Elsevier Health Sciences.
2. PHOTONICS, O. William T. Silfvast School of Optics/CREOL University of Central Florida Orlando, Florida.
3. Flinn, R. A., & Trojan, P. K. (1994). *Engineering materials and their applications* (p. 1056).
4. Davim, J. P. (Ed.). (2008). Machining: fundamentals and recent advances.
5. Jain, V. K. (2009). *Advanced machining processes*. Allied publishers.
6. Pavesi, L. (2006). Silicon light emitters and amplifiers: state of the art. *Silicon Photonics*, *6125*, 65-77.
7. Dahotre, N. B., & Harimkar, S. (2008). *Laser fabrication and machining of materials*. Springer Science & Business Media.
8. Chryssolouris, G. (2013). *Laser machining: theory and practice*. Springer Science & Business Media.
9. Yamaguchi, H., Hongo, M. I. K. I. O., Miyauchi, T. A. T. E. O. K. I., & Mitani, M. A. S. A. O. (1985). Laser cutting of aluminium stripes for debugging integrated circuits. *IEEE journal of solid-state circuits*, *20*(6), 1259-1264.
10. Niziev, V. G., & Nesterov, A. V. (1999). Influence of beam polarization on laser cutting efficiency. *Journal of Physics D: Applied Physics*, *32*(13), 1455.
11. Slocombe, A., & Li, L. (2000). Laser ablation machining of metal/polymer composite materials. *Applied Surface Science*, *154*, 617-621.
12. Griffith, M. L., Ensz, M. T., & Reckaway, D. E. (2003, October). Femtosecond laser machining of steel. In *Photon Processing in Microelectronics and Photonics II* (Vol. 4977, pp. 118-122). SPIE.
13. Li, L., & Achara, C. (2004). Chemical assisted laser machining for the minimisation of recast and heat affected zone. *CIRP annals*, *53*(1), 175-178.
14. Kaldos, A., Pieper, H. J., Wolf, E., & Krause, M. (2004). Laser machining in die making—a modern rapid tooling process. *Journal of Materials Processing Technology*, *155*, 1815-1820.
15. Caiazzo, F., Curcio, F., Daurelio, G., & Minutolo, F. M. C. (2005). Laser cutting of different polymeric plastics (PE, PP and PC) by a CO2 laser beam. *Journal of Materials Processing Technology*, *159*(3), 279-285.
16. Forsman, A. C., Banks, P. S., Perry, M. D., Campbell, E. M., Dodell, A. L., & Armas, M. S. (2005). Double-pulse machining as a technique for the enhancement of material removal rates in laser machining of metals. *Journal of applied physics*, *98*(3), 033302.
17. Rao, B. T., Kaul, R., Tiwari, P., & Nath, A. K. (2005). Inert gas cutting of titanium sheet with pulsed mode CO2 laser. *Optics and Lasers in Engineering*, *43*(12), 1330-1348.
18. Dausinger, F. (2005, March). Machining of metals with ultrashort laser pulses: from fundamental investigations to industrial applications. In *XV International Symposium*

*on Gas Flow, Chemical Lasers, and High-Power Lasers* (Vol. 5777, pp. 840-845). SPIE.

19. Knowles, M. R. H., Rutterford, G., Karnakis, D., & Ferguson, A. (2007). Micro-machining of metals, ceramics and polymers using nanosecond lasers. *The International Journal of Advanced Manufacturing Technology*, *33*(1), 95-102.
20. Yilbas, B. S. (2008). Laser cutting of thick sheet metals: Effects of cutting parameters on kerf size variations. *Journal of materials processing technology*, *201*(1-3), 285-290.
21. Dubey, A. K., & Yadava, V. (2008). Optimization of kerf quality during pulsed laser cutting of aluminium alloy sheet. *Journal of materials processing technology*, *204*(1-3), 412-418.
22. Arif, A. F. M., Yilbas, B. S., & Aleem, B. A. (2009). Laser cutting of thick sheet metals: Residual stress analysis. *Optics & Laser Technology*, *41*(3), 224-232.
23. Mahrle, A., & Beyer, E. (2009). Theoretical aspects of fibre laser cutting. *Journal of Physics D: Applied Physics*, *42*(17), 175507.
24. Genna, S., Leone, C., Lopresto, V., Santo, L., & Trovalusci, F. (2010). Study of fibre laser machining of C45 steel: influence of process parameters on material removal rate and roughness. *International Journal of Material Forming*, *3*(1), 1115-1118.
25. Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., & Pou, J. (2010). Parametric investigation of CO2 laser cutting of 2024-T3 alloy. *Journal of Materials Processing Technology*, *210*(9), 1138-1152.
26. Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., & Pou, J. (2011). Effects of processing parameters on laser cutting of aluminium–copper alloys using off-axial supersonic nozzles. *Applied Surface Science*, *257*(12), 5393-5397.
27. Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., Del Val, J., & Pou, J. (2011). The role of the assist gas nature in laser cutting of aluminum alloys. *Physics Procedia*, *12*, 548-554.
28. Park, J. K., Yoon, J. W., & Cho, S. H. (2012). Vibration assisted femtosecond laser machining on metal. *Optics and Lasers in Engineering*, *50*(6), 833-837.
29. Sharma, P., Dubey, A. K., & Pandey, A. K. (2014). Numerical study of temperature and stress fields in laser cutting of aluminium alloy sheet. *Procedia Materials Science*, *5*, 1887-1896.
30. Dorsch, F., & Kaierle, S. (2014). High-Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications V. In *Proc. of SPIE Vol* (Vol. 9741, pp. 974101-1) –
31. Astarita, A., Genna, S., Leone, C., Minutolo, F. M. C., Paradiso, V., & Squillace, A. (2014). Laser cutting of aluminium sheets with a superficial cold spray titanium coating. In *Key Engineering Materials* (Vol. 611, pp. 794-803). Trans Tech Publications Ltd.
32. Leone, C., Genna, S., Caggiano, A., Tagliaferri, V., & Molitierno, R. (2015). An investigation on Nd: YAG laser cutting of Al 6061 T6 alloy sheet. *Procedia Cirp*, *28*, 64-69.

33. Keles, O., & Yilbas, B. S. (2015). Laser cutting of 2024 aluminium alloy and cutting quality assessment. *Advances in Materials and Processing Technologies*, *1*(1-2), 164-171.
34. Previtali, B., Riva, G., Librera, E., Filios, S., Sbetti, M., Vanin, M., ... & Lochman, B. (2015, October). Laser cutting of copper and brass alloys by high brilliance diode source with an extremely low bpp. In *International Congress on Applications of Lasers & Electro-Optics* (Vol. 2015, No. 1, pp. 968-976). Laser Institute of America.
35. Lutey, A. H., Ascari, A., Fortunato, A., & Romoli, L. (2018). Long-pulse quasi-CW laser cutting of metals. *The International Journal of Advanced Manufacturing Technology*, *94*(1), 155-162.
36. Cui, C., Duan, X., Collier, B., & Poduska, K. M. (2018). Fabrication and wettability analysis of hydrophobic stainless steel surfaces with microscale structures from nanosecond laser machining. *Journal of Micro and Nano-Manufacturing*, *6*(3).
37. Gabdrakhmanov, A. T., Israphilov, I. H., Shafigullin, L. N., & Gabdrakhmanova, T. F. (2019, July). Study of laser cutting of copper and copper alloys. In *IOP Conference Series: Materials Science and Engineering* (Vol. 570, No. 1, p. 012020). IOP Publishing.
38. Marimuthu, S., Dunleavey, J., Liu, Y., Antar, M., & Smith, B. (2019). Laser cutting of aluminium-alumina metal matrix composite. *Optics & Laser Technology*, *117*, 251-259.
39. Parmar, V., Kumar, A., Prakash, G. V., Datta, S., & Kalyanasundaram, D. (2019). Investigation, modelling and validation of material separation mechanism during fiber laser machining of medical grade titanium alloy Ti6Al4V and stainless steel SS316L. *Mechanics of Materials*, *137*, 103125.
40. Kang, D., Zou, P., Wang, W., Xu, J., & Shen, C. (2021). A lens ultrasonic vibration-assisted laser machining system for laser polishing and laser drilling of 304 stainless steel. *Optics & Laser Technology*, *144*, 107419.
41. Boujelbene, M., El Aoud, B., Bayraktar, E., Elbadawi, I., Chaudhry, I., Khaliq, A., ... & Elleuch, Z. (2021). Effect of cutting conditions on surface roughness of machined parts in $CO_2$ laser cutting of pure titanium. *Materials Today: Proceedings*, *44*, 2080-2086.
42. Metalworking and Metal Fabrication Guide, https://finemetalworking.com/, (accessed on 07 May 2022).
43. Zhang, S., Sun, Y., Cheng, Y., Huang, P., Oladokun, M. O., & Lin, Z. (2018). Response-surface-model-based system sizing for Nearly/Net zero energy buildings under uncertainty. *Applied Energy*, *228*, 1020-1031.
44. Kandananond, K. (2010). Using the response surface method to optimize the turning process of AISI 12L14 steel. *Advances in Mechanical Engineering*, *2*, 362406.