LASER DRILLING PARAMETER OPTIMIZATION FOR TI6AL4V ALLOY

Submitted by

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In fulfilment for the award of the Degree Of

BACHELOR OF ENGINEERING

IN

MECHANICAL ENGINEERING

PANIMALAR ENGINEERING COLLEGE, CHENNAI

ANNA UNIVERSITY:: CHENNAI 600 0123

SEPTEMBER 2020

ANNA UNIVERSITY: CHENNAI 600 0125

BONAFIDE CERTIFICATE

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INTERNAL EXAMINER **EXTERNAL EXAMINER**

ACKNOWLEDGEMENT

At the outset we would like to express our gratitude to our beloved correspondent and Secretary **Mr.P.Chinnadurai M.A., M.Phil., Ph.D.,** and our esteemed directors for their support.

We would like to express thanks to our Principal, **Dr. K. Mani M.E., Ph.D.,** for having extended his guidance and cooperation.

We would also like to thank our **Head of the Department**, **Dr.L.Karthikeyan M.E., MBA, Ph.D., Professor, Department of Mechanical Engineering** for his encouragement.

We thank **Professor in Department of Mechanical Engineering** for the persistent motivation and support for this project, who at all times was the mentor of germination of the project from a small idea.

We express our thanks to the project coordinators **Mr.B.Balamugundhan M.E., Professor in Department of Mechanical Engineering** for the Valuable suggestions from time to time at every stage of our project. Finally, we would like to take this opportunity to thank our family members, friends, well-wishers who have helped us for the successful completion of our project.

We also take the opportunity to thanks all faculty and non-teaching staff members to our department for their timely guidance to complete our project.

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ABSTRACT

In the current scenario, the manufacturing sector stresses materials with striking characteristics, directed to developing innovative materials such as superalloys, composites, and ceramics. These materials are highly prospective for aerospace, automobile, defence, and gas turbine components. Laser Beam Drilling (LBD) is a variant and vibrant technique of Laser Beam Machining (LBM), used for hole manufacturing in any conductive or non-conductive materials. The process is extensively used to drill holes in injectors, gas turbine blades, rocket parts, and intricate parts due to high improvement competence. In LBD, the performance characteristics viz Material Removal Rate (MRR), dimensional accuracy, and surface quality usually outline the machining material process. The modern era fully deals with the laser drilling process for making holes in the hardest material for more precise holes. Here we have chosen a titanium alloy Ti6Al4v of 1 mm thickness. The Taguchi method is used to optimize the process parameters. The process parameters we are considering laser power, laser speed, and frequency for Response hole Circularity. The S/N ratio deals with the influencing parameters which affect the hole diameter. The frequency and speed are the more influencing ones. The ANOVA makes the process more significant in responses. However, the quality and accuracy of the holes can be excellent, if the optimal Process parameter has been optimized by using the S/N ratio. Hole circularity increase with frequency and speed increases. ANOVA was found the most significant parameters of hole circularity.

Chapter 1

BACKGROUND OF THE RESEARCH

Nowadays, superalloys are used to manufacture machine parts because of their unique properties like long-lasting, light weighed, and biocompatible. Conventional machining methods aren't suitable to cut these metals through high precision & desired intricate shape. Unconventional or advanced machining processes (AMPs) are used to machined any superalloy with precision and desired shape without tool wear. Many kinds of AMPs are used for machining. Some of them are as follows:
(Dubey and Yadava, 2007; Gautam and Pandey, 2018)

- Abrasive Jet Machining (AJM)
- Electrical Discharge Machining (EDM)
- Electro-Chemical Machining (ECM)
- Electron Beam Machining (EBM)
- Ice Jet Machining (IJM)
- Ion Beam Machining (IBM)
- Laser Beam Machining (LBM)
- Photo Chemical Machining (PCM)
- Plasma Beam Machining (PBM)
- Ultrasonic Machining (USM)
- Water Jet Machining (WJM)

Micromachining operations in groove, hole, or cut are not possible by traditional manufacturing processes because the high cutting force is needed to produce them. AMPs are used to create micro-sized holes or grooves on superalloys like highly thermal-resistant materials such as ceramics, carbide materials, composite materials, satellites, etc. (Phipps, 2004; Zhang and Xu, 2012; Wang et al. 2019A).

A hole generally uses to clamp two components or provide cooling to machine parts in heat engines. This feature usually uses in electronics parts, orthopedic implantations, fuel injectors, disc brake, turbine blades, rocket components, complex shapes, etc. (Giradin et al., 2016; Goyal and Dubey, 2016).

Many advanced machining processes have their limitations. LBM is a thermal-based process; its characteristic makes it different from other conventional or unconventional machining processes. LBM depends upon thermal characteristics like melting temperature, specific heat, and materials' thermal conductivity (Dubey and Yadava, 2008; Pandy and Dubey, 2013B; Pattanayak et al., 2020).

LASER (Light Amplification by Stimulated Emission of Radiation) beam is a tool used to machining any kind of materials. Various types of laser use for the LBM process. This process has an extra benefit of manufacturing complicated components and making intricate shapes with better surface texture (Meng et al., 2015; Michael and Biermann, 2018).

1.2 LASER BEAM - AN OVERVIEW

In LASER, a device is used to generate highly concentrated unidirectional light. This light is emitted by stimulated radiation emission to increase light intensity (Adams, 1965; Chryssolouris, 1991).

The following four laser beam characteristics differentiate conventional light (Maiman, 1960; Phipps, 2003; Rao and Kalyankar, 2014).

a. Highly coherent: The laser beam has a mono wavelength. Hence, photons emission in phase makes it highly coherent.
b. Highly precise directional: The laser beam is highly directional because of the narrowness of the beam. This characteristic helps to concentrate on the targeted surface.
c. Highly intensive: It may be concentrated on a small region with greater intensity.
d. Mono-chromaticity: Laser beam is a monochromatic light.

Due to one color or mono wavelength.

Types of Laser

Lasers classify into four categories (solid-state, gas, liquid & semiconductor laser) according to the kind of laser medium (Dubey and Yadava, 2007; Arif and Yilbas 2008; Lee and Cheng, 2015):

1.2.1.1 Solid-state Laser

Glass material or crystalline uses as a host material to produce solid-state laser, and ions add with host materials as impurities. Doping is a process to add impurities to host materials. Terbium (Tb), erbium (Eu) & cerium (Ce) elements are mostly used as dopants.

Ruby laser used as the first solid-state Laser. Ruby crystal was used as a laser medium to produce Ruby laser. Commonly, Ruby laser is not using presently.

Following materials used as a host material to produced solid-state laser:

a. Al2O3 (Sapphire)
b. Nd:glass (Neodymium-doped glass)

c. Nd:YAG (Neodymium-doped yttrium aluminum garnet)

A laser diode, arc lamp, flash lamp, and flash tube use as elements pumping source in a solid-state laser.

1.2.1.2 Gas Laser

A gaseous state's element is used as a laser medium to produce a gas laser to produce laser light. Electric energy discharges through a gas into a laser medium. Electric energy converts into light energy. A gas laser beam uses a high coherent beam required. Glass tube (filled with a mixture of gases) operates as a laser medium.

Following gases are commonly used as a host material to produced gas laser:

1. He-Ne lasers
2. Ar^+ lasers
3. CO2 lasers
4. CO lasers
5. Excimer lasers
6. N2 lasers
7. H2 lasers.

1.2.1.3 Liquid Laser

A liquid uses as a laser medium, and liquid materials use as host material to produced laser. Organic dye mixed with solvent is used as a laser medium to create liquid laser.

1.2.1.4 Semiconductor Laser

This Laser is different from a solid-state laser. A p-n junction diode is used as a laser medium, and electrical energy is used as a pump source instead of light energy in the semiconductor laser.

Lasers are also operated as pulsed mode (PM) or continuous wave (CW).

A wide range of lasers are available, as shown in Table 1.1 (Phipps, 2003; Steen, 2003; Rao and Kalyankar, 2014):

Table 1.1: Classification of laser & characteristics

Types		Wavelength	Characteristics
Ion	Excimer	200-250 nm	PM
	Ar^+	330-530 nm	PM, CW, 1W-5 kW
Molecular	CO2	10.6 µm	PM, CW, <15 kW
Neutral gas	He-Ne	633 nm	CW, 20 mW
Semiconductor	GaAs	800-900 nm	PM, CW, 2-10 mW
Solid	Nd-glass	1064 nm	PM, CW, 2 mW
	Nd-YAG	1064 nm	PM, CW, 1-800 W
	Ruby	694 nm	PM, 5 W

1.3 ND:YAG LASER

It has wide applications in the scientific and medical fields as used in spectroscopy and surgery. This laser is operated in PM and CW, and its wavelength of 1064 nm. It also generates laser light at wavelengths, including 940 nm, 1120 nm, 1320 nm & 1440 nm (Chryssolouris, 1991; Kathuria, 1998; Yilbas, 2013).

It consists of mainly three elements, as shown in Figure 1.1. These are as follows (Chryssolouris, 1991; Leonne and Genna, 2018):

1) **Source of Energy:** It is used to supply energy to increase crystalline material's energy level in an active medium. A flash tube or laser diode is commonly used as a source of energy.

2) **Active Medium:** It is also known as a laser medium. It is made by synthetic crystal-like substance doped in a chemical solution. YAG (Yttrium Aluminum Garnet) is used as a synthetic crystal-viz substance and Nd (neodymium) as a dopant (chemical element). The energy source (Flash tube) excites Nd ions' electrons to a higher energy level from low energy levels in the active medium.

3) **Optical Resonator:** Lasing medium keeps between two optically or silvered coated mirrors. These two mirrors work as an optical resonator. one fully coated mirror is used for full reflection and partially coated for partial reflection. The partially reflective mirror will allow a tiny portion of the light to produce Nd:YAG laser beam.

Laser Beam Drilling (LBD)

LBD recognizes as a cost-effective process for creating a micron size holes in any kind of structure. It is superior among any traditional or nontraditional machining methods

because of no tool wear, flexibility in production, minimal wastage of material, material changeability, highly precise approach, and edge quality.

1.4 LBD TECHNIQUES

LBD is a procedure to create a hole into a workpiece through a laser. It is much different from the traditional drilling due to absence of physical contact between workpiece and tool, making it non-contact machining process (Maiman, 1960; Anicic, 2017).

A beam has applied repetitively over particular section of object, vaporizing & meltdown material layer-by-layer till hole formation. Blind holes and thru-holes are the types of holes drilled (Maiman, 1960; Steen, 2003; Gautam and Pandey, 2018).

There are many process parameters to control the quality of the hole during LBD like heat, the intensity of the beam, hole diameter, depth, material characteristics, etc. LBD can process effectively in any kind of material like glass, plastics, and metals (Chryssolouris, 1991; Corocoran et al., 2002; Rao and Kalyankar, 2014).

Laser drilling is classified as (Meijer, 2004; Dubey and Yadava, 2008; Parandoush and Hussain, 2014; Goutam and Pandey, 2018):

Single-pulse or shot laser drilling: it is a speedy, efficient, and simple technique of laser drilling. In this, a mono laser beam is pulsated on a predefined place of substance repetitively till substance starts to vaporize and evaporate layer-by-layer. Generally, a single-pulse drilling technique is used to make a thru-hole in a workpiece.

Percussion drilling: This drilling technique seems like a single pulse drilling. In this technique, firing laser pulses work at a particular place of a workpiece. Molten material removes away layer-by-layer from workpiece material. This technique is also used for creating precise thruholes or rough surface of a material. It is used to create a more accurate and deeper hole up to micro-sized hole diameter than single-pulse drilling.

Trepan drilling: Initially laser beam pierces a hole in the workpiece, same as above mentioned technique. Once the beam has a pierced workpiece, the laser beam follows a spiral path to create a hole with a motion system's support.

In other words, a laser beam starts to move from the center of the diameter. It moves and follows a progressively spiral path until a precise hole diameter

(shown in Figure 1. 5). This technique helps create exact holes in many shapes, trimming 3D shapes, slots, counterbores, etc.

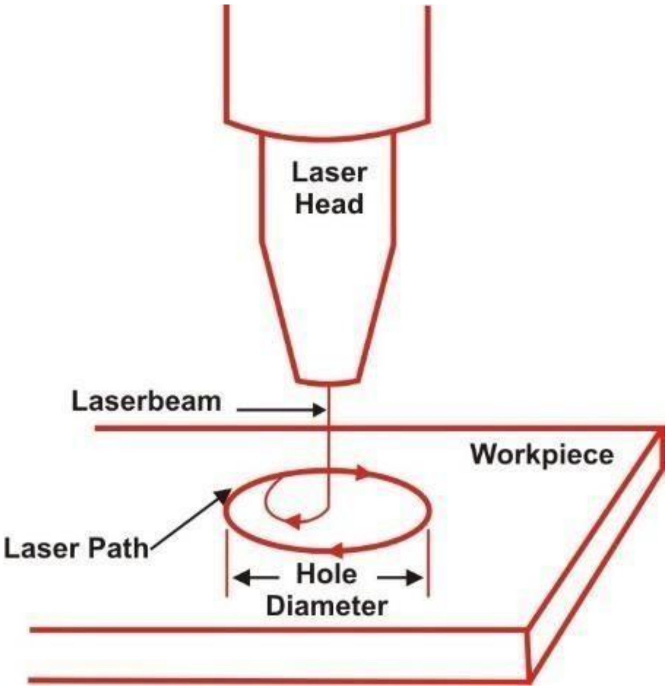


Figure 1.5: Trepanning drilling contour (Dubey and Yadava; 2008)

1) **Helical drilling:** It is a combination of percussion and trepanning drilling. In this technique, the laser beam moves around the desired hole diameter's circumference and is followed by a spiral motion to the hole's desired depth. There is no initial pierce hole created, and the molten material removal process is different from trepan drilling. Molten material moves out from upward during helical drilling.

Comparative analysis between hole drilling techniques and hole accuracy is also shown in Figure 1.6 (Dousinger et al. 2018).

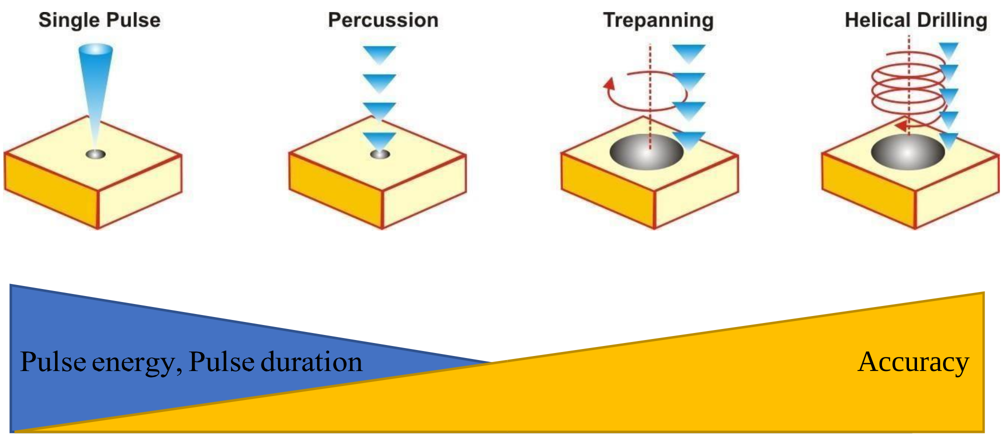
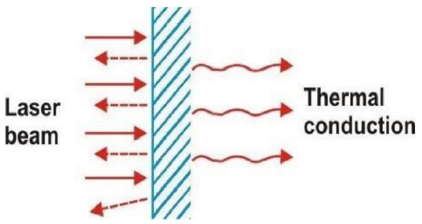


Figure 1.6: LBD techniques & hole accuracy

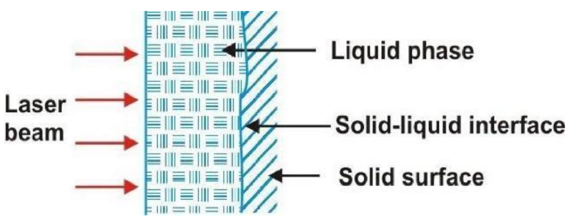
(Dousinger et al. 2018)

1.5 MECHANISM OF LBD

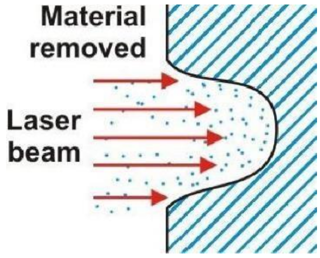
A laser beam focuses over the object, its heat energy is absorbed & heat the object as shown in Figure 1.7a. Workpiece starts to melt in the presence of enough heat, then the evaporation (removal) process of molten material will take place as sown in Figure 1.7b & 1.7c. It is a complex process due to losses due to the dispersion of heat at the material's surface to be machined (Chryssolouris, 1991; Dubey and Yadava, 2008, Saini et al. 2018).



(a) Absorption & heating



(b) Melting



(c) Vaporization

Figure 1.7: Material removal processes during LBD

(Goutam and Pandey, 2018)

Also, the heat dispersion mechanism on the material is completed in three stages to any material while focusing a laser beam on a material's surface (Steen, 2003, Gautam and Pandey, 2018):

1) The phase change of surface material
2) Molten surface material
3) Vaporization (Removal) of material

These are depending upon interaction time and power density of laser beam. Its power density should be high because most heat energy is absorbed in conduction, convection & radiation during the material removal process.

When a powered laser focuses at a point on workpiece surface during LBD. The concentrated laser energy absorbs through targeted region of surface. Heat dispersion mechanism takes place to eject molten material for creating hole. Furthermore, radiation due to the laser beam may cause an ionized vapor trap in a crater & finally form a plasma plume.

The involvement of many thermal and physical mechanisms makes it a very complex machining process. There are specific capabilities and limitations of each mechanism or process. In-depth knowledge and skill about mechanism or process are required to operate on machine setup.

The setup of laser drilling has been presented in Figure 1.8.

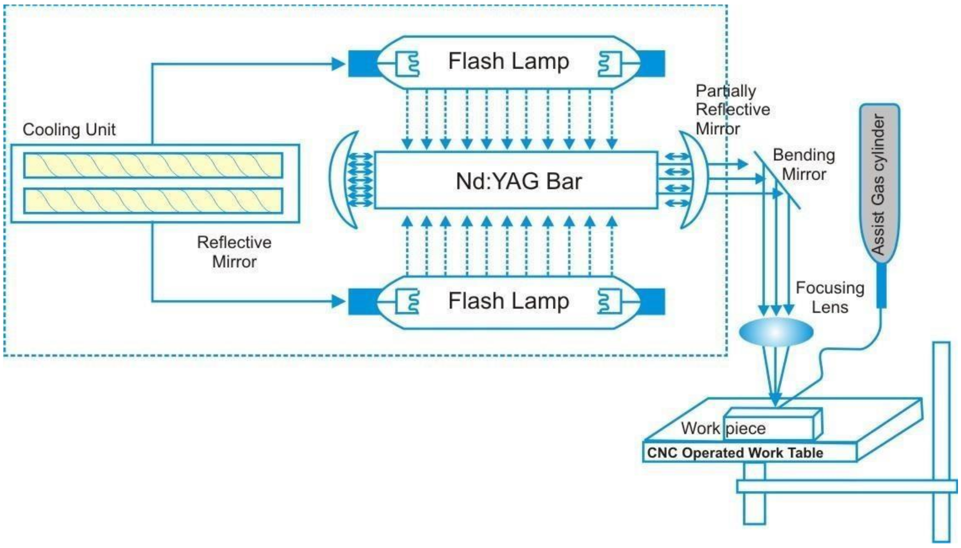


Figure 1.8: Lay out LBD

(Dubey and Yadava, 2008; Goutam and Pandey 2018)

1.6 ADVANTAGES OF LBD

Following advantages make LBD superior from other manufacturing processes (Bellows and Kohls, 1982 and Dausinger, 2001, Radovanovic, 2006; Nisar et al., 2010; Goyal and Dubey, 2016; Zhao and Cheng, 2017):

a. Traditional and non-traditional processes have limitations to the specific machining process, explicit materials characteristics. But, LBD is an unconditional machining process, on any kind of material is possible by the laser beam.

b. LBD process is based on thermal energy. Quality of machining depends upon thermal characteristics of the object during LBD. It is also well suited to machined materials; those are highly brittle or hard, non-conductive, and have favorable thermal aspects.

c. Laser is used as a tool to machine any substance. There is no vibration, no tool wear, no tool chatter during machining. LBD is also known as non-contact machining process.

d. LBD is a cost-effective machining process rather than an unconventional machining process. For example, replacement cost due to tool damage & wear may eliminate during LBD.

e. LBD eliminates replacement costs concerned with breakage & wear of machine tools. Waiting time reduces due to the replacement of the device, and re- calibration eliminates during LBD. It does not need any special environment conditions like vacuum etc. to operate as required in other unconventional machining processes.

f. LBD is a flexible method. When a laser beam combines with CNC-controlled system, it can use for any kind of machining process like welding, grooving, cutting, drilling, etc. on a machine. Highly precise featured cutting width, hole, or groove obtains using LBM while comparing with other machining processes.

1.7 DISADVANTAGES OF LBD

Thermal based machining systems have some disadvantages or limitations as follows (Chryssoloris, 1991; Dubey and Yadava; 2008):

a. It comprises high expenditure like a laser generation plant and associates it with a CNC controlled system.

b. A highly skilled person requires to operate and maintain the LBD setup.

c. The exact depth of the blind hole is very challenging to attain during laser drilling.

d. It can be precisely used to drill up to 50mm thick.ness of materials.

e. Usually, wastage (molten) materials are collected around the hole's bottom side during laser drilling. Positively assist gas pressure need to remove this material.

1.8 PROCESS PARAMETERS OF LBD

Process parameters have been employed for controling LBD to improve performance parameters. Assist gas pressure (GP), pulse frequency (PF), laser power (LP), cutting speed (CS), and focal length are essential machining factors. LBD is based on heat energy. HAZ, spatter formation, hole circularity, hole taper, etc. are essential

performance parameters during LBD (Bellows and Kohls 1982; Chryssollouris, 1991, Bahotre and Harimkar, 20078).

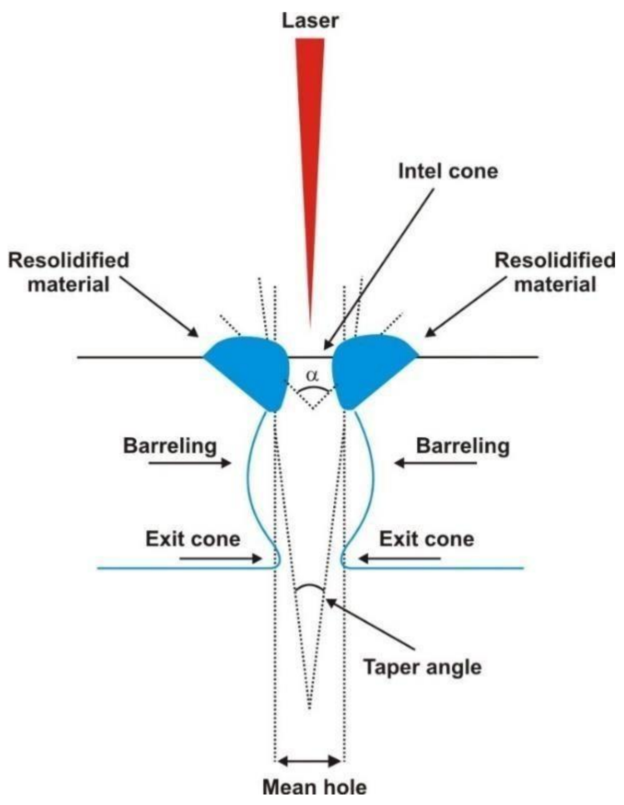


Figure 1.9: Laser drilled hole features (Gautam and Pandey, 2018)

Inherent concentrating features & converging-diverging profiles of laser beam are liable for generating a tapered hole. Inlet cone, barreling, taper angle & exit cone are features of the laser-drilled hole. Laser-drilled hole shape with its features is illustrated in Figure 1.9 (Siegman, 1986; Chryssollouris, 1991; Yilbas, 2013).

As mentioned earlier, performance characteristics can be controlled or optimized by proper utilization of machining factors during LBD. Machining factors and their ranges decide or modify based on the material (ceramics, plastics, or metal, etc.) and thickness.

1.9 PERFORMANCE PARAMETERS OF LASER DRILLED HOLE

Laser percussion drilling is known for a high rate of material removal, repeatability, and increased tolerance. Still, there are some drawbacks of percussion drilled hole like re-solidification, non-circularity of a hole, and hole taper (Ion, 2005; Biswas et al.,

2010A; Yi et al., 2013; Hoffman et al., 2014, Ren et al., 2015; Latif et al., 2016; Saini and Dubey, 2019). Actual percussion drilling processed hole with features is illustrated in Figure 1.9 (Goutam and Pandey 2018). Some molten material resolidifies and deposits on walls of a drilled hole during the LBD process is known as the recast layer. Entrance side resolidification is known as spatter, and the exit side is known as dross. Apart from these, Some essential performance parameters of LBD are summarized below (Goyal and Dubey, 2014; Goyal and Dubey 2016; Latif et al., 2016; Goutam and Pandey, 2018; Saini et al., 2018; Biswas et al., 2019; Saini and Dubey, 2019):

1.11.1 Hole Taper

When the laser beam moves towards deep during LBD, it produces a nonuniform dimension hole due to the laser's converging-diverging nature. Often, this defect is seen in hole processed by laser percussion drilling. Hole taperness shows a decrement of hole diameter with hole depth.

1.11.2 Hole Circularity

Non-uniform hole formation happens because of heating effect of laser beam. Hole circularity represents a uniform radius around its periphery and measurement of the degree of roundness. Ideal hole circularity means no error in radius of hole around its boundary. So the uniform drilled hole is always needed during LBD.

1.11.3 *Heat Affected Zone (HAZ)*

A higher temperature of beam affects various material properties in range of contact area. HAZ doesn't melt, but this area's microstructure is affected during laser drilling.

1.11.4 *Material Removal Rate (MRR)*

It depends upon process parameters, nature of assist gas, and material thickness. MRR is the measurement of removed material concerning time consumed during laser drilling. MRR affects material utilization and quality of cut during laser processing (Goyal and Dubey, 2014; Goyal and Dubey 2016; Goutam and Pandey, 2018).

Micro Cracks

Nitride and oxide layers are formed on hole sidewalls due to N2 or O2 as assist gas during LBD. Thermal gradients or high cooling rates produce micro-cracks on hole sidewalls. The selection of assist gas may eliminate micro-cracks during laser processing. Some essential processes and performance parameters in LBD, as shown in Table 1.2 (Goutam and Pandey, 2018).

Table 1.2: Characteristics of process and performance parameters of LBD

Characteristics of Process Parameters		
Beam Characteristics	**Laser Characteristics**	**Drilling Characteristics**
Beam Quality	Cutting speed	Aspect ratio
Number of pulses	Focal distance	Drilling angle
Pulse duration	Laser Power	Hole Depth

Pulse energy	Nozzle Diameter	
Pulse width	Pressure of Assist gas	Hole Diameter
Wavelength	Pulse Frequency	
Characteristics of Performance Parameters		
Geometrical Characteristics	**Quality Characteristi**	**Metallurgical Characteristics**

	cs	
Hole circularity	Surface Roughness	Spatter Formation
Hole Taper		Micro cracks
Overcut	MRR	Recast layer thickness
		Heat Affected Zone

1.1 METALLURGY OF TITANIUM ALLOY

The properties that have made titanium as an accepted material of construction are its high strength to weight ratio and its exceptional resistance to corrosion like other metals. Titanium and its alloy loose strength with increase in temperature. The specific strength of titanium, with a density just over half that of steel is superior to most of other structural metals and it has high strength to low density characteristic maintained at elevated

temperatures, which has resulted in the rapid growth in its use in aero engines. As an alpha beta alloy, Ti-6Al-4V may have different volume fractions of alpha and beta phases depending on heat treatment and interstitial content (Andrieux *et al*. 2009).

1.1.1 History of Titanium

The process of producing titanium sponge by the magnesium reduction of titanium tetrachloride was discovered by W. J Kroll in 1938. Shortly afterward the united state armed services became interested in the metal primarily because of its high melting point (1470°C).

There was a possibility of developing titanium alloys with strength at elevated temperatures in military equipment for nickel base and cobalt base alloys. Titanium has a density of about 4.78 g/cc compared with steel at 7.28g/cc therefore titanium alloy structures have a high strength to weight ratio and are particularly useful for aircrafts parts.

Titanium has a strong affinity for the gases oxygen, nitrogen, and hydrogen, all of which forms interstitial solid solutions with titanium (Dieter. 2005). When the amount of absorbed oxygen, nitrogen, and hydrogen exceeds specified limits, they embrittle titanium, reduce impact strength, and cause brittle failure under sustained loads at low stresses.

1.1.2 Classification of Titanium Alloy

Pure titanium undergoes an allotropic transformation from hexagonal close packed crystal structure called alpha to body centered cubic called beta as its temperature is raised through 882.5°C. Commercially, pure titanium is lower in strength, has more corrosion resistant, and less expensive than titanium alloys. It is used for applications requiring high ductility for

fabrication but little strength, such as chemical process piping, valves, tanks, aircrafts fire walls, tail pipes, and compressor cases.

The addition of alloying elements to titanium will influence the alpha to beta transformation temperature. It is a common practice to refer to alloying elements as alpha or beta stabilizers. An alpha stabilizer means that as solute is added, the alpha to beta transformation temperature is raised; similarly a beta stabilizer lowers the transformation temperature.

Aluminum additions, dissolved in titanium produce little change in the transformation temperature or cause it to increase is known as alpha stabilizers. They are simple metals or the interstitial elements generally with no transition elements. Vanadium additions which decrease the phase transformation temperature are referred as beta stabilizers. They are generally the transition metals and noble metals. The relative amounts of alpha and beta stabilizers in an alloy and the heat treatment determine whether its microstructure is predominantly one phase alpha, a mixture of alpha and beta, or the single phase beta over its useful temperature range.

1.3.2.1 Alpha alloy

Alpha stabilizers are Al, Ga, Sn, etc. Unalloyed titanium and alloy of it, Ti5Al-2.5Sn, Ti-Al-Ga alloys are alpha alloys and are hcp phase at ordinary temperatures. They are characterized by satisfactory strength, toughness, creep resistance, and weldability. Hot working of alpha alloys containing more than six percent aluminum is difficult. Hot workability of high aluminum alpha is improved by additions of beta stabilizing alloying elements in amounts small enough so that the beta phase is present in small quantities in the annealed microstructure. Some applications of Ti-5Al-2.5Sn alloy include aircraft tailpipe assemblies and chemical process piping. Also,

the absence of a ductile brittle transformation, a property of the bcc structure, renders alpha alloys suitable for cryogenic application.

1.3.2.2 Beta alloy

Transition metals solutes are stabilizers of the bcc phase. All beta alloy generally contain one or more of the “beta-isomorphism” forming additions of V, Nb, Ta and Mo. Beta alloys are Ti-15Mo-5Zr and Ti-15Mo- 5Zr-3Al. Beta alloys are extremely formable, prone to ductile-brittle formation and along with other bcc alloys are unsuitable for low temperature applications.

1.3.2.3 Alpha-beta alloys

These are alloys whose compositions usually at room temperature are such that they support a mixture of alpha and beta phases. Although many binary beta stabilized alloys in thermodynamics equilibrium are two phases, in practice the alpha-beta alloys usually contain a mixture of both alpha and beta stabilizers. The simplest of such alloys is Ti-6Al-4V. Although this alloy is difficult to form, even in the annealed condition, this alloy generally exhibits good fabric ability as well as high room temperature strength and moderate elevated temperature strength. They may contain between 10-50% beta phases at room temperature; if they contain more than 20%, they are not weldable. The properties of alpha- beta alloy by heat treatment, which is used to adjust microstructural and precipitation states of the beta components.

1.1.3 Mechanical Properties of Ti-6Al-4V

Young‟s modulus (E) of Ti-6Al-4V is about mid range of Ti alloys but relatively low compared to other high strength materials. The value of E varies from 100 to 130GPa. In a multiphase alloy like Ti-6Al-4V, the value of E is determined by the module of specific phase and their volume fraction. Thus heat treatment of Ti-6Al-4V has an effect on its modulus. In general, interstitial and substitution alpha-stabilizing solutes increase the modulus, whereas beta stabilizing solutes decrease it. Compressive elastic modulus of Ti-6Al-4V is close to the materials tensile elastic modulus (Young‟s modulus), where in all cases, the compressive modulus slightly exceeds the materials tensile modulus.

CHAPTER 2

LITERATURE SURVEY

Low et al. [11] (2000) studied the effect of process parameter on spatter deposition in laser percussion drilling. According to them, short pulse width, low beam power and high pulse frequency generated smaller spatter deposition area. Also, focal plane position between -0.5 and 1.5 mm produced relatively smaller spatter area. However, with very long pulse width, the spatter deposition area was also reduced. A longer focal length (l60mm) generated smaller spatter deposition area as compared to shorter focal length **(l20mm).**

Voisey et al. [12] (2001) experimentally studied the effect of assist gas on laser drilling . According to them, the use of assist gases (Oxygen / Nitrogen) in laser drilling of the thermal barrier coated (TBC) and uncoated super alloy had no mechanical and chemical effect

Hirogaki et al. [13] (2001) conducted comparative studies on the drilling performance using Armid and glass epoxy composite as workpiece materials.

Low et a1. [14] (2001) used specially developed anti-spatter composite coating material (containing a mixture of ceramic filler particles embedded in silicone elastomeric matrix) on the workpiece surface prior to laser drilling and found that the spatter decomposition rate was effectively reduced.

Low et al. [15) (2001) reported the characteristics of spatter formation

under the effect of different laser parameters during laser drilling. According to them, a larger proportion of the spatter (approximately greater than 70%) was accumulated due to the initial laser pulse required to drill a through hole. They reported that short pulse width, low peak power and high pulse frequency produced smaller spatter area.

Ng and Li [16] (20fll) claimed that better repeatability was due to shorter pulse width (shorter melt ejection duration) and higher peak power (higher vapour recoil pressure) thus shorter melt ejection duration. Greater spatter thickness was obtained when the drilling operation was carried out with long pulse width and low peak power.

Yung et al. [17] (2002) reported that laser power and pulse frequency were found to be the most important parameters that had significant effect on the size of the heat affect zone (HAZ). According to them, with low power and low pulse frequency, the thickness of the HAZ was very small.

Ng and Li [18] (2003) developed the relationship between the percentage standard deviation of entrance hole diameter and operating parameters like laser peak

power and pulse width in a 2mm thick stainless sheet. According to them, the values of percentage standard deviation vary between 1.8 to 5.6 %. More the value of standard deviation less was the repeatability and vice versa.

Ganguly, et al. [19] (2012) have worked on parameter optimization of micro- drilling of zirconia by pulsed Nd:YAG laser. They have taken lamp current, pulse frequency, pulse width and assist gas pressure as the process parameters and hole aspect ratio and width of HAZ as the response. They conclude that lamp current is the most dominative parameter in quality

control of laser drilled holed in zirconia ceramics. The other parameters in order of reduced influence are the pulse frequency, air pressure and pulse width. Higher lamp current produces greater taper in a non-liner manner. The best combination of parameters to obtain best settings is when the lamp current, pulse frequency and air pressure are maximized, and pulse width is minimized.

Guo et al. [20] (2003) reported a spatter free hole with more uniform shape on gel cast green alumina sheet. Gel casting is an attractive ceramic forming technique for making high quality ceramic parts. In this process, ceramic slurry was obtained by dispersing the powder in the premixed monomer solution is cast in a mould of the desired shape. After adding a suitable initiator, the entire system was polymerized insitu in green bodies and excellent mechanical properties could be obtained.

Dumitru et al. [21] (2003) had conducted metallographic study of the hole profile on steel and hard material after deep drilling with femtosecond laser pulses (5•10* number of pulse / s) They reported that the surface of the drilled profile were hardened because of the process and the value of the increase in hardness varied from at some isolated spots where the material properties were modified could occur but the spot did not form a continuous layer surrounding the layer induced cores.Low et al. [22] (2003) used an anti-spatter composite coating (ASCC) (a mixture of ceramic filler particle embedded in a silicon elastomeric matrix) on the surface of three different workpiece materials (Iron-100,nimonic PK-33 and 263 alloys) and observed that ASCC effectively prevented the spatter in laser drilling by using 400W Nd-YAG laser. The incorporation of ASCC allowed the production of laser drilled holes whilst retaining the as- received surface condition of the alloys. More importantly, the ASCC prevented the undesired surface modification that could be caused by preventing the diffusion of the spatter into the parent alloys, as well as by any subsequent spatter removal processes.

Jackson and Neill [23] (2003) conducted laser drilling experiments on M2 tool steel using three different wave lengths of Nd-YAG pulsed laser (i.e 1064,532 and 355 rim) and observed that the maximum drilling rates were obtained from 532 and 355 rim wave length.

Wang et al. [24] (2004) carried out laser drilling for machining small orifices on 305 stainless steel using a pulsed Nd-YAG laser with Oxygen ,Argon and Nitrogen as assist gases. They studied the micro-structure of recast layer using SEM analysis. According to them, the micro structural morphologies of recast layers were independent of the assist gases and characterized by a columnar structure of dendrites composed of austenite probably with minor phase of delta ferrite in the interdendritic region. They also

reported that the nitrogen content was increased in recast layer in the order of oxygen, argon and nitrogen as the assist gases.

Li ct al. [25] (2005) used a novel high peak power (400 kW) Nd-YAG laser with 5 to 50 kHz repetition rate and 200 nanosecond pulse duration to drill Copper and Nickel alloy. The holes diameter obtained was 200pm. They observed that the recast layer was very narrow (10 pm). They also observed through SEM that there was no micro crack. They concluded that 10 kHz is an approximate repetition rate which resulted in the smallest spatter deposition area. Also they proposed that with the burst of Q-switch's laser pulse the material vaporization was predominant resulting in sharp hole entrance.

Bandopadhya et al. [26] (2005) used a statistical approach (Tauguchi's design of Experiment) to determine the effect of process parameters in Nd-

YAG laser drilling of IN7I8 and Ti-6Al-4V steel and reported the optimum process parameters for better micro-hole .They reported that the focal position, pulse energy and pulse duration were the most significant process parameters influencing hole quality .They also reported that laser drilling with focal position on the surface of the materials being drilled and employing low level value of pulse duration and pulse energy were ideal conditions to achieve minimum taper in laser drilled hole.

Singhal et al. [27] (2005) reported that the energy required to remove materials by melt ejection process is about one-quarter of that required to vaporize the same volume.

Ostermeyar et al. [28] (2005) conducted percussion drilling on lmm Aluminium sheet with a Q-switched Nd-YAG laser having 10 nanosecond pulse duration. They investigated the optimum parameters with regard to the burr height and the ablation rate.

Forsman et al. [29] (2005) used a double pulse drilling technique with the pulse duration in the order of nano second between the two conjugative pulses and reported that this condition resulted in high material removal rate with high aspect ratio and with high quality (less heat affected zone and minimum spatter deposition) micro-holes.

Sezer et aI. [30] (2006) conducted laser drilling operation of thermal barrier coating (TBC) Nickel super alloy and observed that the extent of heat affected zone (HAZ), recast layer and oxide layer were increasing with decreasing the drilling angle to the surface.

Karnakis et al. [31] (2006) **demonstrated** that high **quality efficient laser micro-** machining could be accomplished using high laser intensity from diode-pumped solid state laser as 532 and 352 nanometer comparable to ultra-fast laser machining .The key of this process was due to the combined application of high peak and average power on the target. They used two materials like stainless steel and silicon.

French et al. [32] (2006) used various pulse shape for percussion drilling on nickel base alloy of 3mm thickness and tried to improve the hole quality . They used four different types of pulses such as square, ramping-up pulse, ramping-down pulse and pulse burst. According to them, in terms of hole taper the ramping—up pulse gave the best performance. The ramping-up pulse also gave a consistence performance with respect to the entrance diameter .

Bhatt et at. [33] (2007) studied the effect of various lasers and process parameters of excimer laser drilling in glass. They reported that the hole taper was reduced to 14% by optimization of process parameter. It was also **reported** that protective polymer film coating on the glass successfully reduced the amount of debris adhesion.

Masmiati and Phillip (34] (2007) used Taguchi’s method considering orthogonal array to optimize the circularity of the hole, spatter thickness, hole taper and material removal rate. They had used four input parameters such as number of pulse, standoff distance (SOD), assist gas pressure and nozzle diameter. They reported that, there was no relationship between the hole entrance diameter, hole taper and hole circularity in drilling of polymers. In order to get a better quality hole each of this different machining condition were to be optimized.

Champbell et al. [35] (2007) used a femosecond laser to study the interaction of ultra shot laser pulses with aluminum. According to them, ultra shot pulses caused melting while machining the materials. In aluminium the melt was minimum and virtually eliminated by using the second harmonic of 800 nanometer beam and processing under vacuum. The improved hole quality came at the cost of processing speed which was[16] slowest when using the second harmonic beam. The nanosecond component of the beam is responsible for high drilling rate.

Wang et al. [36] (2007) studied the influences of the laser parameters on the diameter of perforation, the outer diameter of the crater and roundness of the hole on a “gold” coated Fe-Ni alloy thin plate drilled by Nd-YAG laser. After the study through SEM, they found that the diameter of the perforation increased gradually with

corresponding increase in pulse width from 0.3 to 8 milisecond at fixed average power. At the same time the frequency increased with corresponding increase in average laser power from 10 to 25W at the fixed pulse width and frequency. Good roundness of the perforation could be achieved at either the lowest pulse width or lowest laser power.

Nedialkov et al. [37] (2007) studied the material removal rate during the laser drilling of AlN ceramic. The material removal was governed by different mechanism depending on the processing conditions. At intensities below the threshold, an irregular shape and uneven bottom was formed. As the intensities were increased above the threshold values, a well defined regular hole having smooth walls covered by Al layer was formed.

Rana et al. [38) (2007) used Taguchi’s technique for the optimization of laser process parameters to get a quality hole. They used three different parameters like pulse width, pulse frequency and assist gases (oxygen and air) flow rate as the input parameters and hole diameter and heat affected zone (HAZ) as the output parameters. Using L» orthogonal array, they had studied the effect of input parameters. According to them, the minimum possible hole size was due to air as assist gas compared to oxygen. On the other hand, for minimization of HAZ, oxygen was suitable compared to air.

Ghoreishi and Nakhjavani [39] (2007)[17] used neural network technique for modeling laser percussion drilling process. They had used Nd-YAG laser system with oxygen as assist gas. They claimed that neural network and its combination with genetic algorithm (GA) could be used for optimization of laser percussion drilling process.

Solonitis et al. [40] (2008) conducted experimental investigation on pulsed laser drilling. They had recorded the following observations. According to them, the irradiation time required for achieving melting temperature on the surface of the workpiece was dependent upon pulse frequency. The maximum drilling depth that could be achieved was not a function of pulsing frequency, when the laser drilling was carried out with low and medium power density.

Choi and Li [41] (2008) studied temperature variations in the radial directions of the laser percussion drilled hole using C-type micro thin film thermocouple (TFTC) with a junction size of 2x2 pm' and observed that, there was steep temperature gradient in the radial direction. Moreover, they studied topographical characterization by varying the laser energies on Nickel workpieces. The chemical characterization (oxide formation) in the areas around the laser spot was also studied using energy distribution spectroscopy (EDS) and observed that the amount of oxygen in the laser spot centers is lower than that at around the edges. They suggested that melt ejection by recoil pressure was a dominant mechanism for pulsed laser micro-machining process.

CHAPTER -III

EXPERIMENTAL SETUP

3.1 DESIGN OFEXPERIMENTS

A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. By the statistical design of experiments the process of planning the experiment is carried out,so that appropriate data will be collected and analyzed by statistical methods resulting in valid and objective conclusions. When the problem involves data that are subjected to experimental error, statistical methodology is the only objective approach to analysis. The advantages of design of experiments are as follows:

- Numbers of trials is significantly reduced.
- Importantdecisionvariableswhichcontrolandimprovetheperfor manceof the product or the process can be identified.
- Optimal setting of the parameters can be found out. Qualitative estimation of parameters can be made. Experimental error can beestimated.
- Inferenceregardingtheeffectofparametersonthecharacteristicsof the process can bemade.

In the present work, The Taguchi’s method has been used to plan the experiments and subsequent analysis of the data collected.

3.2 SELECTION OF ORTHOGONAL ARRAY(OA)

In selecting an appropriate OA, the pre-requisitesare:

Selection of process parameters and/orinteractions to be evaluated Selection of number of levels for the Selected parameters

Several methods are suggested by Taguchi for determining which parameters to include in an experiment. These are:

a) Brainstorming

b) Flowcharting

c) Cause-Effectdiagrams

The total Degrees of Freedom(DOF)of an experiment is a direct function of total number of trials. Thus, increasing the number of levels for a parameter increases thetotal degrees of freedom in the experiment which in turn increases the total number of trials.Thus,twolevels for each parameter are recommended to minimize the size of the experiment.Fig. 3.1 Taguchi Experimental Design and Analysis Flow Diagram. ouldbeconsidered[164].

Thetotaldegreeoffreedomwascomputedtoselectanappropriateorth ogonalarray for experiments. The degree of freedom associated with interaction between two processes parameters are given by the product of degree of freedom for the two process parameters. In the present study, the interaction between the welding parameters is neglected.In this study,an L_9orthogonalarraywiththreecolumnsand 9 rows was used (Table 3.1). This array has eight degrees of freedom and it can handle three level process parameters.

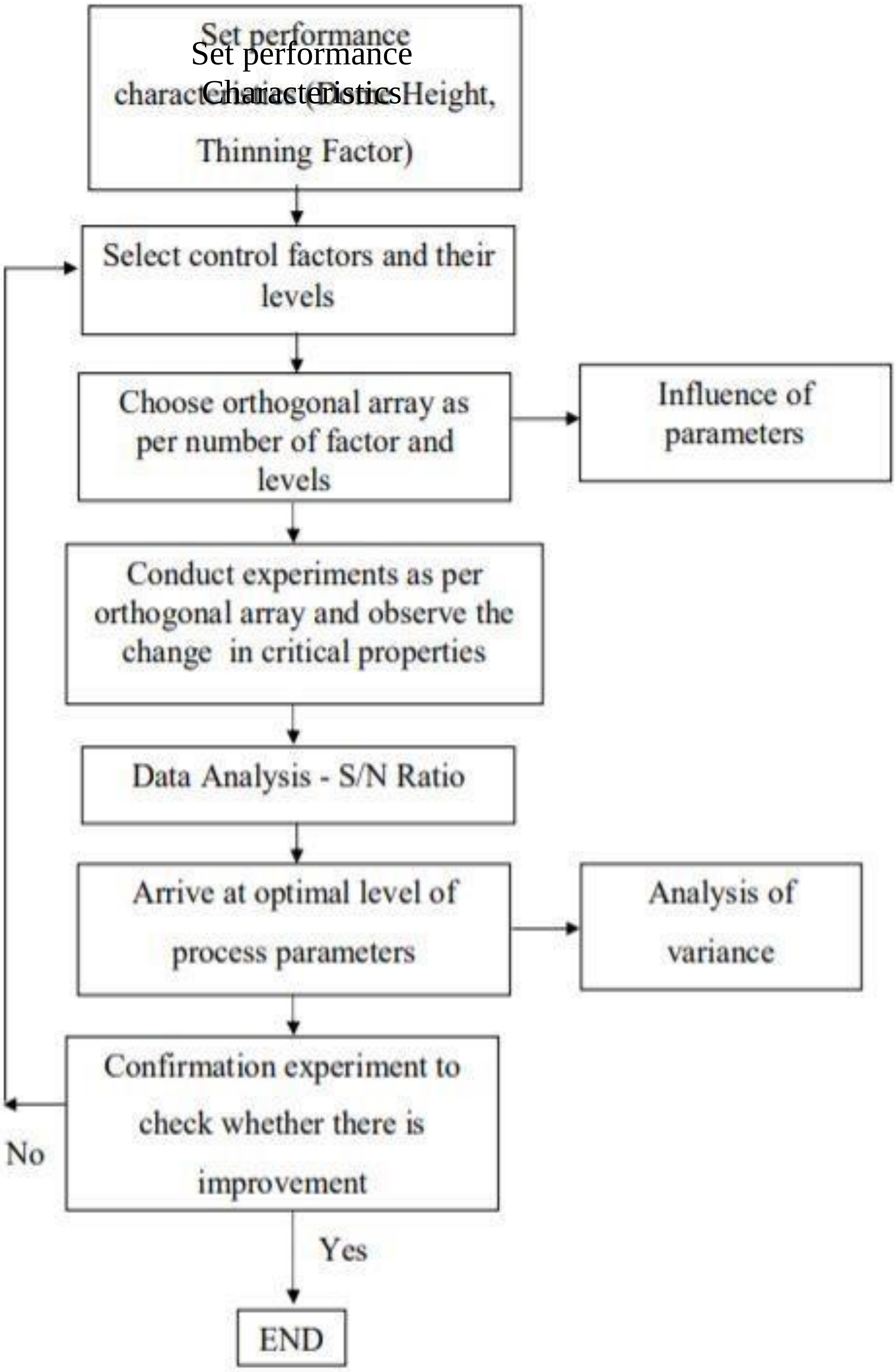


Fig 3.1 Taguchi analysis flow chart **3.3 SIGNAL TO NOISERATIO**

Signal to Noise ratio is a performance measure and it is the ratio of the mean(signal) to(noise). The S/N equation depends on the criterion for the quality characteristic to be optimized.The standard S/N ratios in practice are Bigger-the-better quality characteristic (strength, yield, surface finish), Smaller-the-better quality characteristic (contamination, surface roughness in turning), and Nominal-the-better quality characteristic (dimension).

Table 3.1 Taguchi's L_9 Standard Orthogonal Array

Trial	**Level 1**	**Level 2**	**Level 3**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	1
5	2	2	2
6	2	3	3
7	3	1	1
8	3	2	2
9	3	3	3

The breaking load belongs to higher-the-better quality characteristic and surface roughness belong to smaller the better characteristic .Loss function of the higher-the-better quality characteristic can be expressed as

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{ijk}^{2}}$$

And lower-the-better quality characteristic can be expressed as

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}^{2}$$

3.4MACHINE SPECIFICATION

The laser machine used for experimentation has the following specifications:

- Working Area :1500 x 3000mm / 6000 x 1500mm / 4000 x 2000mm / 6000 x 2000mm
- Laser Power :500 - 3000 W
- Accuracy :+/-0.03 mm
- Repeatability :+/-0.02 mm
- Ideal speed :100 m/min
- Max.Cutting speed :60 m/min
- Voltage :380 V
- Frequency :50/60 Hz

Fig 3.2 MLS-F20 CO2 Laser Cutting Machine

The experiments are carried out based on the Taguchi L9 orthogonal array with the above machine parameters. The process parameters for the experiments The responses of these parameters are discussed in the next chapter AND shown in the CHAPTER BELOW.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 MECHANICAL PROPERTY TESTING OF 5083 AL SPECIMEN:

Titanium Alloy provide the ability to machine in various machining. Laser drilling is a precious and easy machining process for complex shapes and hardness materials. To understand the mechanical behaviour of laser drilling for 5083AL, for testing standard ASTM test procedures are adopted.

Mechanical Properties	ASTM Standards
Tensile Strength (MPa)	D638
Tensile Modulus (MPa)	D638
Compressive strength (MPa)	D638
Flexural Strength (MPa)	D790
Flexural Modulus (MPa)	D790
Izod impact, notched, kJ/m^2	D256
Hardness (Rockwell, R scale)	D785

Table 4.1 ASTM Testing standards

4.1.1 HOLE CIRCULARITY MEASUREMENTS

The roughness measurements were carried according to IS: 3073-1967, RA-2006 at Metrology and Measurements lab, Panimalar Engineering College. Table 6.2 shows the 'Ra' values of 5083 Al samples. Table shows the results for surface roughness tests.

4.1. HOLE CIRCULARITY MEASUREMENTS

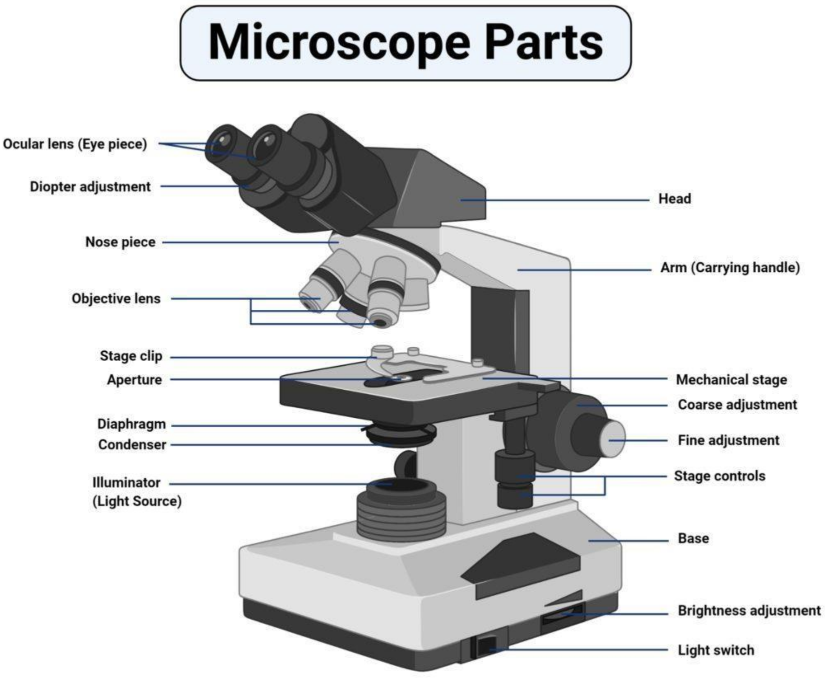


Figure: Parts of a microscope, Image Copyright © Sagar Aryal, www.microbenotes.com

Figure 3.1 microscope machine

The measurement of the response for the hole is entry circularity. The entry circularity for the entire set of the experiment is conducted by measuring the hole diameter in an interval of 30 degrees each along the circumference of the hole using a microscope image which is taken in a magnification of 100x using a scanning electron micro- scope and average the result using the equation1 as given in Fig..

$$Circularity(c) = \left(\frac{Dmin}{Dmax}\right)$$

Table no 4.3

Expt. No.	Power (W)	Frequency (KHz)	Speed (mm/s)	HOLE circularity
1	80	200	20	0.835
2	80	400	30	0.865
3	80	600	40	0.922
4	85	200	30	0.873
5	85	400	40	0.856
6	85	600	20	0.845
7	90	200	40	0.911
8	90	400	20	0.845
9	90	600	30	0.928

4.2 ANALYSIS OF DATA-TAGUCHI METHOD

Taguchi suggests two different routes to carry out the complete analysis. First, the standard approach, where the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal- to- noise ratio (S/N) for the same steps in the analysis. In the present investigation, the raw data analysis and S/N data analysis have been performed.

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method,
ANOVA, S/N ANOVA, plot of average response curves, interaction graphs etc. However, in the present investigation the following methods have been used.

- Plot of average and S/N response curves
- ANOVA for raw and S/N data Interaction graphs
- Residual graphs

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of parameter on the response. The change in the response characteristic with the change in levels of a parameter can easily be visualized from theses curves.
Typically, ANOVA for OA's are conducted in the same manner as other structured experiments. The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. A standard ANOVA can be conducted on S/N ratio which will identify the significant parameters (mean and variation). Interaction graphs are used to select the best combination of interactive parameters. Residual plots are used to check the accuracy.

4.2.1 PARAMETER CLASSIFICATION AND SELECTION OF OPTIMAL LEVELS

When the ANOVA on the raw data (identifies control parameters which affect average) and S/N data (identifies control parameters which affect variation) are completed, the control parameters may be put into four classes:

- Class I: Parameters which affect both average and variation
(Significant in both i.e. raw data ANOVA and S/N ANOVA)
- Class II: Parameters which affect variation only (Significant in S/N ANOVA only)
- Class III: Parameters which affect average only (Significant in raw data ANOVA only)
- Class IV: Parameters which affect nothing. (Not significant in both ANOVAs)

The parameters design strategy is to select the proper levels of class I and class II parameters to reduce variation and class III parameters to adjust the average to the target value. Class IV parameters may be set at the most economical levels since nothing is affected.

4.3 SINGLE OBJECTIVE OPTIMIZATION USING TAGUCHI ANALYSIS:

TAGUCHI is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the TAGUCHI function. The characteristics of a goal may be altered by adjusting the weight or importance. For several responses and factors, all goals get combined into one TAGUCHI function. For simultaneous optimization each response must have a low and high value assigned to each goal. The "Goal" field for responses must be one of five choices: "none", "maximum", "minimum", "target", or "in range". Factors will always be included in the optimization, at their design range by default, or as a maximum, minimum of target goal.

Table 4.4 Table for levels and parameters

Parameter/level	1	2	3
power	80	85	90
Frequency	20	30	40
Speed	200	400	600

TAGUCHI is used for conversion of the multi-response characteristics into single-response characteristics. Here, the single-responses such as Hardness TAGUCHI using DFA. It reflects the desirable ranges for each response *(di)* which are from zero to one. The steps for the Taguchi are given below.

Step 1: calculate the individual TAGUCHI index (di):

There are three forms of the TAGUCHI functions according to the response characteristics. In this study, ‘Larger the better’ characteristics are applied to determine the individual TAGUCHI values for UTS and microhardness (VHN), since both responses should be maximized. The weightage for UTS and VHN were considered as 0.5.

For Larger the better, the formula used for calculating the individual TAGUCHI index is given below.

$$S / N \text{ ratio } (\ ) = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}}\right)$$

For Larger the better, the formula used for calculating the individual TAGUCHI index is given below.

$$S / N \text{ ratio } (\ ) = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_{ij}^{2}\right)$$

The value ‘y j ’ is expected to be the larger the better. When ‘y j ’ exceeds a particular criterion value, which can be viewed as the requirement, the TAGUCHI value equals to 1; if ‘y j ’ is less than the particular criteria, which is unacceptable, the TAGUCHI value equals to 0.

Step 2: Determine the optimal parameter and its level combination:

The higher composite TAGUCHI value implies better product quality. Therefore, on the basis of the composite TAGUCHI (dG), the parameter effect and the optimum level for each controllable parameter are estimated.

Step 3: Perform ANOVA for identifying the significant Parameters:

Analysis of variance (ANOVA) establishes the relative significance of the parameters. The calculated total sum of square values is used to measure the relative influence of the parameters.

Table no 4.5 Table OF TAGUCHI

Expt. No.	**power**	**Frequency**	**speed**	**Hole circularity**	**S/N RATIO**
1	80	200	20	0.835	1.5663
2	80	400	30	0.865	1.2597
3	80	600	40	0.922	0.7054
4	85	200	30	0.873	1.1797
5	85	400	40	0.856	1.3505
6	85	600	20	0.845	1.4629
7	90	200	40	0.911	0.8096
8	90	400	20	0.845	1.4629
9	90	600	30	0.928	0.6490

Table 4.6 Table for Taguchi level and Ranking

	time on	**time off**	**discharge current**
Level1	-1.1771	-1.1852	-1.4973
Level2	-1.3310	-1.3577	-1.0295
Level3	-0.9738	-0.9391	-0.9552
Delta	0.3572	0.4186	0.5422
Rank	3	2	1

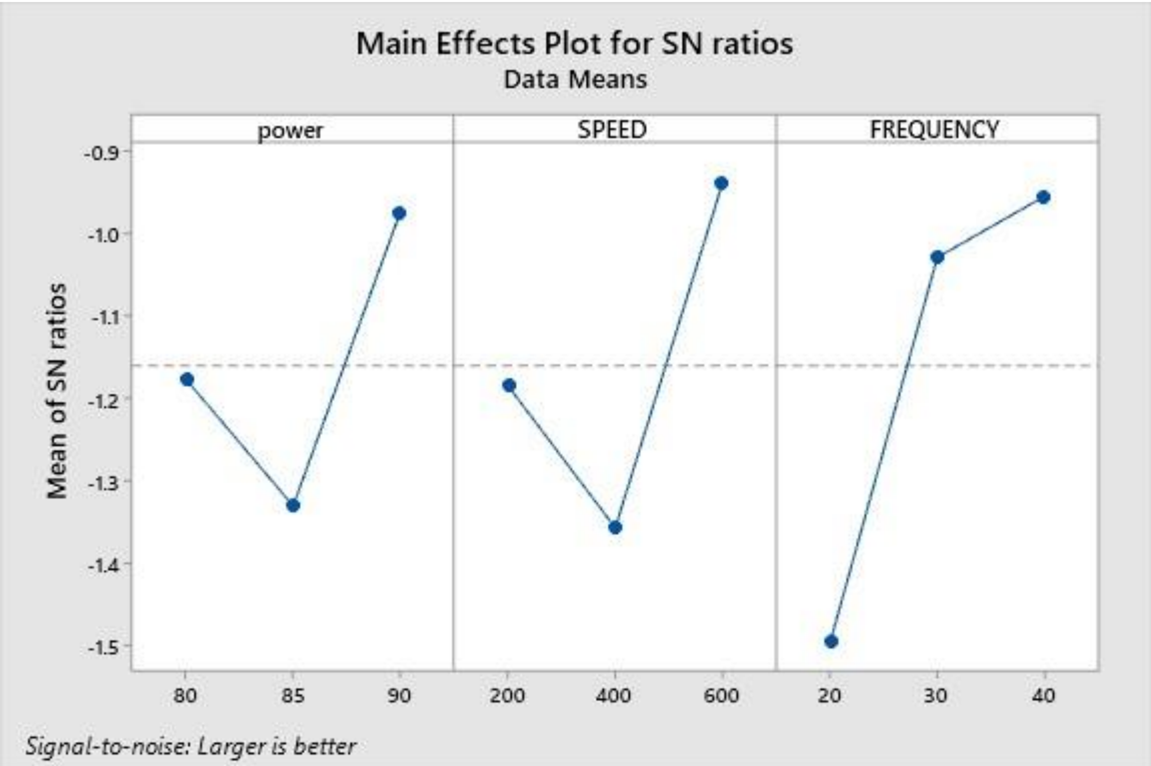


Fig 3.2 EFFECT OF PROCESS PARAEMETERS ON tAGUCHI

Therefore, the optimum characteristics are found to be A3-B3-C3.

4.3.1 ANOVA:

Param eters	DOF	Su m of Sq uar es	M ea n Sq ua re	F-Calcu lated	% Contri bution	Param eters
powe r	2	0.1 93	0. 09 6	**21.0 01**	***19.54 0***	**powe r**
frequ ency	2	0.2 66	0. 13 3	**28.9 55**	***26.94 1***	**frequ ency**
spee d	2	0.5 18	0. 25 9	**56.5 21**	***52.58 9***	**spee d**
Error	2	0.0 09	0. 00 5		***0.930***	Error
Total	8	0.9 86			***100.0 00***	Total

Analysis of variance (ANOVA) is an analysis tool used in statistics that splits an observed aggregate variability found inside a data set into two parts: systematic factors and random factors. The systematic factors have a statistical influence on the given data set, while the random factors do not. Analysts use the ANOVA test to determine the influence that independent variables have on the dependent variable in a regression study. In order to study the significance of the process variables towards dilution, ANOVA was performed. It was found that the layer thickness is a nonsignificant process parameter for dilution. The below table shows the significance of the parameters.

Table 4.7 ANOVA

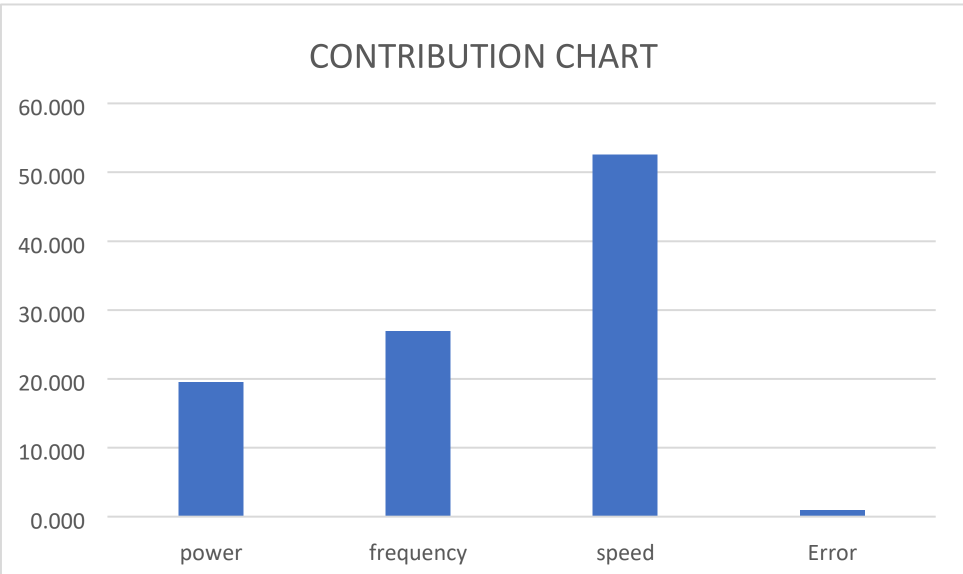


Fig 3.3 CONTRIBUTION CHART OF PARAMETERS BASED ON ANOVA.
Where, 1- Pattern, 2- LT, 3- Shell count

3.2 CONFIRMATION EXPERIMENT:

The confirmation experiment is a final step in verifying the conclusions from the previous round of experimentation. The optimum conditions are set for the significant parameters (the insignificant parameters are set at economic levels) and a selected number of tests are run under specified conditions. The average of the confirmation experiment results is compared with the anticipated average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended to verify the experimental conclusion. After the optimal level of process parameters is found, the final step is to predict and confirm the improvement of the performance characteristics using those values. The predicted composite TAGUCHI can be calculated using

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{n} (\bar{\gamma}_j - \gamma_m)$$

Where,

- *γm* is the total mean value of the composite TAGUCHI,
- $\bar{\gamma}$ *j* is the mean of the composite TAGUCHI at optimum level,
- n is the number of process parameters that significantly affects the singleple performance characteristics.

Considering the individual responses, the optimum tensile strength and Vickers hardness number was predicted using

$$T_{\text{predicted}} = T_m + \sum_{i=1}^{n} (T_0 - T_m)$$

Where,

- *Tm* is the mean response.

- $T0$ is the mean response at optimal level.
- n is the number of process parameters that affect the quality characteristics.

Table 4.8 Confirmation test and the final composite desirability

Process parameter	**Input process parameter**	**Output process parameter**	
Setting value	A3-B3-C1	Predicted A3-B3-C3	Experimental A3-B3-C3
Micro Hardness (VHN)	0.928	-	0.962

CHAPTER 5

PROJECT PHOTO

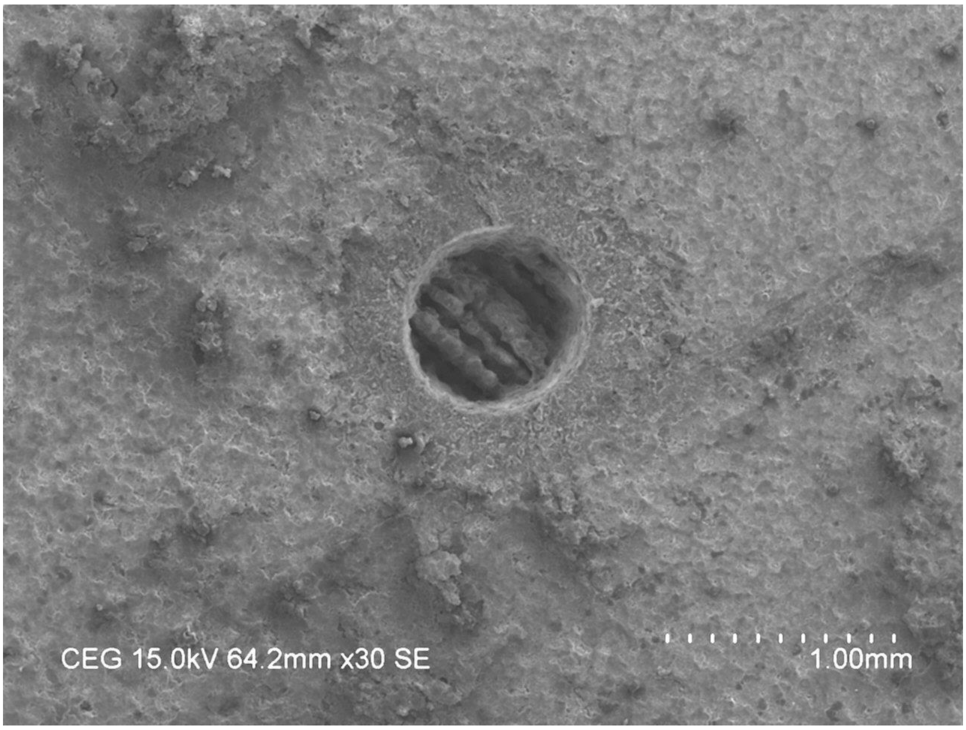


Fig 5.1 Scanning electron microscope

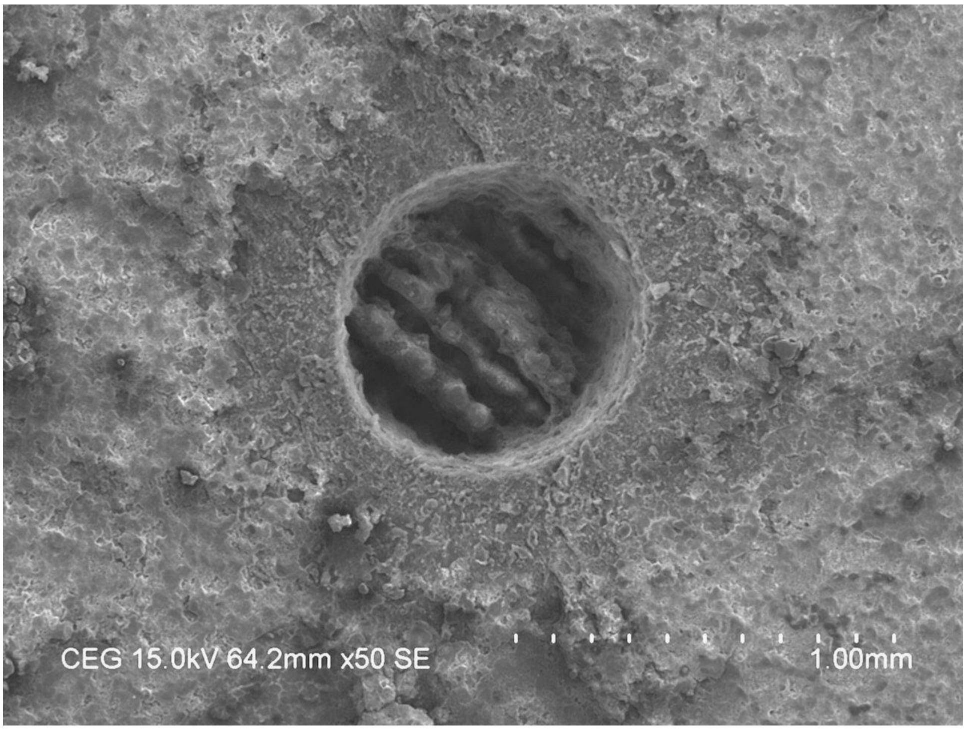


Fig 5.2 Scanning electron microscope

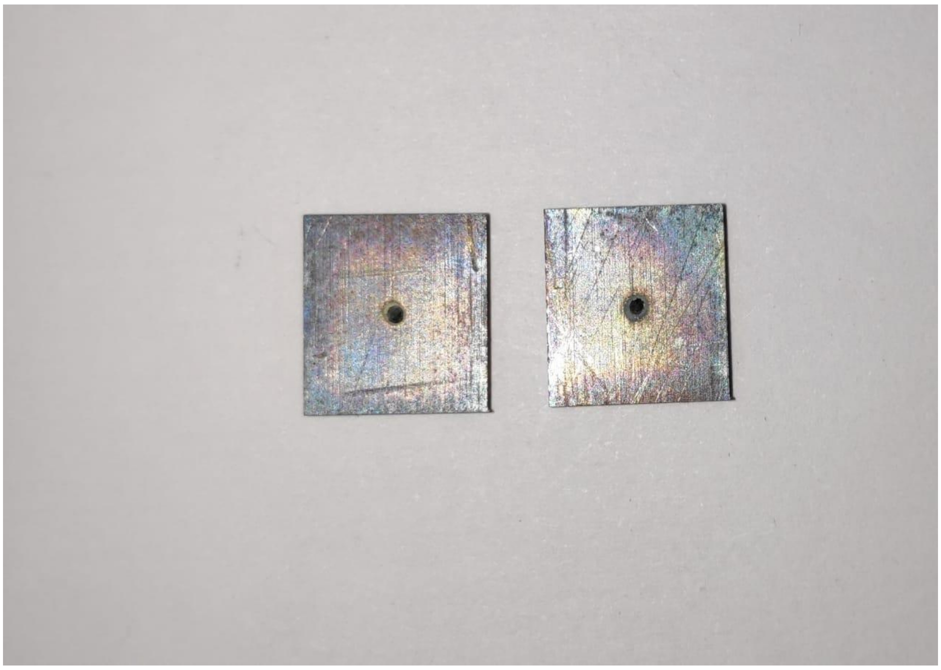


Fig 5.3 sample works

CHAPTER 5

CONCLUSION, APPLICATION AND SCOPE OF FUTURE WORK

5.1 CONCLUSIONS OF THIS RESEARCH:

Based on the results obtained from the present investigation after conducting the Hole circularity tests on Ti6Al4V alloy in Laser drilling.

- The most optimal parameters For Laser drilling obtained as A3-B3-C3
- The most significant parameter is the Speed followed by the Frequency at 95 % confidence level. The Power of the specimen is a relatively less

significant parameter that affects the output based on the applied machine parameters in this research.

- The parameter that has the highest influence on the output product is found to be frequency (contribution= 52.589 %). The parameter that has a moderate level of influence is speed (contribution = 26.9 %). Meanwhile, power is the parameter that is found to be the least influential (Contribution = 15.66 %).

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