CRANFIELD UNIVERSITY

SHOAIB SARFRAZ

INVESTIGATION OF PRODUCTIVITY, ENERGY EFFICIENCY, QUALITY AND COST FOR LASER DRILLING

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING

PhD
Academic Year: 2019 - 2020

Supervisor: Prof. Essam Shehab
Associate Supervisors: Prof. Konstantinos Salonitis and
Dr. Wojciech Suder
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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Laser drilling is a high speed, non-contact advanced machining process and has proven to be an important industrial process for producing cooling holes in various aeroengine components; in particular high-pressure turbine blades, combustor liners and nozzle guide vanes. However, an increase in the number of cooling holes demands the need for effective utilisation of laser drilling process capability. Material removal rate (MRR), specific energy consumption (SEC), hole taper and the drilling cost are the basic performance indicators to meet this goal. Hence, this research aims to examine the laser drilling process in terms of the mentioned performance measures.

Taking into account the significance of material removal quantity, energy efficiency, product quality and manufacturing cost, this study is performed in the form of an experimental investigation for three laser drilling processes, namely, single-pulse drilling, percussion and trepanning. Two different laser drilling setups were prepared to produce holes in Inconel 718 superalloy sheets using flashlamp-pumped Nd:YAG laser and Quasi-CW fibre laser.

This research contributes to an evaluation of the influence of laser drilling process parameters on the MRR, SEC, hole quality and drilling cost. Moreover, the performance of laser drilling methods has been compared in relation to the selected performance measures. To further understand the significance of laser sources, the performance of laser drilling was compared for the mentioned drilling setups. This research also introduced a detailed cost analysis to explore the economic implications of the laser drilling process. In addition, optimal drilling conditions were determined aiming to maximise the MRR and minimise hole taper and drilling cost.

Keywords:

Laser drilling, Single-pulse, Percussion, Trepanning, Material removal rate (MRR), Specific energy consumption (SEC), Hole taper, Cost estimation, Optimisation.

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LIST OF PUBLICATIONS

Journal Papers

1. Sarfraz, S., Shehab, E., Salonitis, K. and Suder, W. (2019) “Experimental Investigation of Productivity, Specific Energy Consumption, and Hole Quality in Single-Pulse, Percussion, and Trepanning Drilling of IN 718 Superalloy”, *Energies,* 12 (24): 4610. doi:10.3390/en12244610.
2. Sarfraz, S., Shehab, E., Salonitis, K., Suder, W., Niamat, M. and Jamil, M. (2020) “An Integrated Analysis of Productivity, Hole Quality and Cost Estimation of Single-Pulse Laser Drilling Process”, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* doi:10.1177/0954405420968161.

Conference Papers

1. Sarfraz, S., Shehab, E. and Salonitis, K. (2017) “A Review of Technical Challenges of Laser Drilling Manufacturing Process”, *Proceedings of the 15th International Conference on Manufacturing Research (ICMR 2017)*, 5th to 7th September, 2017, University of Greenwich, UK, pp. 51-56. doi:10.3233/978-1-61499-792-4-51.
2. Sarfraz, S., Shehab, E., Salonitis, K., Suder, W., and Sajid, M. (2018) “Towards Cost Modelling for Laser Drilling Process”, *Proceedings of the 25th International Conference on Transdisciplinary Engineering (TE2018)*, 3rd to 6th July, 2018, University of Modena and Reggio Emilia, Italy, pp. 611-618. doi:10.3233/978-1-61499-898-3-611.
3. Sarfraz, S., Shehab, E., Salonitis, K., Suder, W. and Zahoor, S. (2018) “Evaluation of Productivity and Operating Cost of Laser Drilling Process – A Case Study”, *Proceedings of the 16th International Conference on Manufacturing Research (ICMR 2018)*, 11th to 13th September, 2018, University of Skövde, Sweden, pp. 9-14. doi:10.3233/978-1-61499-902-7-9.

4. Sarfraz, S., Shehab, E., Salonitis, K., Suder, W., Jamil, M. and Khan, A.M. (2019) “An Experimental Investigation of Productivity, Cost and Quality for Single-Pulse Laser Drilling Process”, *Proceedings of the 17th International Conference on Manufacturing Research (ICMR 2019),* 10th to 12th September, 2019, Queen’s University Belfast, UK, pp. 334-339. doi:10.3233/ATDE190059.

Book Chapter

Sarfraz, S., Shehab, E., Salonitis, K. and Suder, W. (2020) “Laser Drilling of Superalloys and Composites”, In *Additive and Subtractive Manufacturing of Composites.* Springer Book series "Advanced Manufacturing Technologies”, (Accepted for publication).

Non-Refereed Paper

Sarfraz, S., Shehab, E., Salonitis, K., Suder, W., Khan, A.M. and Jamil, M. (2018) “Experimental Evaluation of Productivity and Hole Quality during Laser Drilling of Inconel 718 Superalloy”, *Proceedings of the 19th International Symposium on Laser Precision Microfabrication (LPM 2018)*, 25th to 28th June, 2018, Heriot-Watt University, Edinburgh, UK.

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
ANOVA	Analysis of Variance
df	Degree of Freedom
ECM	Electrochemical Machining
EDM	Electrodischarge Machining
GRA	Grey Relational Analysis
GRC	Grey Relational Coefficients
GRG	Grey Relational Grade
HAZ	Heat Affected Zone
HT	Hole Taper
MBD	Model-Based Definition
MRR	Material Removal Rate
MRV	Material Removal Volume
MS	Mean Square
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
NOP	Number of Pulses
NSGA	Non-dominated Sorting Genetic Algorithm
PSO	Particle Swarm Optimisation
QCW	Quasi Continuous Wave
RLT	Recast Layer Thickness
RSM	Response Surface Methodology
SEC	Specific Energy Consumption
SP	Single-Pulse
SS	Sum of Squares
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution

1 INTRODUCTION

1.1 Research Background

Machining is a fundamental method to transform raw material into a finished product. Machining processes of various types are involved in crafting the solid structure into intricate parts of desired geometry. Despite the usage of advanced conventional machining technologies, the manufacturing of complex parts with high accuracy has remained a challenge for the manufacturing industry. Certain complex parts such as gas turbine or aero-engine components need highly accurate and miniature-sized machining which can be of microsize. For instance, holes in nozzle guide vanes, turbine blades and combustor linings are mainly in milli to microsize; therefore, the accomplishment of these complex holes warrants the selection of a highly accurate drilling process (Yilbas, 2013).

Laser drilling is a high power, high speed and non-contact machining process which is specified for the drilling of holes of various shapes and sizes in almost any material, such as composites, metals and non-metals (Sarfraz et al., 2017). This process has established its applications in areas where conventional machining processes are restricted due to the problems of thermal damage, tool deformation or inaccessibility to the workpiece (Meijer, 2004; Dubey and Yadava, 2008a, 2008b; Schulz et al., 2013). On the other hand, the high capital cost of laser drilling equipment (Yeo et al., 1994), low energy efficiency (Fysikopoulos et al., 2012) and associated inherent defects (Gautam and Pandey, 2018) demand a need for effective utilisation of laser drilling process capability.

The laser drilling process is complex as it involves different methods and controlled parameters. Moreover, different types of laser sources are available to perform the drilling operation. All these aspects affect the performance of the laser drilling process in terms of quality, productivity and efficiency. This is essential to understand for the user. Recently, Sarfraz et al. (2019a) reported that the process parameters affecting the performance of the laser drilling process also have a substantial impact on cost which needs to be investigated as well.

In the light of the aforementioned limitations, previous research studies focused mainly on the product quality of laser drilling and provided limited documented knowledge on productivity and process efficiency. Also, there is no research work available discussing the cost of the laser drilling process. Therefore, this research aims at investigating the productivity, quality, efficiency and cost of the laser drilling process taking into account laser drilling methods and laser sources together. It is expected that the research results will serve as a guide for practitioners to select an appropriate laser drilling method and laser source with suitable process parameters for required productivity, efficiency, quality and cost.

1.2 Research Motivation

Growing market competition has forced manufacturing industries to extract maximum gain from their investment by improving productivity, quality and efficiency while persistently reducing manufacturing costs. Figure 1-1 illustrates an overview of the production fundamentals of a typical manufacturing industry. It encourages looking into opportunities to deliver a product that can satisfy customer needs with reduced manufacturing cost and efficient utilisation of resources.

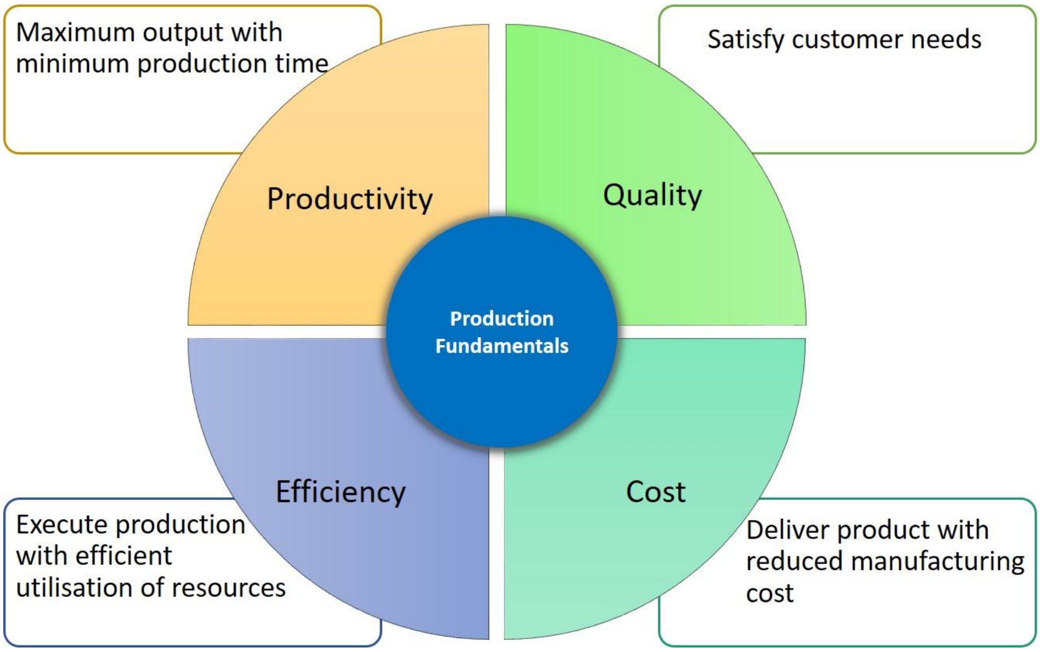


Figure 1-1 Fundamentals of production

Laser drilling is extensively used in aerospace industries for the machining of high strength and high-temperature resistant metals and alloys. This method has been proven as an important industrial process to produce numerous holes of various sizes (0.25 – 1.0 mm) in aeroengine components (Marimuthu et al., 2019b). These holes, usually known as cooling holes, provide the function of cooling for hot section components such as combustion chambers, turbine blades, afterburners and nozzle guide vanes. Advancements in aeroengine efficiency have resulted in the enhancement of exhaust gases and combustion temperature; this needs supplementary cooling of components to sustain such elevated temperatures. In the last few decades, an increase in the number of cooling holes in turbine design has been observed to improve the performance and efficiency of an aeroengine. For instance, 40,000 holes are drilled in the afterburner component of a gas turbine engine (McNally et al., 2004). For a typical modern engine, the figure of cooling holes is expected to reach 150,000 in the near future (Antar et al., 2016). This highlights a need to improve productivity and at the same time deliver high product quality with a cost-effective solution, which is an important concern for manufacturing industries targeting to become successful in the current competitive scenario. Therefore, this research intends to explore the implications of the laser drilling process in terms of productivity, efficiency, quality and cost.

1.3 Research Scope

This research focused on evaluating and comparing the performance of laser drilling methods and laser sources in relation to productivity, efficiency and quality. Cost estimation of the laser drilling process has also been performed and the relationship between the process parameters and drilling cost have been examined. This study involved the experimental investigation of three different laser drilling methods, namely single-pulse drilling, percussion and trepanning using Inconel 718 as workpiece material. Two types of laser sources were considered for this research i.e. flashlamp-pumped Nd:YAG (neodymium-doped yttrium aluminium garnet) laser and Quasi-CW (quasi-continuous wave) fibre laser. Selection of the workpiece material and laser sources was based on their extensive application in the aerospace industry. Productivity was defined by the material removal rate which specifies the amount of material removed per unit time; energy efficiency was calculated by specific energy consumption which determines the energy consumed to remove a unit volume of material; for quality evaluation, hole taper was selected which indicates the difference between the entry and exit hole diameters for a specific plate thickness.

The research outcome will benefit both industry and academia in understanding different aspects of laser drilling. The relationships studied between performance measures and process parameters will help practitioners to select suitable process parameters for desired hole quality, productivity, efficiency and manufacturing cost. Furthermore, the cost analysis can assist manufacturing companies by providing complete cost information related to the laser drilling process and drive them a step forward in the cost-competition race against competitors.

1.4 Research Aim and Objectives

This research aims to determine the optimal laser drilling conditions with taken into consideration the productivity, energy efficiency, quality and cost. The investigation comprises experimental studies of three laser drilling methods (single-pulse, percussion and trepanning) considering flashlamp-pumped Nd:YAG laser and Quasi-CW fibre laser. It will permit the laser systems operators to improve the selection of drilling parameters while ensuring the productivity, energy efficiency, quality and cost requirements.

The main objectives of this study are to:

1. Identify key process parameters and their influence on productivity, energy efficiency and hole quality.
2. Demonstrate the capability of laser drilling methods in terms of productivity, energy efficiency and hole quality.
3. Provide the insight of the process characteristics of laser drilling while using flashlamp-pumped Nd:YAG laser and Quasi-CW fibre laser.

4. Determine the impact of process parameters on drilling cost and identify major cost elements of the laser drilling process.
5. Obtain optimal drilling conditions with taken into consideration productivity, quality and cost.

1.5 Thesis Organisation

This research work has been structured into eight chapters as shown in Figure 1-2. The contents of these chapters are given below:

Chapter 1 covers the research introduction which includes research background, motivation and scope. This chapter also clearly mentions the aim and objectives of this research.

Chapter 2 outlines a critical literature review which helps to distinguish different laser drilling methods, process parameters, performance measures, laser sources and cost estimation techniques. An extensive literature review has been performed to summarise published research work in the field of laser drilling and cost estimation. The research gaps are also identified.

Chapter 3 presents the research methodology adopted to achieve the research aim and objectives. The research methodology consists of three phases: these are comprehending the context, experimental setup preparation and experimentation, data analysis and cost estimation.

The selection of material used for experimentation is reported in Chapter 4. The details of the experimental setup and the procedure used for the measurement of responses are also discussed.

In Chapter 5, the influence of process parameters on material removal rate, specific energy consumption and hole taper results are examined and discussed. Moreover, the performance of single-pulse, percussion and trepanning drilling is compared.

Chapter 6 presents and discusses the results obtained from a flashlamp-pumped Nd:YAG laser in comparison to Quasi-CW fibre laser. The advantages and limitations of Quasi-CW fibre laser are also described.

Chapter 7 provides a detailed cost analysis depicting potential cost drivers and major cost elements involved in laser drilling. An integrated analysis of productivity, hole quality and drilling cost has also been performed to identify optimal drilling conditions.

Finally, in Chapter 8 the research findings are highlighted along with the conclusions. This chapter explains the research contribution to knowledge. Furthermore, research limitations and recommendations for future work have been pointed out.

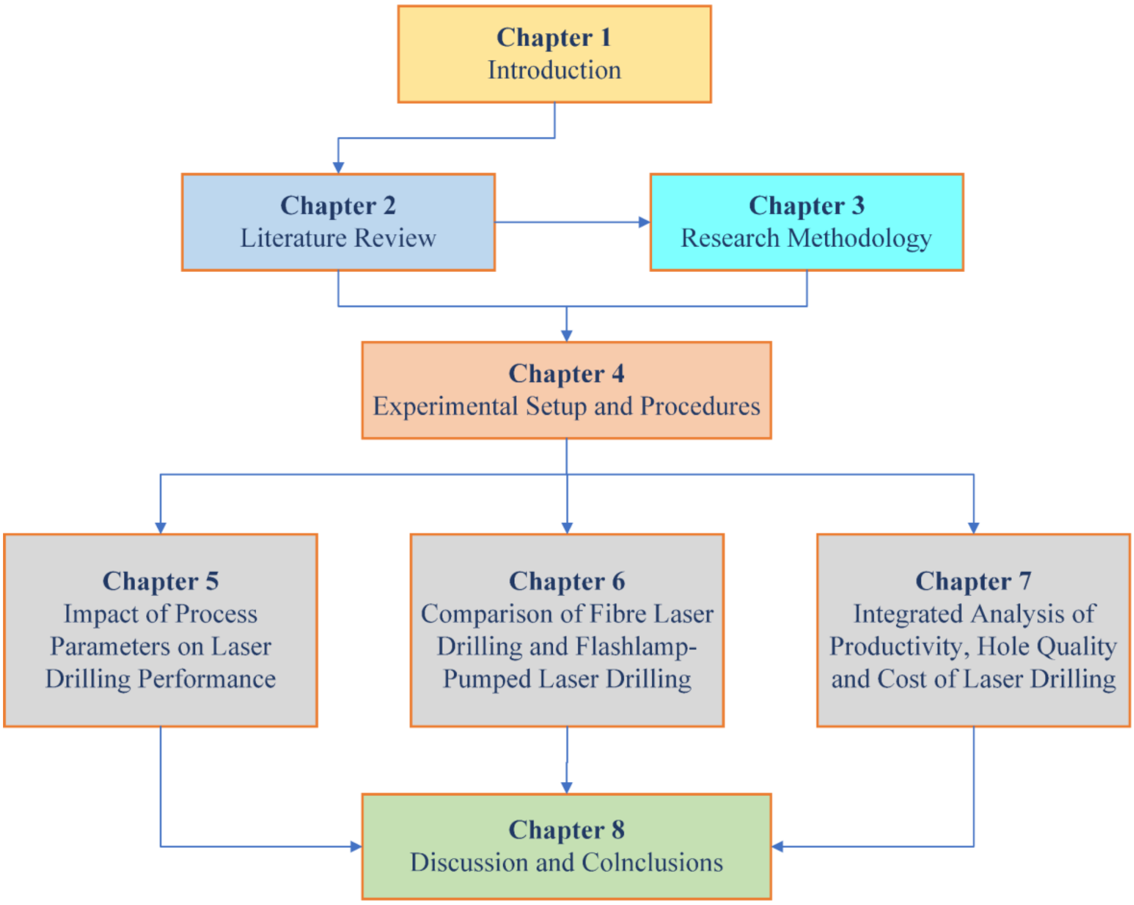


Figure 1-2 Thesis structure

2 LITERATURE REVIEW

2.1 Introduction

One of the primary objectives of this research is to develop an understanding of the research context and find out the existing research gap. In view of this objective, a comprehensive literature review is conducted. The outline of this chapter is provided in Figure 2-1.

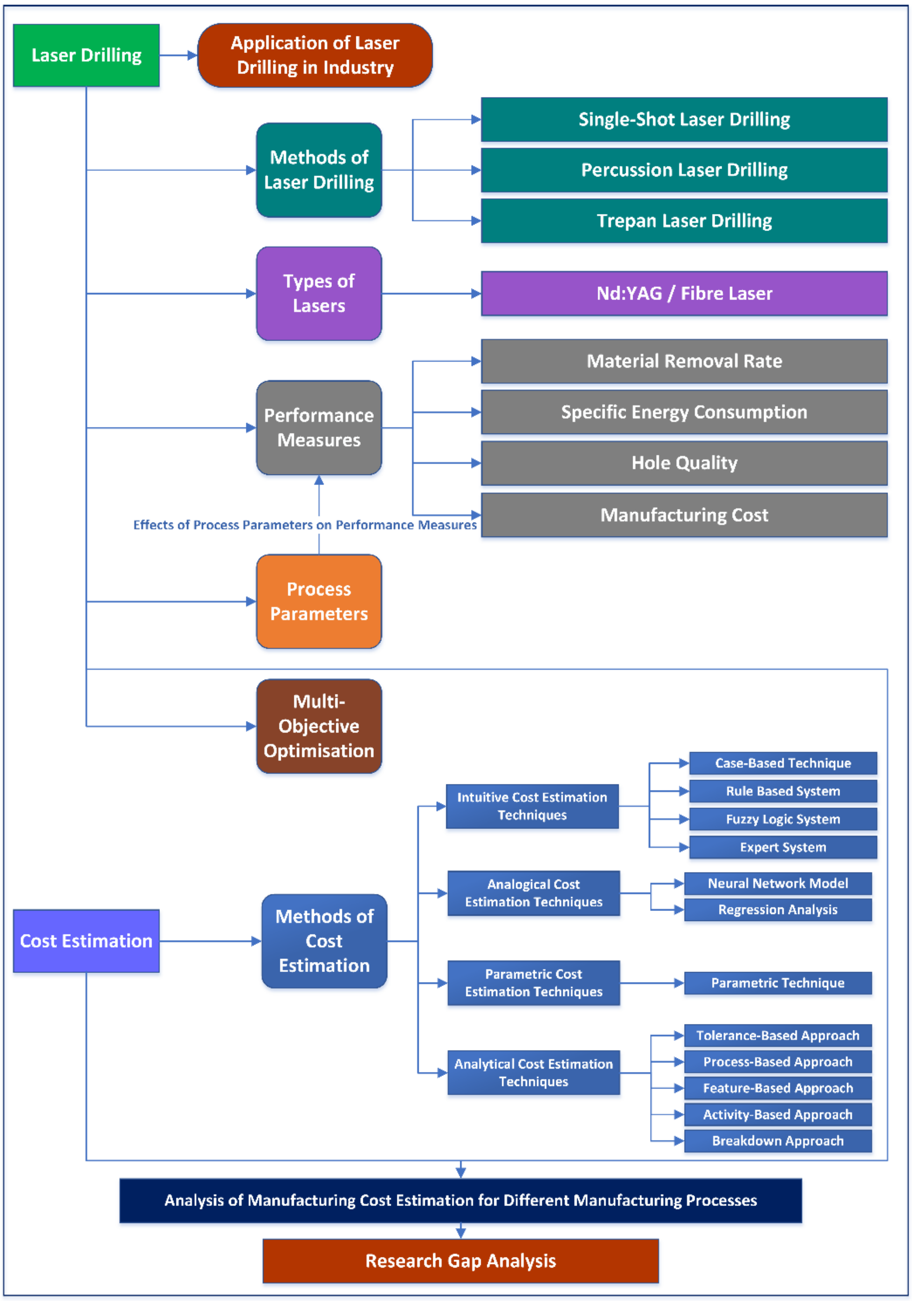


Figure 2-1 Layout of the Literature Review

Firstly, background knowledge about laser drilling, its methods, process parameters, laser types, and performance measures along with cost estimation and its methods have been provided. Secondly, the effects of laser drilling process parameters on the selected performance measures have been introduced. Thirdly, analysis of manufacturing cost estimation for different manufacturing processes has been presented. Finally, knowledge gaps identified in the literature are specified.

2.2 Drilling in the Aerospace Industry

Advancements in aeroengine efficiency are associated with the enhancement of exhaust gases and combustion temperatures in aircraft gas turbines (Mazumder, 2010). Although superalloys can sustain these elevated temperatures, the supplementary cooling of components is necessary for effective engine performance. This can be achieved through drilling multiple cooling holes in hot-section components. Hole dimensions as well as the number of holes vary in different components, as shown in Table 2-1.

Table 2-1 Hole dimensions of gas turbine components (McNally et al., 2004)

Components	**Wall thickness (mm)**	**Diameter (mm)**	**Angle to surface (deg)**	**Number of holes**
Nozzle guide vane	1.0 – 4.0	0.3 – 1.0	15	25 – 200
Turbine blade	1.0 – 3.0	0.3 – 0.5	15	25 – 200
Baseplate	1.0	0.5 – 0.7	30 – 90	10000
Afterburner	2.0 – 2.5	0.4	90	40000
Cooling ring	4.0	0.78 – 0.84	79	4200
Seal ring	1.5	0.95 – 1.05	50	180

Different methods are available to drill these holes such as electrochemical machining (ECM), electrodischarge machining (EDM) and laser drilling. The latter method has an advantage over ECM and EDM because of the following reasons (Yeo et al., 1994; Meijer, 2004; Dubey and Yadava, 2008a, 2008b; Majumdar and Manna, 2011):

i. There is no direct contact with the material surface and therefore no tool wear or breakage is involved.
ii. Proper design of the motion-control system and beam delivery facility enables the achievement of high precision and repeatability.
iii. The laser beam can be focused precisely on the defined area, which allows drilling of holes of various shapes and sizes.
iv. It is easy to program and automate the laser drilling process.
v. A wide range of materials can be operated including composites, plastics, silicon, rubber or metals.
vi. The process duration is shorter as compared to EDM and ECM techniques.
vii. Some of the laser machines are versatile and it is possible to perform multiple functions using the same laser such as welding or cutting.

However, there are some limitations of laser drilling which must be considered, which are provided below (Yeo et al., 1994; Steen and Mazumder, 2010; Fysikopoulos et al., 2012; Gautam and Pandey, 2018).

i. High capital cost is needed to buy a laser drilling setup.
ii. The energy efficiency of a laser-based process is low.
iii. Laser drilling is associated with some inherent defects, such as hole taper, circularity, recast layer thickness (RLT), heat affected zone (HAZ), surface roughness, spatter and microcracks.
iv. Appropriate laser safety precautions need to be implemented.
v. Optical setup needs regular maintenance.

Therefore, this research is focused on the laser drilling process taking into consideration productivity, cost, energy efficiency and quality aspects.

2.3 Laser Drilling

Laser drilling is a non-traditional machining process, which is widely used in aerospace industries for the machining of high strength and high-temperature resistant metals and alloys. This technique is preferable than the other manufacturing processes especially when drilling of aerospace components is considered (Rockstroh et al., 2002; Mazumder, 2010). It is extensively adopted for producing cooling holes for aerospace gas turbine components, in particular combustor liners, nozzle guide vanes and high-pressure turbine blades (Naeem, 2004).

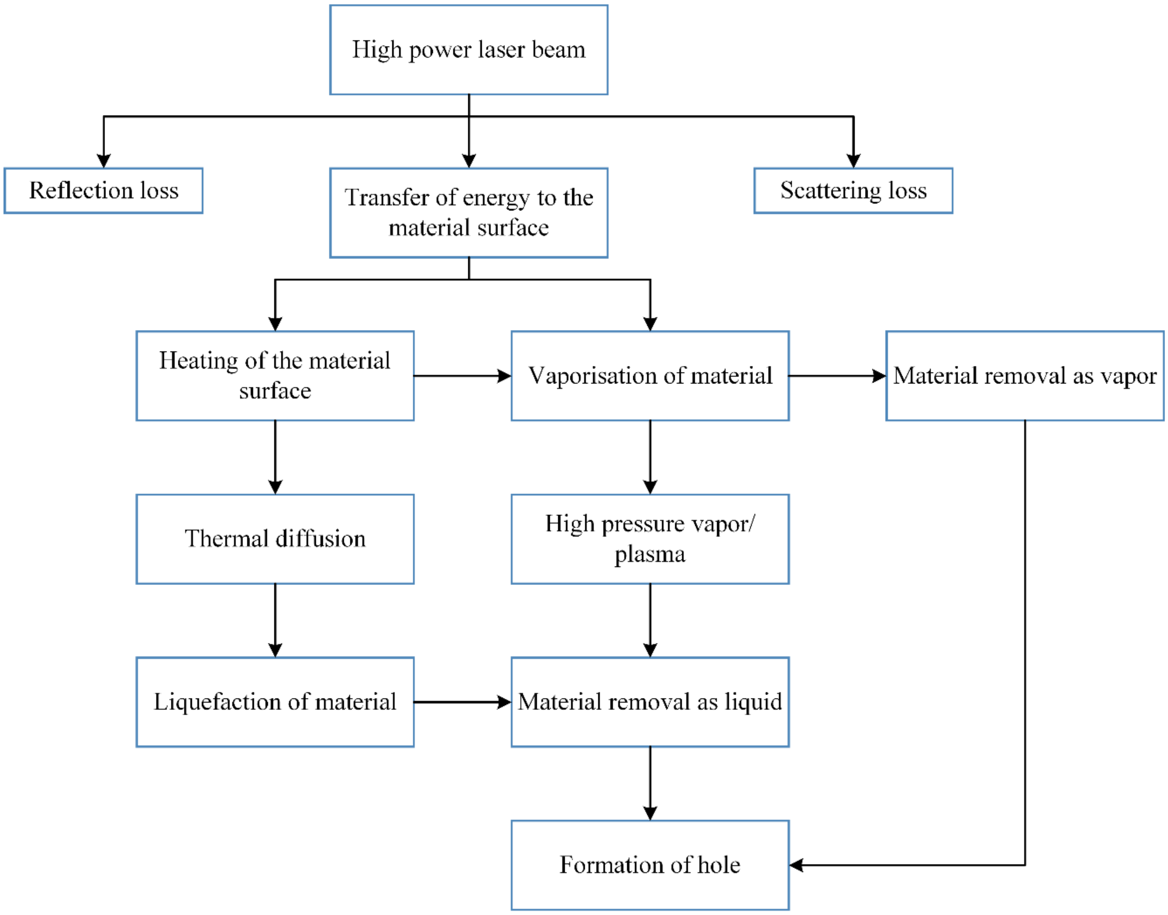


Figure 2-2 Hole formation physical mechanism in the laser drilling process (Mishra and Yadava, 2013a)

In the laser drilling process, a high power laser beam is directed on the surface of the workpiece, where the optical energy of the laser beam is thermalised and rapidly heats the base material. Some of the energy is lost due to scattering and reflection of the laser beam. Depending on laser intensity, the material is removed in both the liquid and/or vapour state. The process of hole formation during laser drilling is shown in Figure 2-2. Plasma and recoil pressure normally appear in laser drilling due to the high intensities used in the process which help in the expulsion of molten metal and result in the formation of a hole cavity (Figure 2-3 (a)) (Schneider et al., 2011). Assist gas is also used to remove the melt and/or vapours from the hole, as shown in Figure 2-3 (b). The assist gas pressure together with the plasma and recoil pressure control material ejection in the laser drilling process (Ng et al., 2006; Schaaf, 2010).

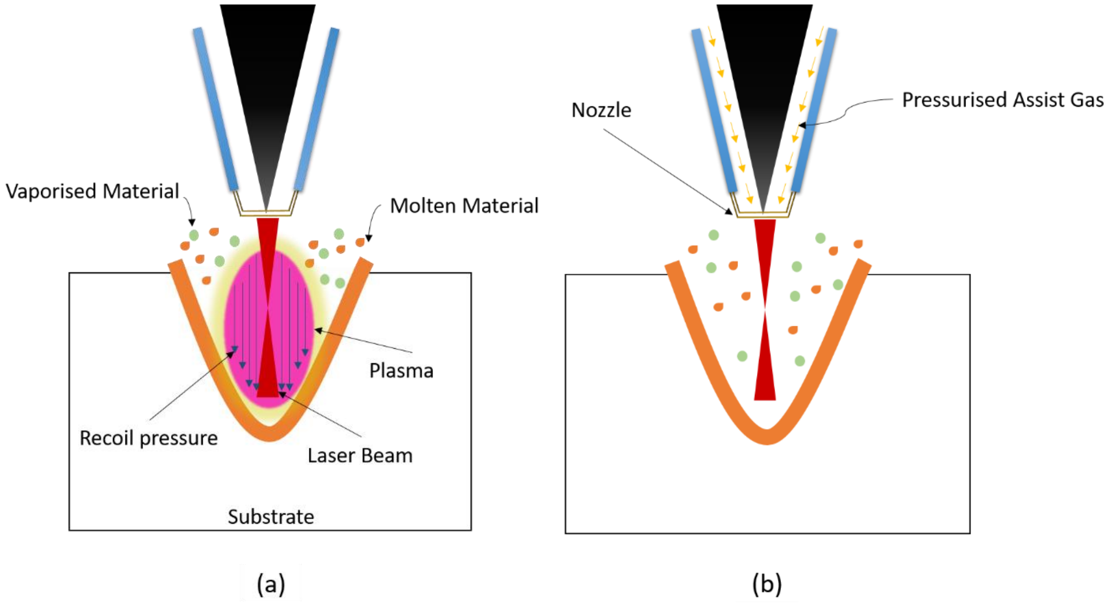


Figure 2-3 Schematic of the laser drilling process (a) vapour driven melt expulsion (b) assist gas melt expulsion

Different types of methods are available for the laser drilling operation, which include single-shot, percussion and trepan laser drilling. The following section outlines the description of these methods.

2.3.1 Methods of Laser Drilling

Laser drilling can be performed by using different methods. Depending on the required applications, a particular method is selected, as indicated in Figure 2-4.

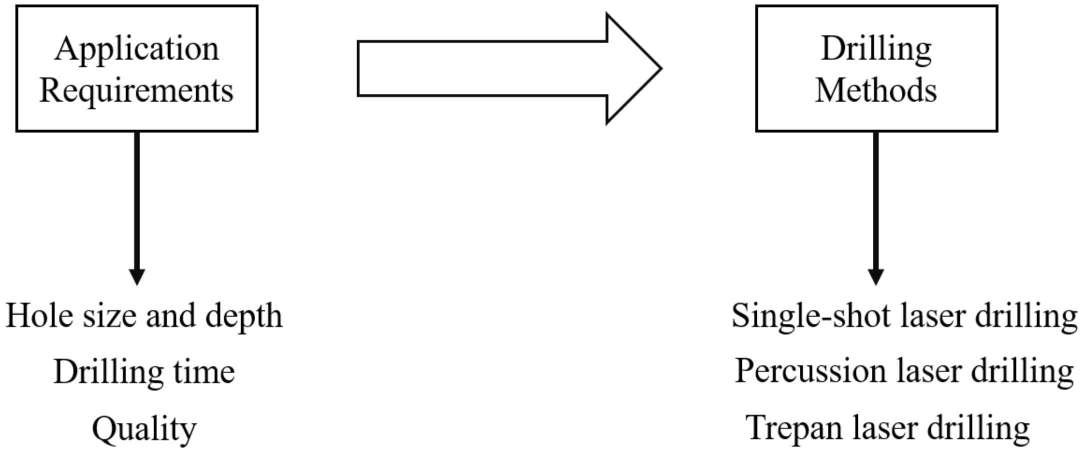


Figure 2-4 Laser drilling methods and the application requirements

2.3.1.1 Single-Shot Laser Drilling

Single-shot laser drilling, also known as single-pulse laser drilling, is a simple method of drilling holes. It involves the use of a single pulse with high energy to create a hole throughout the material thickness. The maximum thickness of material that can be drilled is limited by the pulse energy of the laser. The hole size and quality depend on material thickness and spatial as well as temporal profiles of the laser beam (Ready et al., 2001).

Using this method, a large number of holes can be produced in a relatively short amount of time which depend on laser frequency and the speed of the motion system. Single-pulse drilling is a better choice when productivity is the priority compared to quality (Sarfraz et al., 2019b). It is to be noted that above certain thickness very high pulse energy lasers are required which are expensive, therefore this method is suitable to produce holes in thin sheet materials

2.3.1.2 Percussion Laser Drilling

Percussion laser drilling involves a series of laser pulses that are fired at a particular spot of a material where each pulse generates a proportion of the hole. The productivity of this process is a function of pulse energy (edge depth per pulse) and pulse frequency.

Better hole quality can be attained with percussion drilling which depends on the laser beam quality and its intensity profile; on the other hand, this process is slower in comparison to single-pulse drilling and requires more energy to drill a hole (Sarfraz et al., 2019b).

2.3.1.3 Trepan Laser Drilling

Trepan laser drilling or trepanning is employed to drill large diameter holes. This process begins by piercing a central hole into the material in a similar way as percussion drilling; the laser beam is then moved in a spiral configuration using a motion control system to cut the required size hole. A significant benefit of this method is the delivery of good quality holes but it takes a longer time for drilling compared to other methods (Marimuthu et al., 2019a). Figure 2-5 shows hole quality and drilling time associated with various laser drilling methods. It is evident that trepanning is the best choice when hole quality is the priority. It is also important to mention that in trepanning, hole quality depends on the accuracy of the motion system (Misawa and Juodkazis, 2006).

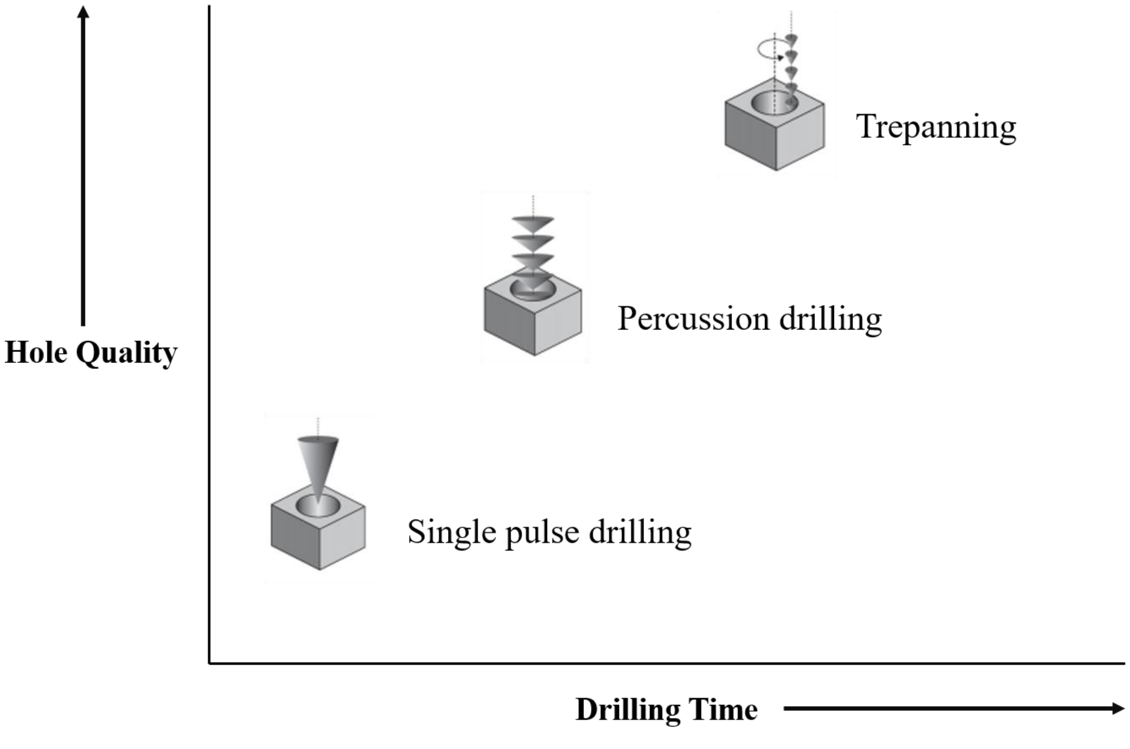


Figure 2-5 Correlation between hole quality and drilling time for different laser drilling methods, Source: (Dausinger, 2000)

2.3.2 Types of Lasers

Different types of lasers are used for laser drilling operations, such as carbon dioxide (CO_2), neodymium-doped yttrium aluminium garnet (Nd:YAG) and fibre lasers. The selection of an appropriate laser source is important as it affects the cost efficiency of the process (Dietrich et al., 2011). Nd:YAG and fibre lasers are the most commonly used laser sources for drilling in the aerospace industries (Marimuthu et al., 2016). A comparison between these two lasers is provided in Table 2-2. It is noted that the purchase cost of a fibre laser is higher than Nd:YAG but its running cost is much lower because of higher electrical efficiency and longer operating life. Nd:YAG laser does require periodic maintenance and service for alignment, cleaning and replacement of optics; on the other hand, fibre laser is maintenance free. It is important to mention that these laser sources have different beam quality, which ultimately affects hole quality and productivity (Kudesia et al., 2001; Naeem, 2010). Therefore, it is important to evaluate the laser source being used for the drilling process.

Table 2-2 Fibre laser and Nd:YAG laser comparison

	Fibre laser	**Nd:YAG laser**
Laser capital cost	higher	lower
Laser operating cost	lower	higher
Electrical efficiency	higher	lower
Operating life	longer	shorter
Maintenance	low	high

2.4 Performance Measures

High value manufacturing industries always try to improve productivity and process efficiency without affecting product quality and manufacturing cost. Taking into account the significance of these factors, material removal rate (MRR), specific energy consumption (SEC), hole taper and manufacturing cost were selected as performance measures for this study.

2.4.1 Material Removal Rate (MRR)

Material removal is a key feature of the machining process. Laser drilling process involves the removal of molten material to produce a hole cavity. Material removal rate indicates the volume of material removed per unit time, specified as mm^3/s. It also determines the productivity of the laser drilling process (Sarfraz et al., 2019b).

2.4.2 Specific Energy Consumption (SEC)

The energy efficiency of the laser drilling process is associated with the specific energy consumption i.e. the amount of energy consumed to remove a unit volume of material, usually measured in J/mm^3 (Franco et al., 2016). Energy consumption is also an important cost driver of the laser drilling process therefore, it is reasonable to achieve higher material removal with lower energy consumption.

2.4.3 Hole Quality

Hole quality is a primary concern of the aerospace industry. Several characteristics are used to judge the quality of laser drilled hole i.e. geometrical features (hole circularity, hole taper and surface roughness) and metallurgical features (microcracks, recast layer, spatter and heat affected zone) (Gautam and Pandey, 2018). A detail of these quality attributes is provided in the following sections.

2.4.3.1 Hole Circularity

Hole circularity defines the roundness of a hole. It varies with the deviation of hole diameter across the circumference of a drilled hole, as shown in Figure 2-6. It is always important to increase hole circularity, which can be calculated by the following relation (2-1). In single-pulse and percussion drilling, hole circularity depends on the roundness of the laser spot and laser beam intensity profile. Whereas in trepanning it is influenced by the accuracy of the motion system.

$$\mathrm{Hc} = \frac{D_{Min}}{D_{Max}} \tag{2-1}$$

where:

Hc = Hole circularity

D_{Min} = Minimum hole diameter

D_{Max} = Maximum hole diameter

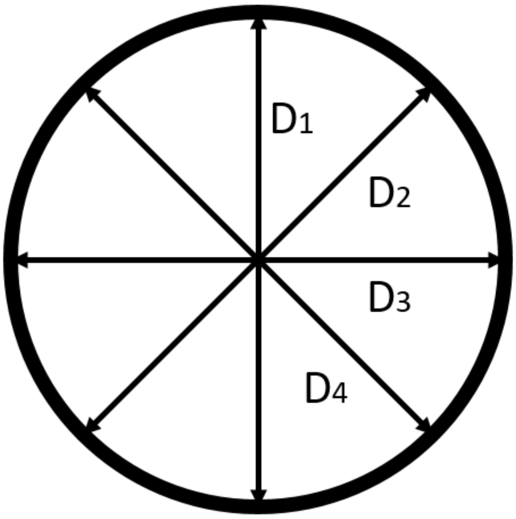


Figure 2-6 Measurement of hole circularity

2.4.3.2 Hole Taper

Taper formation is an inherent characteristic of laser material processing. It is an important attribute which significantly influences drilled hole quality (Bahar et al., 2016). Near-zero hole taper is always desirable specifically in aeroengine components where close tolerances and high quality are strict requirements (Bandyopadhyay et al., 2005).

Hole taper angle is the ratio of the difference between entry and exit hole diameters and plate thickness. It is usually measured in degrees and can be calculated by using the following equation (2-2).

$$\tan\theta = \frac{D_{ent} - D_{ex}}{2 \times t} \tag{2-2}$$

where:

θ = Taper angle

D_{ent} = Entrance hole diameter

D_{ex} = Exit hole diameter

t = Material thickness

Taper angle can be positive or negative depending upon entrance and exit hole diameters. Figure 2-7 shows the position of hole taper where the exit hole side is smaller than the entry side (positive hole taper). The major cause of this drawback is the diffraction of the laser beam inside the hole cavity (Hernandez-Castaneda et al., 2020).

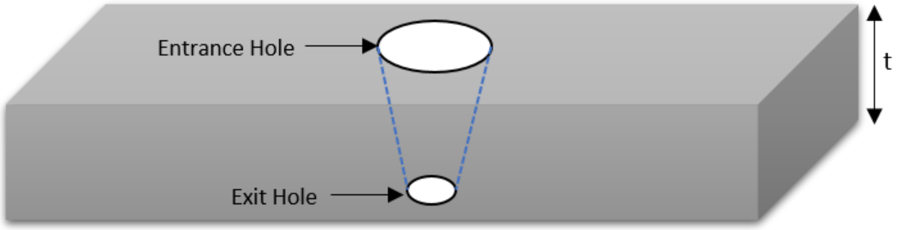


Figure 2-7 Schematic representation of a (positive) hole taper

2.4.3.3 Surface Roughness

Surface roughness is one of the important factors considered for quality evaluation of laser drilled parts (Solati et al., 2019). It refers to the surface irregularities formed on the inner side of the hole which is a product of the recast layer. It also reflects the dynamics of the liquid film prior to solidification and local reflectivity of the laser beam. It is usually measured as the arithmetic mean of absolute values of the vertical deviations of the actual surface from the ideal or nominal surface profile over the defined evaluation length, as presented in Figure 2-8. Small deviation presents a smooth surface and if the deviation is large the surface obtained is rough. A smooth and uniform surface is required to ensure smooth airflow and to avoid being turbulent specifically for the turbine blades (Gurav et al., 2019). Surface roughness is majorly influenced by laser intensity, laser power and trepan speed (Solati et al., 2019; Tewari et al., 2020).

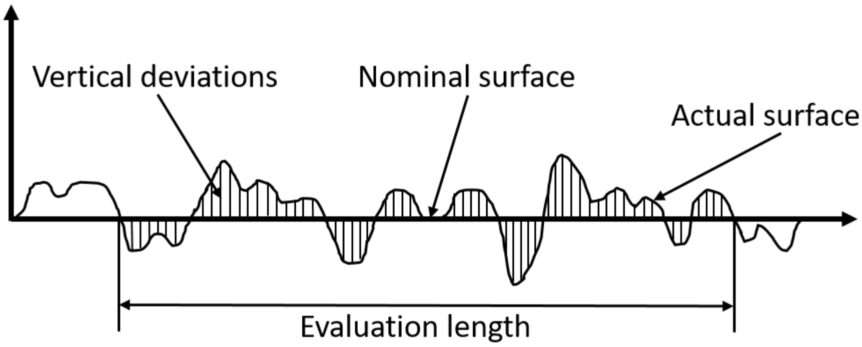


Figure 2-8 Average surface roughness (Ra) representation (Whitehouse, 2002)

2.4.3.4 Microcracks

Rapid drilling induces a high cooling rate in the material and in some cases it may lead to the formation of microcracks (Gautam and Pandey, 2018). Microcracks normally arise when drilling is performed in brittle or hard material. The propagation of these cracks in operation affects the fatigue life of components, leading to failure (Morar et al., 2018). Figure 2-9 indicates microcracks formed on the laser drilled surface. Microcracks can be avoided by minimising thermal input into the material.

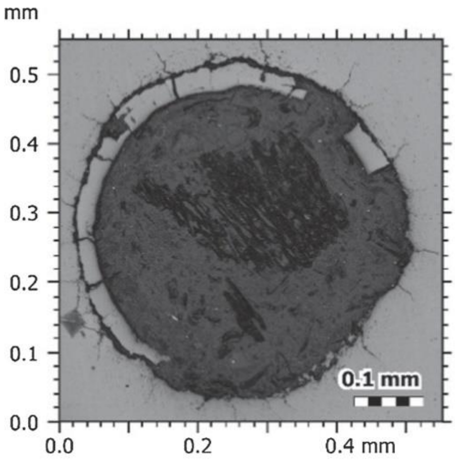


Figure 2-9 Microcracks formation around the drilled hole (0.5 mm thick yttria-stabilized zirconia) (Feng and Shen, 2019)

2.4.3.5 Recast Layer

During the laser drilling operation, some of the melted material is not removed appropriately and is re-solidified along the walls of the hole, which is known as a recast layer (Gautam and Pandey, 2018). This layer has contrasting properties compared to the parent material. Sometimes, microcracks are also formed in the recast layer which adversely affects the component's integrity and its lifespan (Morar et al., 2018). Therefore, recast layer formation must be avoided. Figure 2-10 shows the recast layer and associated microcracks in a trepan drilled hole. For a given material, recast layer depends on laser beam intensity. The higher the laser beam intensity, the more efficient is the material removal which ultimately reduces the chances of recast layer formation.

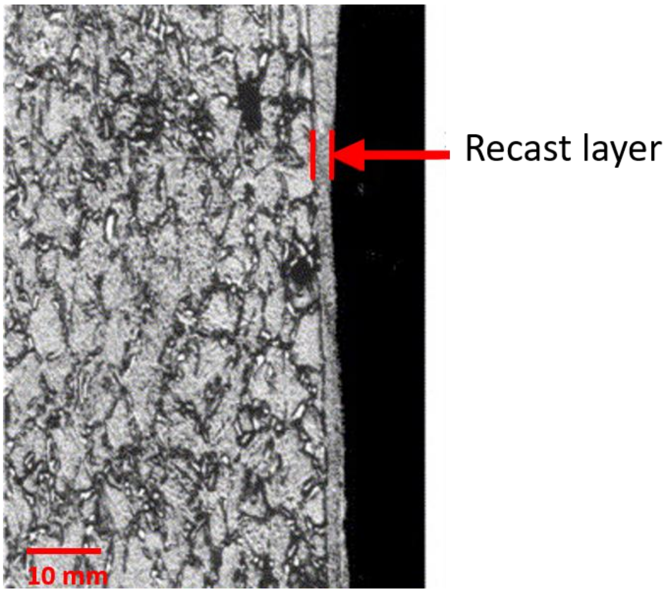


Figure 2-10 Recast layer in a percussion drilled hole (4 mm thick IN 718) (Bandyopadhyay et al., 2005)

2.4.3.6 Spatter

Incomplete expulsion of melted material occasionally causes the scattering of molten droplets around the edges of the hole, which later resolidify. These droplets get stuck to the hole surface and are known as spatter (Guo et al., 2003). It is an innate defect of the laser drilling process and is not desirable especially for effusion cooling application, whereby the material surface is important for the efficiency and flow of the cooling air (Low et al., 2003). Figure 2-11 depicts the spatter area formed near the edges of laser drilled holes of Nimonic sheet.

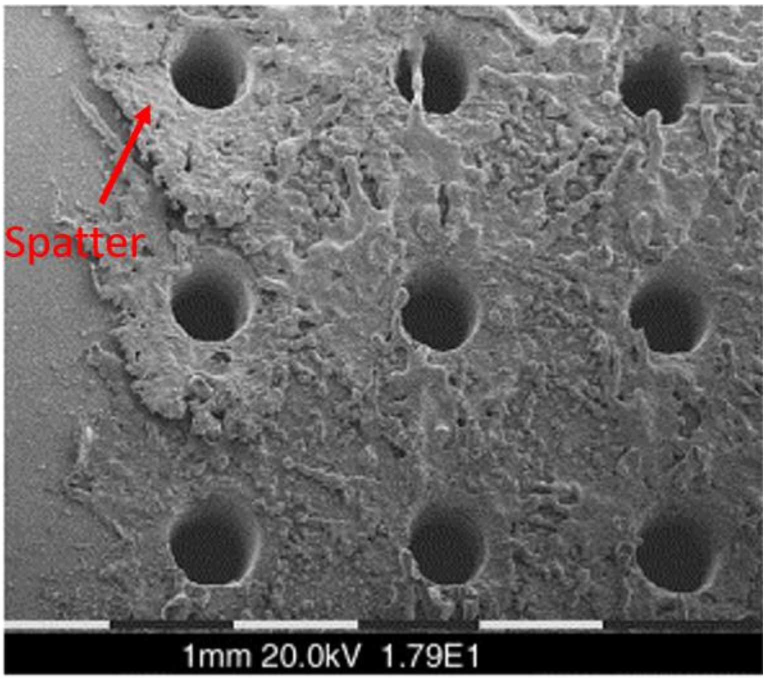


Figure 2-11 SEM image of spatter deposited over the periphery of the hole (2.05 mm thick Nimonic PK 33) (Low et al., 2003)

2.4.3.7 Heat Affected Zone (HAZ)

Laser drilling is a thermal process which involves the interaction of a laser beam with the surface of the workpiece. Higher temperature is involved in the process due to which the (mechanical, physical and chemical) properties of the workpiece surrounding the interaction area are changed. This results in the creation of a distinct zone known as heat affected zone. The HAZ area is not melted, though lateral heat conduction produces a significant change in the microstructure. The microstructure interface clearly differentiates HAZ from the base material and the recast layer as shown in Figure 2-12. HAZ is directly linked to pulse duration and laser beam intensity (Mishra and Yadava, 2013a). Low pulse duration allows less time for the energy to dissipate into the material. On the contrary, high laser beam intensity leads to efficient removal of molten material and results in less contact time between the hot liquid and bare material.

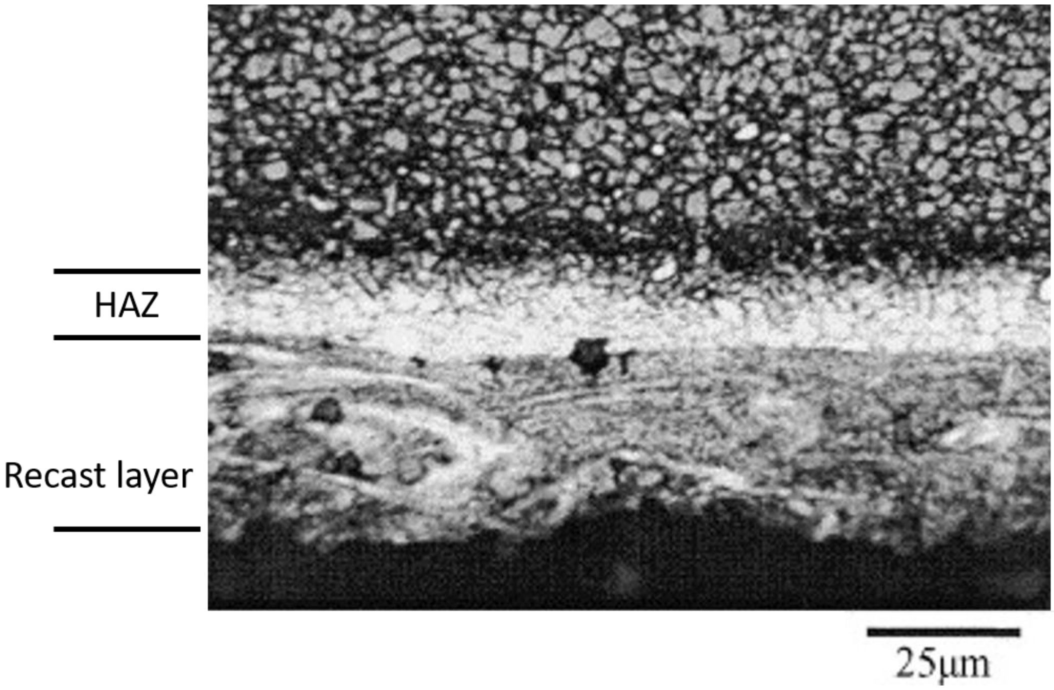


Figure 2-12 HAZ and recast layer in laser drilled hole (8.0 mm thick IN 718) (Bandyopadhyay et al., 2002)

2.4.4 Manufacturing Cost

Manufacturing cost of a product plays an important role in its successful design and production. In the majority of cases, it is used for making several types of decisions for product designing and manufacturing. These decisions include:

- Material type to be utilised for the product
- Manufacturing process type to be utilised for the product
- Number of products to be manufactured
- Whether to buy or make the part/product
- Product design

Product manufacturing cost is a major cost element of its selling price i.e. 40% (shown in Figure 2-13), which further consists of various elements: labour cost (direct & indirect), material cost, equipment depreciation, energy and plant cost as illustrated in Figure 2-14 (Scallan, 2003). It is important to estimate the manufacturing cost as it assists the manufacturing companies to evaluate their performance and effectiveness (D’Urso et al., 2017).

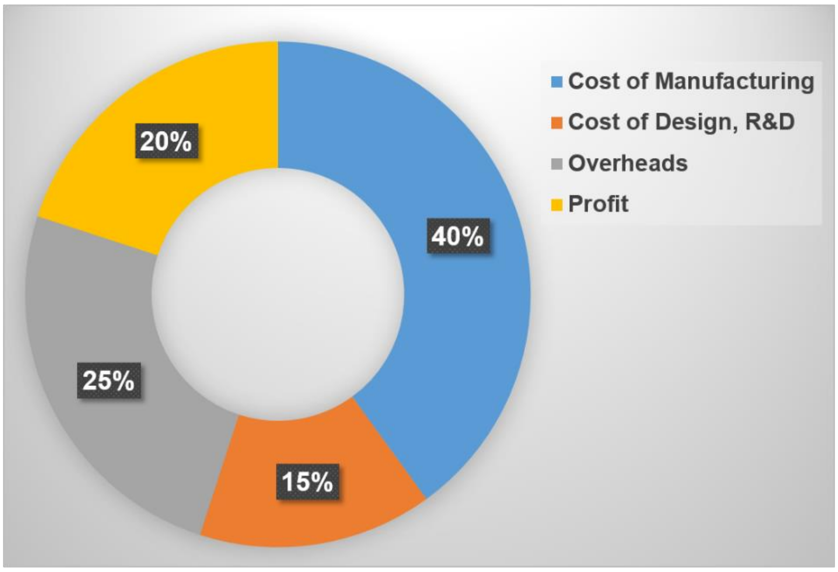


Figure 2-13 Product selling price cost elements (Scallan, 2003)

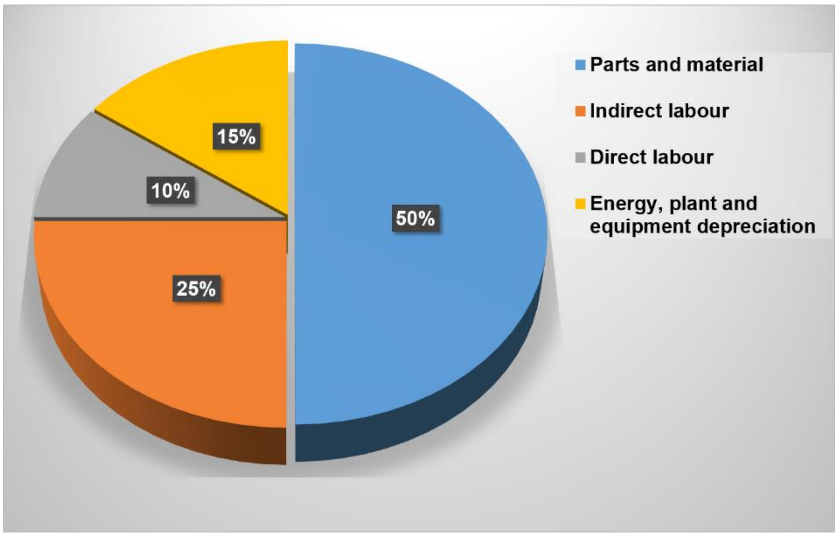


Figure 2-14 Manufacturing costs elements (Scallan, 2003)

2.5 Laser Drilling Process Parameters

Different parameters are involved in the practical implementation of the laser drilling process. Yeo et al. (1994) grouped these parameters into five main categories, as shown in Figure 2-15. Laser pulse parameters include pulse energy, pulse duration, pulse frequency and the number of pulses. Environment conditions are the surrounding temperature and humidity level. Material based parameters include material reflectivity, thickness and type of material. Optical setup involves beam shape, intensity profile, focal length and focal position of the laser beam. Assist gas-based parameters are gas pressure, gas flow rate, nozzle design and the type of assist gas employed. The performance and efficiency of the process depend on the appropriate selection of these parameters.

Figure 2-15 Classification of process parameters

2.5.1 Pulse Energy and Pulse Duration

Pulse energy and pulse duration are the critical process parameters of laser drilling. Pulse energy provides the energy to melt or vaporise a proportion of the material. Pulse duration or pulse width determines the duration at which this energy is applied, as shown in Figure 2-16. Depending on laser specifications, the ranges of pulse duration and pulse energy can be varied and have a significant impact on the hole characteristics (Gautam and Pandey, 2018).

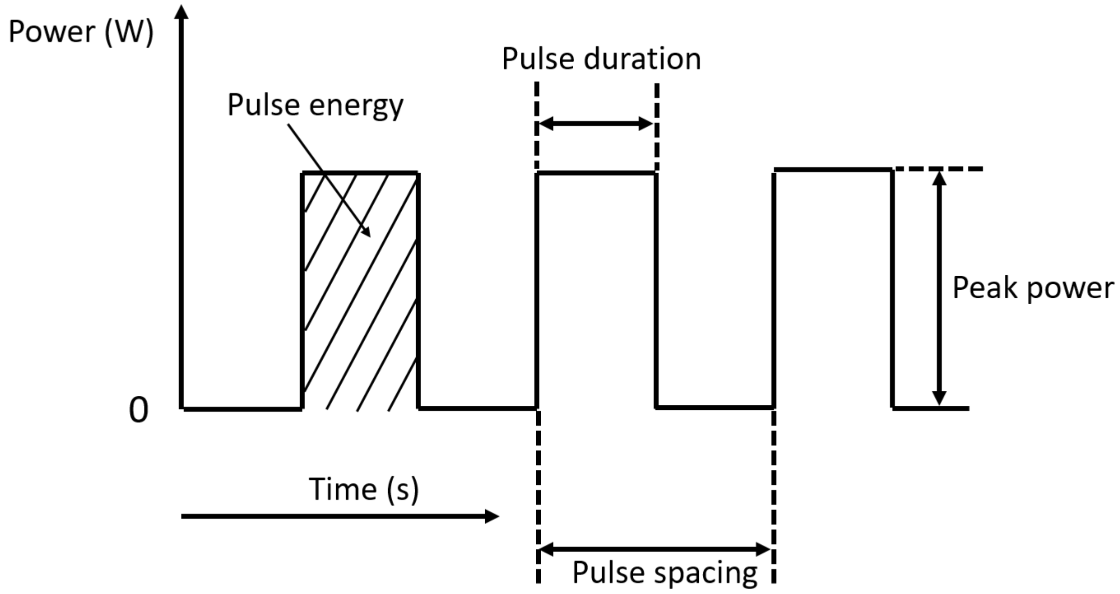


Figure 2-16 Laser pulse waveform

Both of these parameters are interdependent (see equation (2-3)) and define the laser peak power that controls the rate at which pulse energy is applied into the material (Marimuthu et al., 2019a). To attain the same pulse energy with a short pulse width, higher peak power is required. There is a significant impact of peak power on the material removal process. Higher peak power with short pulse duration typically leads to rapid melting and high vapour pressure which subsequently accelerates the liquid (molten metal) removal (Sarfraz et al., 2019b). It has been noted that drilling with a high peak power significantly reduces the hole taper (Mishra and Yadava, 2013b; Goyal and Dubey, 2016), recast layer thickness (Bandyopadhyay et al., 2002; Naeem, 2006; Chien and Hou, 2007) and microcracks (Morar et al., 2018).

$$Peak\ power = \frac{Pulse\ energy}{Pulse\ duration} = \frac{joule\ (J)}{second\ (s)} = watt\ (W) \qquad (2\text{-}3)$$

It is clear from equation (2-3) that peak power is directly proportional to pulse energy and inversely proportional to pulse duration. High pulse energy helps to remove the molten material outside the hole cavity and therefore reduces the RLT (Chien and Hou, 2007) and microcracking (Corcoran et al., 2002). On the other hand, hole taper increases with an increase in pulse energy (Yilbas, 1997;

Chatterjee et al., 2018a). Generally, long pulse duration produces large diameter and deeper hole because of sufficient laser beam-workpiece interaction time (Basiev and Powell, 2004), however, too long pulse duration is not ideal for laser drilling as it produces a large HAZ (Mishra and Yadava, 2013a). Short pulse duration is found to produce a very small difference between entry hole and exit hole diameters because of the high-power intense laser beam (Goyal and Dubey, 2014; Chatterjee et al., 2018a) and also reduces microcracking (Corcoran et al., 2002). The above mentioned studies have revealed a significant influence of pulse energy and pulse duration on drilled hole quality, therefore, it is important to select a suitable value for these parameters.

Single-pulse drilling

Single-pulse drilling employs one high-energy laser pulse to perform the drilling operation. The laser pulse can be of a short pulse duration with high peak power (Figure 2-17 (a)) or long pulse duration with low peak power (Figure 2-17 (b)), each has a significant effect on hole characteristics. The combination of short pulse width with high peak power is recommended as it improves the repeatability of hole diameter (Ng and Li, 2001) and hole circularity (Ng and Li, 2001; Ghoreishi, 2006).

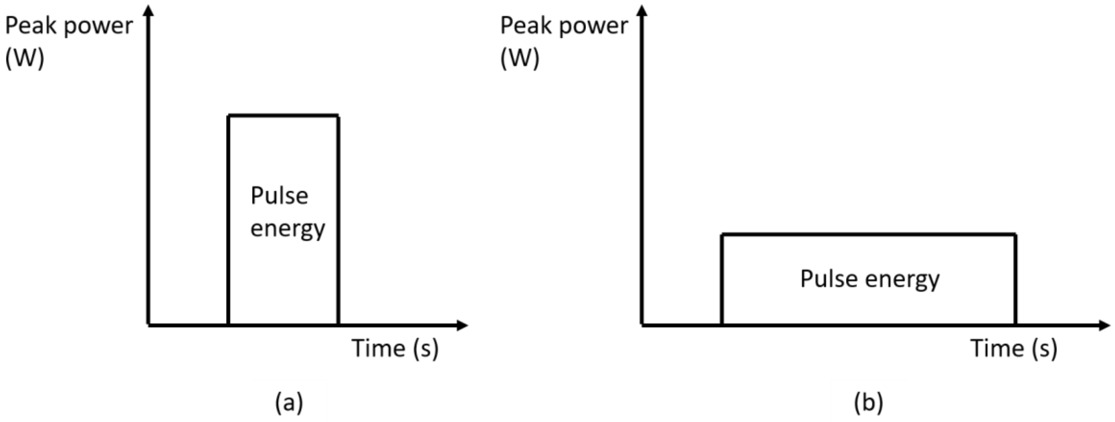


Figure 2-17 Schematic representation of single-pulse drilling regimes (a) higher peak power (b) lower peak power

Percussion

In case of percussion drilling, more than one number of pulses are involved therefore the energy transferred to the material is calculated as cumulative pulse energy i.e. a total sum of energy associated with each pulse, as shown in Figure 2-18. Typically, the cumulative pulse energy required to drill a hole is higher in comparison to single-pulse drilling due to pulse off stage in percussion drilling which allows the molten metal to solidify. Laser pulse off time depends on the duty cycle and pulse frequency. This indicates that the number of pulses and pulse frequency are also important parameters, which are explained in the following sections.

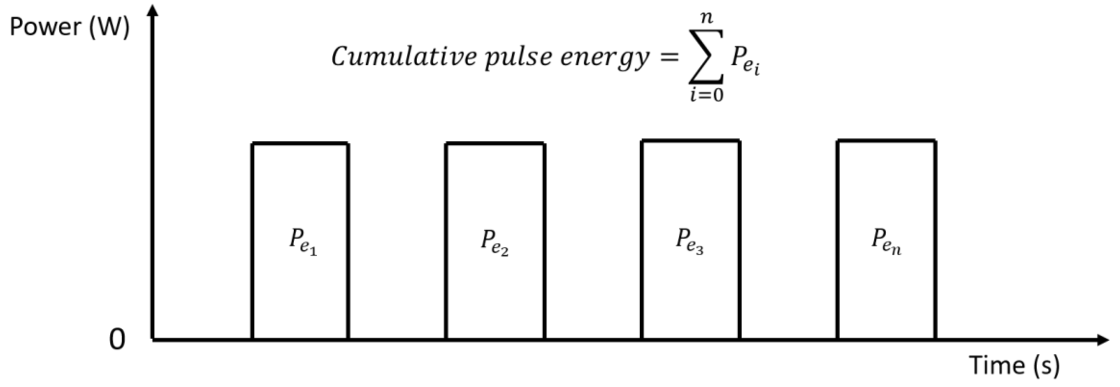


Figure 2-18 Schematic representation of cumulative pulse energy - percussion drilling

2.5.2 Number of Pulses (NOP)

In laser drilling, it has been found that an increase in the number of pulses helps to remove material from the bottom side of the hole, after the formation of through-hole, and consequently produces lower hole taper (Ghoreishi et al., 2002b; Ghoreishi and Nakhjavani, 2008; Leigh et al., 2010; Nawaz et al., 2019; Sarfraz et al., 2019b). The circularity of holes also improves with higher number of pulses (Han and Pryputniewicz, 2004). However, spatter volume can be minimised using a small number of pulses (Wang et al., 2018).

2.5.3 Pulse Frequency

Pulse frequency controls the number of laser pulses fired per second. It also defines the average power of the laser that can be calculated by using the following equation (2-4).

$$\begin{aligned} Average\ power &= Pulse\ energy \times Pulse\ frequency \\ &= (joule\ (J))/(second\ (s)\ ) = watt\ (W) \end{aligned} \tag{2-4}$$

Hole quality is significantly influenced by the change in pulse frequency (Nath, 2014). At high pulse frequency, the time gap between consecutive pulses is short which reduces the chances of heat loss due to convection and allows sufficient energy to enter into the workpiece material (Sarfraz et al., 2019b). Lower hole taper with less RLT can be obtained with high pulse frequency (Bandyopadhyay et al., 2002; Ghoreishi and Nakhjavani, 2008; Panda et al., 2011; Mishra and Yadava, 2013b; Chatterjee et al., 2018a). On the other hand, HAZ increases with pulse frequency (Mishra and Yadava, 2013b).

2.5.4 Material Properties and Environment

Material properties have a considerable effect on laser drilling performance. The (reflective) characteristics of material surface directly influence the amount of energy absorbed during the laser drilling operation. Reflectivity or absorptivity is required to calculate the amount of energy absorbed by the material as indicated in equation (2-5) (Salonitis et al., 2007). Single-pulse drilling is more sensitive to material reflectivity, whereas in percussion drilling there is a preheating effect and absorptivity increases with subsequent pulses.

$$E_{abs} = A \times P \times P_d \tag{2-5}$$

where:

E_{abs} = Energy absorbed by the material (J)

A = Material absorptivity $(1 - Reflectivity)$

P = Laser power (W)

P_d = Pulse duration (s)

In addition to this, the thermal conductivity of material also affects process efficiency. It is obvious that material with high thermal conductivity transfers heat quickly throughout the workpiece instead of rapidly heating the targeted zone, therefore more time is needed to reach the melting state (Shen et al., 2001). Material thickness was also found as a significant influencing factor related to the geometry and metallurgical features of hole quality. Hole taper decreases with an increase in material thickness. On the contrary, spatter and recast layer increase when thicker material is used (Bandyopadhyay et al., 2002).

Environmental factors including humidity, mist, dust, ambient temperature and machine vibration could also influence laser performance. Also, the surface of optical elements should be cleaned and contain no oil vapour or dust particles; otherwise, it may damage the optical system (Sarfraz et al., 2017).

2.5.5 Beam Shape and Intensity Profile

The temporal profile of a laser beam defines the intensity distribution and material removal capability of a laser pulse (Yeo et al., 1994). Gaussian beam profile is generally used in the laser drilling process as it provides small focused spot and high laser beam intensity which results in efficient removal of molten material (Steen and Mazumder, 2010). The diameter and roundness of a laser beam directly affect the dimensions of a hole. The size of a hole is directly dependent on beam size, and the smallest beam size of a particular laser system is determined by its optics and the optical settings.

2.5.6 Focal Length and Focal Position

Focal length is the distance from the centre of the lens to the focal point (see Figure 2-19). Hole characteristics are greatly influenced by a change in focal length since it directly affects the beam spot size that is related with the laser power density, as shown in equations (2-6) and (2-7) (Adelmann and Hellmann, 2015). High power density is associated with shorter focal length and therefore results in higher melt removal. On the other hand, the spatter area was shown to increase with shorter focal length (Low et al., 2000a).

$$S_d = F_l \times \theta \tag{2-6}$$

$$P_d = \frac{P}{A_s} = \frac{4P}{\pi {S_d}^2} \tag{2-7}$$

where:

S_d = Minimum spot diameter (mm)

F_l = Focal length (mm)

θ = Beam divergence (angle)

P_d = (max) Laser power density (W/mm^2)

P = Laser power (W)

A_s = Cross-sectional area of the laser spot (mm^2)

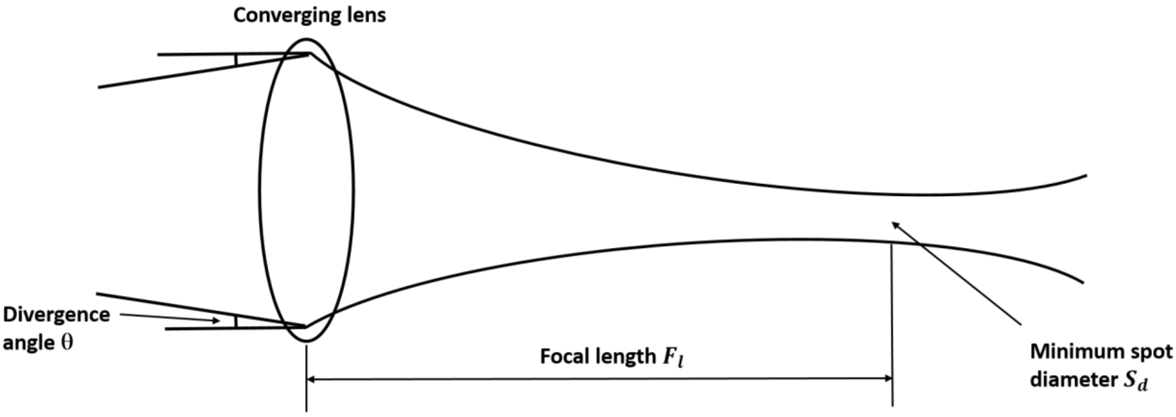


Figure 2-19 Focus pattern of a laser beam

Focal position of a laser beam is divided into three categories based on its position relative to the workpiece surface (see Figure 2-20) (Han and Pryputniewicz, 2004):

- Zero – when the focal position of the laser beam is located exactly at the workpiece surface.
- Positive – when the focal position of the laser beam is located above the workpiece surface.

- Negative – when the focal position of the laser beam is located below the workpiece surface.

Focal position significantly affects the quality and geometry of a hole. Minimum RLT was noticed by Marimuthu et al. (2019a) and Leigh et al. (2010) when the focal position of the laser beam was maintained exactly at the workpiece surface. The circularity of holes has also been shown to increase with zero focal plane position (Han and Pryputniewicz, 2004). Shin and Mazumder (2016) found a significant improvement in the values of hole taper with zero focal plane position.

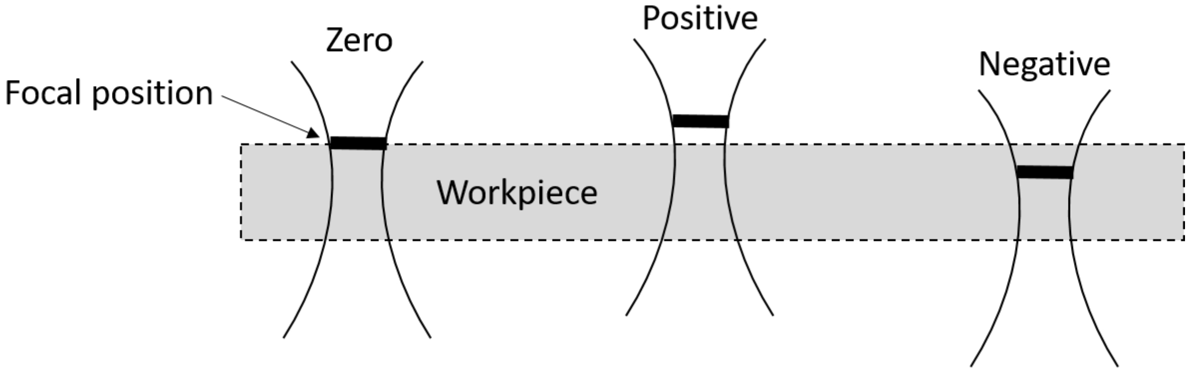


Figure 2-20 Schematic diagram showing the variation of focal position (Ghoreishi et al., 2002a)

2.5.7 Assist Gas

In the laser drilling process, an assist gas is employed to facilitate the removal of molten material and to blow out the recast layer and spatter which is deposited inside and on the top of the hole cavity, respectively. Different types of assist gases are utilised for the laser drilling operation. They are broadly classified as reactive gases or inert gases. Reactive gases provide additional exothermic energy as a result of chemical reaction between the molten metal and the gas and subsequently improve drilling efficiency. Oxygen and compressed air are categorised as reactive gases (Riveiro et al., 2011). On the other hand, inert gases only provide kinetic energy to evacuate the molten material from the hole cavity without undergoing any chemical reaction. Nitrogen and argon fall under this category. The quality of the drilled hole is significantly affected by the type of assist gas employed (Bahar et al., 2016). Low et al. (2000b) observed lower spatter thickness with weak bonding strength when applying oxygen as the assist gas. On the contrary, the drilling edge is oxidised which requires further cleaning (Wang et al., 2017). Compressed air is the cheapest option but the disadvantages associated with this gas are the formation of dross and oxidised surface. Using inert gases (nitrogen and argon), these oxidation scales can be avoided. Marimuthu et al. (2019b) compared the quality of laser drilled holes using different assist gases. A regular hole profile with minimum RLT was obtained with argon and nitrogen compared to oxygen and compressed air.

The gas pressure must be enough to overcome the surface tension holding the liquid (molten) metal so that the liquid can be ejected. The value of gas pressure influences hole quality. Higher gas pressure facilitates the removal of molten material along the sidewalls and therefore results in less RLT (Chien and Hou, 2007; Marimuthu et al., 2019a) and lower hole taper (Chatterjee et al., 2018a). On the other hand, excessive gas pressure is also not desirable as it results in the formation of microcracks due to the phenomena of rapid solidification (Chien and Hou, 2007).

Gas flow rate is also an important process parameter which affects the efficiency of the laser drilling process. In the case of reactive gas, increasing gas flow rate enhances the melting phenomenon and assists in removing the molten metal by providing additional thermal energy (Panda et al., 2011). However, high gas flow rate increases the material deposition on the entry side of the drilled hole (Nawaz et al., 2020).

It is noted that the nozzle design also affects hole quality. Biffi and Previtali (2013) designed an innovative nozzle and achieved a significant decrease in spatter compared to a standard nozzle. Low values of recast layer were reported by Khan et al. (2007) when a small nozzle diameter was used.

Proper control of these process parameters is necessary as they significantly influence the performance of the process. The influence of laser drilling process parameters on the selected performance measures is provided below.

2.6 Effect of Process Parameters on MRR and SEC

The laser drilling process is associated with the removal of molten material to produce a particular hole geometry. Material removal volume (MRV) and process duration define the material removal rate where higher MRV with less process duration is required for improved productivity. On the other hand, specific energy consumption depends on the amount of material removed versus the amount of energy applied. Higher MRV is always desirable with less energy input as it improves process efficiency.

There are various process parameters which influence the MRR and SEC in laser drilling. This section covers the previous research work conducted by the researchers to study the MRR and SEC in connection with the laser drilling process.

Bright et al. (2007) examined the laser drilling parameters influence on the melt removal rate during percussion drilling. They concluded that pulse energy and pulse duration directly influence the MRR. Mishra and Yadava (2013c, 2013d) developed a thermal model to predict MRR during percussion drilling of Inconel (IN 718) and aluminium sheets, and the results were compared with the experiments. It was found that the MRR is directly proportional to pulse frequency, peak power and pulse duration.

Panda et al. (2011) examined the impact of the laser drilling process parameters including pulse duration, gas pressure, number of pulses and gas flow rate on the material removal rate and hole quality. It has been shown that variation in the process parameters significantly affects MRR. Priyadarshini et al. (2015, 2017) extended this work to optimise the MRR using grey-fuzzy and fuzzy-TOPSIS (technique of order preference similarity to the ideal solution) methods.

Sarfraz et al. (2019b) investigated the effects of laser drilling parameters on MRR using three different laser drilling methods. The results showed that pulse width, number of pulses and trepan speed are the most important parameters that influence MRR.

Biscaia et al. (2020) conducted a series of experiments on nickel superalloy using trepan laser drilling to explore the influence of process parameters on MRR. Results indicated trepan speed as the significant parameter influencing the MRR. Higher trepan speed produced higher MRV with reduced drilling time.

An investigation was performed by Fysikopoulos et al. (2009; 2012) to evaluate laser drilling process energy efficiency by examining different process parameters. For energy efficiency, MRV was calculated against the energy applied. The results revealed that increase in laser power and pulse frequency enhances process efficiency.

Franco et al. (2016) evaluated the energy efficiency of laser drilling and electrodischarge machining. Laser drilling was found as an energy-efficient process with low specific energy consumption value compared to EDM.

Wang et al. (2017) analysed the effects of assist gas including oxygen and argon on drilling efficiency. Improved efficiency was reported using oxygen as an assist gas due to its combustible-supportability that generates excessive heat and results in higher MRV with less energy consumption.

The relationship between SEC and laser drilling process parameters was explored by Sarfraz et al. (2019b). The experimentation was conducted for single-pulse drilling, percussion and trepanning. It was determined that SEC is mainly influenced by pulse energy, number of pulses and pulse frequency.

2.7 Effect of Process Parameters on Hole Quality

Different experimental studies have been performed by researchers to study the impact of laser drilling process parameters on hole quality, aiming to enhance the quality attributes of the laser drilled holes.

Taper control is the most important issue during the laser drilling process. High value manufacturing industries dealing with aircraft engine components demand holes without any taper. Different factors influence hole taper and the following studies address the significant process parameters.

Bandyopadhyay et al. (2005) investigated the hole taper of laser drilled holes produced in titanium alloy and nickel superalloy sheets. Pulse duration, pulse energy and focal position were found as significant parameters affecting hole taper. Low levels of pulse duration and pulse energy with zero focal position resulted in improvement of hole taper. In another study, Bandyopadhyay et al. (2002) found that increase in material thickness caused improvement in hole taper.

Kacar et al. (2009) observed the influence of pulse duration and peak power on hole taper using alumina ceramic. An increase in pulse duration and peak power produced improvement in hole taper.

A study was conducted by Mishra and Yadava (2013c) on laser drilling of IN 718 sheet. Results showed improvement in hole taper with an increase in pulse frequency. Bathe and Padmanabham (2014) reported the influence of laser drilling parameters using TBC (thermal barrier coated) IN 718 as a substrate. Pulse duration produced a significant impact on hole taper. Decreasing pulse duration produced a reduction in hole taper.

Goyal and Dubey (2014) investigated the impacts of laser drilling parameters on hole taper of laser drilled IN 718 sheet. Hole taper was found to decrease with the increase in trepan speed and pulse frequency. Similar findings were reported by Dhaker and Pandey (2019).

Bahar et al. (2016) admitted the importance of laser power and laser frequency in the laser drilling process. They reported that higher laser power and increased pulse frequency help to improve hole taper. The study also revealed that comparing the effects of compressed air, oxygen and nitrogen on hole taper, improved hole quality was obtained with compressed air and nitrogen. Shin and Mazumder (2016) stated that hole taper can be improved when higher laser power is applied with lower trepan speed and zero focal position.

Chatterjee et al. (2018a) explored studies on laser drilling of titanium alloy. Pulse duration, pulse energy, pulse frequency and gas pressure were varied to observe their effects on hole taper. They stated that increasing pulse frequency and gas pressure resulted in improvement of hole taper. It was also discovered that hole taper was increased by increasing pulse energy and pulse width. Chatterjee et al. (2018b) conducted another study on stainless steel (AISI 316). Similar results were found for this material except for gas pressure and pulse energy effect due to a difference in material properties.

Sarfraz et al. (2019b) conducted experiments to investigate the impact of pulse energy, pulse frequency, number of pulses, pulse duration and trepan speed on hole taper. Pulse duration and pulse energy produced the most significant effect on hole taper.

2.8 Effect of Process Parameters on Manufacturing Cost

Laser drilling process depends on several process parameters that affect the productivity, process efficiency and product quality as described above. Sarfraz et al. (2018a; 2019a) specified in their work that these process parameters also influence manufacturing cost. These researchers provided a cost breakdown structure of the laser drilling process and identified cost drivers involved in the process. However, no detailed work has been reported so far explaining the laser drilling process parameters impact on the manufacturing cost.

In this study, the author has performed a detailed cost analysis to estimate the laser drilling manufacturing cost. The parametric effect has also been studied to find out significant process parameters.

2.9 Multi-Objective Optimisation in Laser Drilling

There are several parameters involved in the laser drilling operation which affect the performance of the process in terms of productivity, energy efficiency, quality and cost, as explained above. This shows that laser drilling is a complex process with multi-input process parameters and multi-output performance measures. Traditionally, the trial and error method was used to obtain the optimal drilling conditions to achieve the desired performance levels by using a combination of different input parameters. However, this method required a huge amount of time and cost as well.

Due to the complex nature of the laser drilling process, researchers have developed several techniques to solve the multi-objective optimisation problems. A summary of the optimisation approaches carried out by different authors is provided by the following studies.

Panda et al. (2011) performed optimisation of laser drilling of high carbon steel (Domex C67) in relation to different performance characteristics. The effects of laser drilling process parameters i.e. pulse duration, number of pulses, gas pressure and gas flow rate were studied. The optimum laser drilling process parameters were determined utilising the experimental observation data based on the Taguchi method. Performance characteristics involved drilled hole diameter, heat affected zone and material removal rate. It was reported that by employing grey relational analysis, the optimum process parameters can be found for the required laser drilling performance characteristics.

An investigation was performed by Padhee et al. (2012) to examine the quality of laser drilled holes in Al-SiC_p composite. Response surface methodology (RSM) approach was used to describe the relationship between hole quality and drilling parameters. Then the optimal process parameters (pulse duration, number of pulses, SiC_p concentration) were determined using grey relational analysis (GRA). The output parameters involved hole taper, HAZ and spatter. It was found that GRA is a reliable method to find optimal drilling conditions.

Bharatish et al. (2013) combined the RSM with GRA to investigate the optimum process parameters involved in laser drilling of alumina. The aim was to optimise hole circularity, HAZ and hole taper. The optimal process parameters settings were listed as pulse frequency of 7.5 kHz, scanning speed of 3.85 mm/s, laser power of 240 W and hole diameter of 1 mm. It was reported that this technique can be used to identify the optimal drilling settings when multi-objective optimisation is required.

Priyadarshini et al. (2015, 2017) applied grey-fuzzy and fuzzy-TOPSIS methods for multi-objective optimisation of laser drilling of high carbon steel. The performance characteristics considered for this study include hole circularity, HAZ and material removal rate. The effects of input parameters (pulse duration, number of pulses, gas pressure and gas flow rate) on the mentioned performance characteristics were also highlighted.

Laser drilling quality characteristics were investigated by Bara et al. (2018) using the desirability function technique. Hole quality was evaluated based on hole taper and hole circularity. Desirability function technique was then used to find out the optimal drilling conditions aiming to maximise hole quality. Same quality characteristics were studied by Dhaker and Pandey (2019) for laser drilling of IN 718 alloy. Particle swarm optimisation (PSO) was used to determine the optimum values of input parameters.

The above-mentioned optimisation techniques were stated as suitable for optimisation of the laser drilling process. Therefore, grey relational analysis is used in this study to determine optimal drilling conditions with taken into consideration material removal rate, hole taper and drilling cost.

2.10 Cost Estimation

Cost is an important business engine for every industry. It is also an important factor that has a great influence on product outcome due to the competitive global market. Since a major portion (70%) of the product cost is committed by the conceptual design phase of a product (Shehab and Abdalla, 2001), the product design and development team must consider this phase critically and put in some important measures to avoid mistakes and unexpected circumstances that could hinder the successful manufacturing of a commodity. The manufacturing cost of a product can be estimated easily during the design phase only if the product designer is provided with the capability of cost estimation.

Cost estimation has been defined by several authors. For instance, Aderoba (1997) defined cost estimation as “the process of forecasting the manufacturing cost of a product before its production”. Shehab and Abdalla (2001) explained cost estimation as the prediction of costs associated with a number of activities before they are actually executed. Tammineni et al. (2009) explained cost estimation as the methodology of predicting the cost of a product before the implementation of any product development stage.

It is also very important to differentiate cost estimation, cost accounting and cost engineering. The term cost accounting is widely used by cost estimators to calculate the product cost after the commencement of a task/project; on the other hand, cost engineering deals with the cost estimation, cost control, project planning and profitability analysis of engineering processes (projects) (Xu et al., 2012). It is clearly understood from the aforementioned definitions that cost accounting determines the real use of resources; cost estimation employs cost accounting and variant useful information for predicting the future cost. However, cost engineering utilises cost estimations and different associated activities to deliver a successful business.

There are different methods of cost estimation classified by several researchers, which are explained in the following subsections.

2.11 Methods of Cost Estimation

Selection of a suitable cost estimation method is necessary for authentic cost estimation. Different categories of cost estimation methods have been proposed by several researchers. Shehab and Abdallah (2001) categorised four cost estimation approaches as intuitive, analogical, parametric and analytical. Roy (2003) classified cost estimation methods into five different categories as depicted in Figure 2-21. Niazi et al. (2006) provided a comprehensive classification of cost estimation methods and divided them into qualitative and quantitative cost estimation techniques as shown in Figure 2-22 and Figure 2-23 respectively. Cost estimation methods along with detailed explanation are described in the following sections.

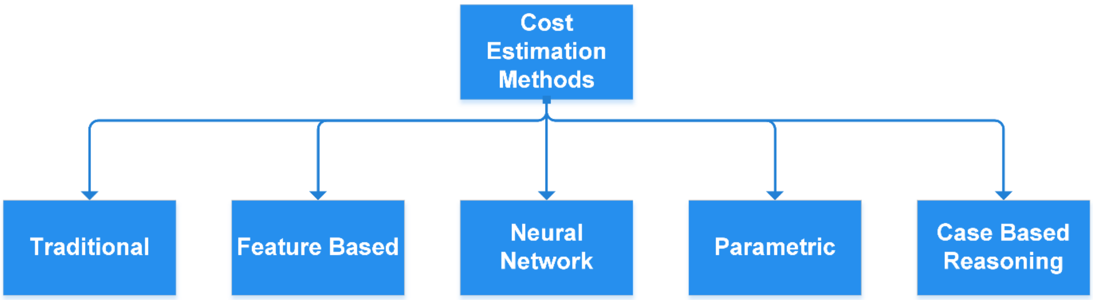


Figure 2-21 Classification of cost estimation methods (Roy, 2003)

2.11.1 Qualitative Techniques

Qualitative cost estimation techniques are associated with estimating the cost of a new product by using the past data of similar products without involving detailed information. Past design and manufacturing data or the previous experience of a cost estimator can provide useful information to generate cost estimation for new products that are similar to previous design features (Rush and Roy, 2000). Regression analysis and neural networks are the best examples of qualitative cost estimation. In these approaches, previous historical data is used to estimate the cost of new products. Qualitative cost estimation techniques are further classified into intuitive and analogical techniques.

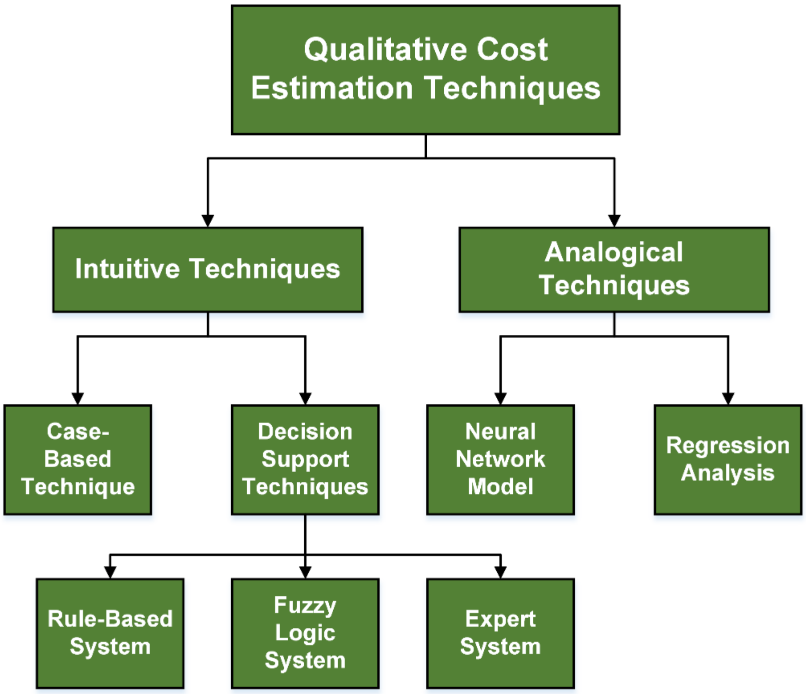


Figure 2-22 Classification for qualitative cost estimation techniques (Niazi et al., 2006)

2.11.1.1 Intuitive Cost Estimation Technique

In this cost estimation approach, an expert's knowledge is used for cost estimates of products or parts. Accuracy of cost estimation depends upon the experience of the cost estimator (Mandolini et al., 2020). It is further classified into case-based technique and decision support technique.

2.11.1.1.1 Case-Based Technique

The case-based technique is a cost estimation technique where previous cases similar to new or present ones are used to estimate the cost by comparing their attributes. To estimate the cost of a new product, a similar case is selected from the stored information that closely matches the attributes of the new product. The changed part specifications are then incorporated to estimate the cost (Niazi et al., 2006).

2.11.1.1.2 Decision Support Techniques

Decision support techniques help the cost estimators to make better decisions using stored knowledge of field experts (Maciol, 2017). These techniques include fuzzy logic, rule-based and expert systems.

Rule-Based System

A rule-based system is associated with estimating the time and cost of feasible manufacturing processes based on manufacturing and/or design (rules) constraints (Maciol, 2017).

Fuzzy Logic System

This cost estimation method helps to handle uncertainties. A reliable cost estimate can be generated by using fuzzy logic-based knowledge which covers uncertainties (Shehab and Abdalla, 2002).

Expert System

An expert system is associated with the storage of human logical reasoning (cost knowledge) in a database and retrieving it on request to make fast, reliable and accurate cost estimates (Niazi et al., 2006).

2.11.1.2 Analogical Cost Estimation Technique

This cost estimation technique uses similarity criteria to identify the cost of a new product by comparing it with the cost of old similar products. A large database is needed to make use of this technique (Mandolini et al., 2020). It is further classified into neural network models and regression analysis.

2.11.1.2.1 Neural Network Models

Neural network models process the information based on the principle of a human brain. It uses a neural network that is trained by storing information of previous (similar) products in the system, enabling it to provide solutions (output) for complex conditions (García-Crespo et al., 2011).

2.11.1.2.2 Regression Analysis

Regression analysis uses historical cost data to develop a relationship between the selected variables of a new product and the product cost of past design cases, which can be used to predict the (new) product cost (Niazi et al., 2006).

2.11.2 Quantitative Techniques

In quantitative cost estimation techniques, a detailed analysis of product design, features and manufacturing processes is done to estimate the cost quantitatively. By using this technique, costs are either calculated using an analytical function of specific variables representing different product parameters or as the sum of fundamental units representing different resources utilised during the whole production life cycle of the specific product. Quantitative cost estimation techniques provide more accurate results (Niazi et al., 2006). They are further classified into parametric and analytical cost estimation techniques.

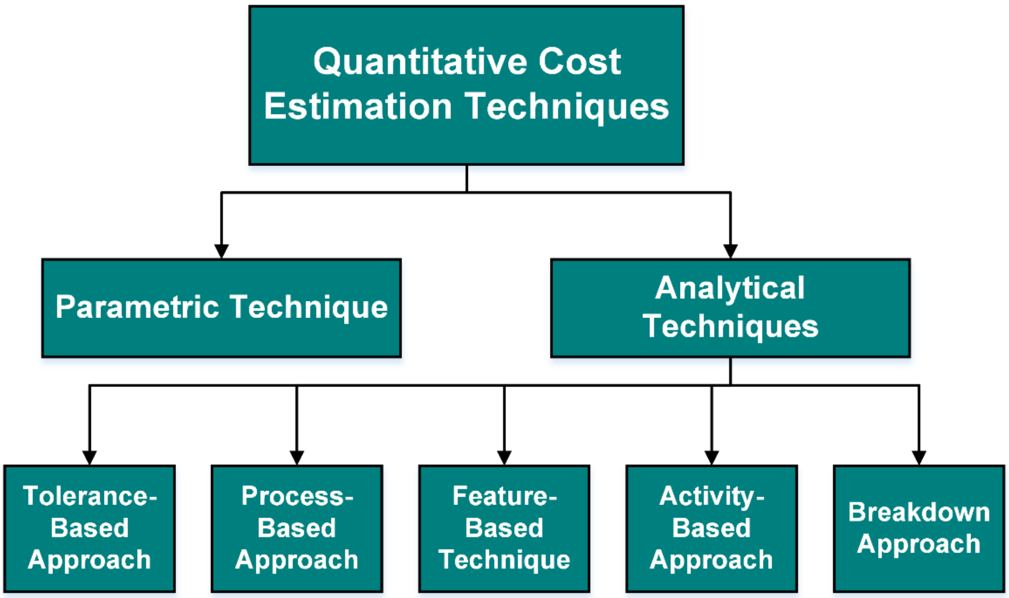


Figure 2-23 Classification for quantitative cost estimation techniques (Niazi et al., 2006)

In parametric cost estimation, product cost is estimated by developing a relationship between the products' parameters (cost drivers) and cost (Mandolini et al., 2020). Whereas, in the analytical cost estimation technique, the product is disintegrated into its elementary parts (units) and cost estimation is done separately for each unit. Total cost is then calculated by adding all the costs associated with each unit (Niazi et al., 2006). These techniques are further classified into tolerance-based approach, process-based approach, feature-based approach, activity-based approach, and breakdown approach.

The tolerance-based approach takes into consideration the tolerances of product design as a function of cost. In this approach, it is a principle that high manufacturing cost is always associated with tighter tolerances (Cao et al., 2010).

The process-based approach is also known as operation-based cost estimation approach. It is associated with the identification of all the processes or operations required to manufacture the product. The cost is then estimated based on the total (operational and non-operational) time required for the execution of tasks (Niazi et al., 2006).

In feature-based cost estimation approach, all product's features related to cost are identified and their associated costs are determined (García-Crespo et al., 2011).

Activity-based costing is a quantitative technique to estimate product cost. All the activities associated with product manufacturing are identified followed by calculating costs associated with the individual activity (García-Crespo et al., 2011).

Breakdown approach is used to estimate product cost by adding all the costs involved during the manufacturing cycle of a product. Material cost and overheads are also involved. With an increase in the number of components of breakdown cost, the accuracy of cost estimation improves (García-Crespo et al., 2011).

2.12 Analysis of Cost Estimation for Different Manufacturing Processes

Manufacturing cost is always an important concern of every industry. The total cost of a manufacturing process includes all the resources and the associated costs involved in that process. Manufacturing cost estimation at an early design phase provides product designers with different options to reduce production cost. Various researchers have developed cost estimation models or tools for different manufacturing processes to provide an insight into overall manufacturing cost for that process.

Venkatachalam et al. (1993) integrated design and manufacturing activities for different casting and forging processes to provide cost-effective production. An expert system was developed that could select a suitable manufacturing process based on the provided (design and manufacturing) parameters and estimate the manufacturing cost. Sajid et al. (2018) developed a cost estimation tool for the sand casting process integrating the design features, material and process parameters selection into the system.

Shehab and Abdalla (2001) developed an expert system to estimate the manufacturing cost of a product involving more than one machining process. The key advantage of this system is that apart from cost estimation it also provides a complete process plan including the selection of a suitable material, manufacturing processes and sequence of machining processes. In another study, Shehab and Abdalla (2002) extended the system with an injection moulding process.

Cost estimation system developed by Jung (2002) can be utilised by designers to get appropriate product cost information at the early design stage. However, this system was established for machined components based on their features that were listed into four categories (slab, prismatic, revolving and rotational).

Masmoudi et al. (2007) and Chayoukhi et al. (2009) developed a program to estimate and compare the cost for different welding processes. Benyounis et al. (2008) calculated the operating cost of the laser welding process and studied the impact of process parameters on cost. The aim was to identify optimum parametric conditions with minimum operating cost and maximum product quality.

Quintana and Ciurana (2011) developed a cost estimation tool that enabled users to predict the market cost of a product based on product features and machine characteristics. This tool was developed for high-speed machining processes. Zhai (2012) developed a model to compare the manufacturing cost of CNC machining with Wire & Arc Additive Manufacturing (WAAM) process. A software tool has been developed by Shehab et al. (2018) to predict the manufacturing cost of the Additive Layer Manufacturing (ALM) process.

Yazdi et al. (2014) and Nedic et al. (2016) developed a tool to calculate the cost of laser and water jet cutting processes. D'Urso et al. (2017) reported the manufacturing cost for the µ-EDM drilling process. A model was developed depicting the relationship between the process cost and hole depth. A study has been reported by Sarfraz et al. (2018b) where the authors provided only a brief overview of the key cost drivers involved in the laser drilling process.

An overview of research efforts done for the cost estimation of different manufacturing processes is provided in Table 2-3. It is evident that the cost estimation models or tools developed in the previous researches covered a wide range of manufacturing processes. However, limited or no scientific information is available on manufacturing cost analysis for the laser drilling process, irrespective of its emerging applications in the aerospace industry.

Table 2-3 Summary of cost estimation efforts made for different manufacturing processes

Author(s)	Manufacturing processes
Venkatachalam et al. (1993)	Casting, forging
Masel et al. (2010)	Forging
Sajid et al. (2018)	Casting
Shehab and Abdalla (2001)	Milling, mechanical drilling, EDM
Shehab and Abdalla (2002)	Milling, mechanical drilling, EDM, injection moulding
Wang et al. (2002)	Injection moulding
Jung (2002)	Turning, milling, mechanical drilling
Masmoudi et al. (2007)	Welding
Benyounis et al. (2008)	
Chayoukhi et al. (2009)	
Monserrate et al. (2017)	
Karadgi et al. (2009)	Sheet metal forming
Landi et al. (2019)	
Ciurana et al. (2008)	High-speed machining
Quintana and Ciurana (2011)	
Zhai (2012)	CNC machining, Wire & Arc Additive Manufacturing (WAAM)
Facchini et al. (2018)	
Ruffo et al. (2006)	Laser sintering
Sharma and Dixit (2019)	
Shehab et al. (2018)	Additive layer manufacturing
Ilii and Coteaţă (2009)	Plasma arc cutting
Yazdi et al. (2014)	Laser cutting, water jet cutting
Eltawahni et al. (2012)	Laser cutting
Nedic et al. (2016)	
Riveiro et al. (2016)	
D’Urso et al. (2017)	micro-Electric Discharge Machining (µ-EDM)
Continente et al. (2015)	
Sarfraz et al. (2018b)	Laser drilling

2.13 Research Gap Analysis

Laser drilling is a well-established technology especially in the aerospace sector, where this process is involved in large volume production of holes. Existing literature shows the attention of several authors towards this advanced machining process. However, there are some gaps identified in the literature covering the domain of laser drilling and cost estimation research.

The main research gaps identified are summarised as follows:

- Different types of methods are available to perform laser drilling operations. From the literature, it has been found that there is a lack of research characterising laser drilling methods in terms of productivity, energy efficiency and quality. A characterisation of laser drilling methods for the mentioned performance measures can contribute to provide a comprehensive understanding for designers and practitioners to select a suitable laser drilling technique for the required productivity, energy efficiency and quality.
- Laser drilling process has been examined by the majority of scholars. These studies have overlooked the significance of laser source used in the process. This shows a lack of research investigating laser drilling performance for different laser sources.
- Several studies were found discussing the cost of different manufacturing processes. The literature reveals that there is no research work available on estimating the cost of the laser drilling process. Therefore, the evaluation of manufacturing cost is necessary to explore the economic implications of the laser drilling process.
- Previous research studies indicated that the laser drilling process parameters have a substantial impact on the manufacturing cost that needs to be evaluated. Consequently, examining the impacts of process parameters on manufacturing cost along with productivity, energy efficiency and quality is a knowledge gap that will be covered in this study.

2.14 Summary

This chapter delivers a detailed review of the laser drilling process and cost estimation. In the first phase of literature review, laser drilling and its methods, process parameters, laser types and performance measures have been reviewed. This provides an understanding of the fundamentals of the laser drilling process and its quality attributes. The effects of laser drilling parameters on different performance measures have also been addressed. In the second phase, cost estimation is focused upon. A brief summary of different cost estimation methods has been provided. Cost estimation efforts made by previous researchers for different manufacturing processes are also highlighted. At the end, a summary of the research gaps identified from the literature review has been presented.

In the following chapter, the author describes the research methodology adopted for this study.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter aims to present the research methodology followed to ensure the accomplishment of research aim and objectives. It explores the research purpose, research design, research strategy and data collection method adopted for this research. A rationale of the research methodology adopted and a description of its different phases are also provided.

3.2 Selection of Research Methods

This section describes the various research methods that were adopted by the author in formulating the research methodology. An overview of selected research methods is illustrated in Figure 3-1. Subsequently, the justification for the selection of research methods is explained in the following sections.

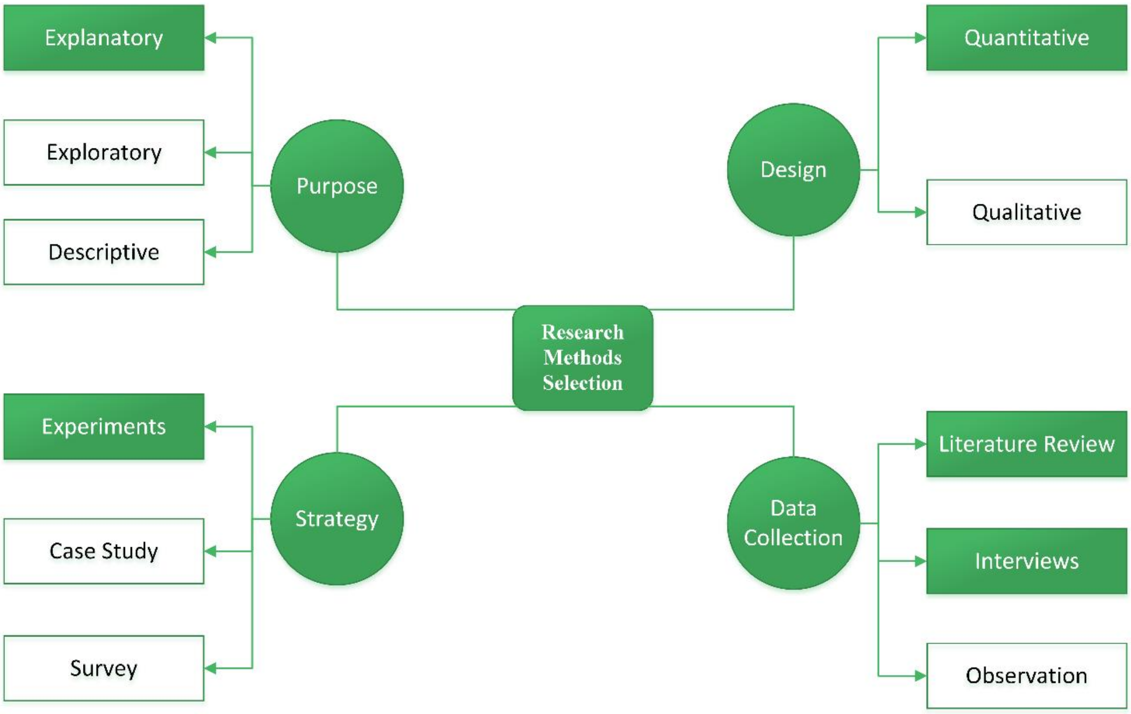


Figure 3-1 Research methods selection

3.3 Research Purpose

There are different purposes of research including explanatory, exploratory and/or descriptive (Kumar, 2019).

- Explanatory research: it helps to explore the problems or situations of the study by connecting research ideas and explaining the relationship between different aspects of a situation.
- Exploratory research: it helps to discover, uncover and explore a research problem that is not clearly defined.
- Descriptive research: it helps to describe an accurate profile of events and situations of the study.

After taking into account the research aim and objectives, explanatory research was considered as the most suitable approach for this study. Because of little information being available on the performance of the laser drilling process, this approach is suitable to understand different aspects of the laser drilling process.

3.4 Research Design

Research design selection depends on the research question, availability of data and capabilities of the researcher (Durdella, 2017). Qualitative research and quantitative research are the two main approaches to research design. In qualitative approach, data is collected in the form of words by means of interviews, documents and surveys. On the other hand, quantitative approach focuses on data collection in a numerical format (numbers) and the researcher can control experimental conditions or the environment.

Quantitative research approach was employed for this study because of the following reasons.

- The research purpose was explanatory and further information was needed to achieve the research objectives.
- This approach is more appropriate to collect and analyse data statistically.
- The relationship between variables can be easily understood.

3.5 Research Strategy

A research strategy is a structured plan adopted by the researchers to answer research questions by collecting and analysing data. Experimental strategy was found as more relevant in the context of this research work. The main reasons for the selection of this approach are provided below.

- Investigating the laser drilling performance and its cost estimation is a comparatively new field of research. Therefore, it was difficult to collect data from previous studies.
- This approach helps to collect real time data and provides more detailed information.
- Better results can be achieved under a controlled environment.

3.6 Data Collection Approach

Data collection is a research element which is concerned with the gathering of information or data related to the research project. There are several data collection methods available such as literature review, survey, interview, documents, workshops etc. The following methods were used for data collection of the present study.

Literature Review

Literature review refers to gaining insights into the research topic by transferring existing knowledge acquired from the literature into well organised text. The rationales for conducting a literature review include the following:

- Summarising ideas and arguments of other authors.
- Avoiding repetition of work.
- Preventing mistakes of previous research.
- Uncovering gaps in existing studies.

Articles, books, research reports, reviews, dissertations and conference papers are the main types of literature reviewed in this research work.

Interviews

Interviews are associated with a series of questions asked by a researcher to obtain the required information from an interviewee. Generally, interviews can be conducted face-to-face, through video calls (e.g. Skype), email or using a telephone. Three main types of interviews are:

I. Structured interviews (standard set of questions is enquired in a structured approach)
II. Semi-structured interviews (addition of open-ended questions to a standard set of questions that allows a flexible range of responses)
III. Unstructured interviews (open-ended questions are asked with the flexibility of wording and order)

In this study, unstructured interviews were conducted using video calls and telephones to identify key process parameters and potential cost drivers of the laser drilling process.

3.7 Research Methodology: An Overview

In order to fulfil the research aim and objectives in a rational way, the researcher adopted explanatory research using quantitative approach and experimental strategy. The research methodology is comprised of three phases, which are discussed in the following subsections. Figure 3-2 represents the adopted research methodology for this study.

Phase 1: Comprehending the Context

The initial phase of this research pays particular attention to gain a contextual understanding of ongoing practices in the laser drilling process as well as comprehend different cost estimation techniques. An extensive literature review has been accomplished which covers the domain of cost estimation and the laser drilling process. In the area of laser drilling, the main purpose was to identify the basic characteristics of the laser drilling process and its current practices as employed in high value manufacturing industries. In the domain of cost estimation, the primary focus was to identify cost estimation methods to support a cost analysis of the laser drilling process. A major outcome of this phase was the identification of the knowledge gap missing in the literature.

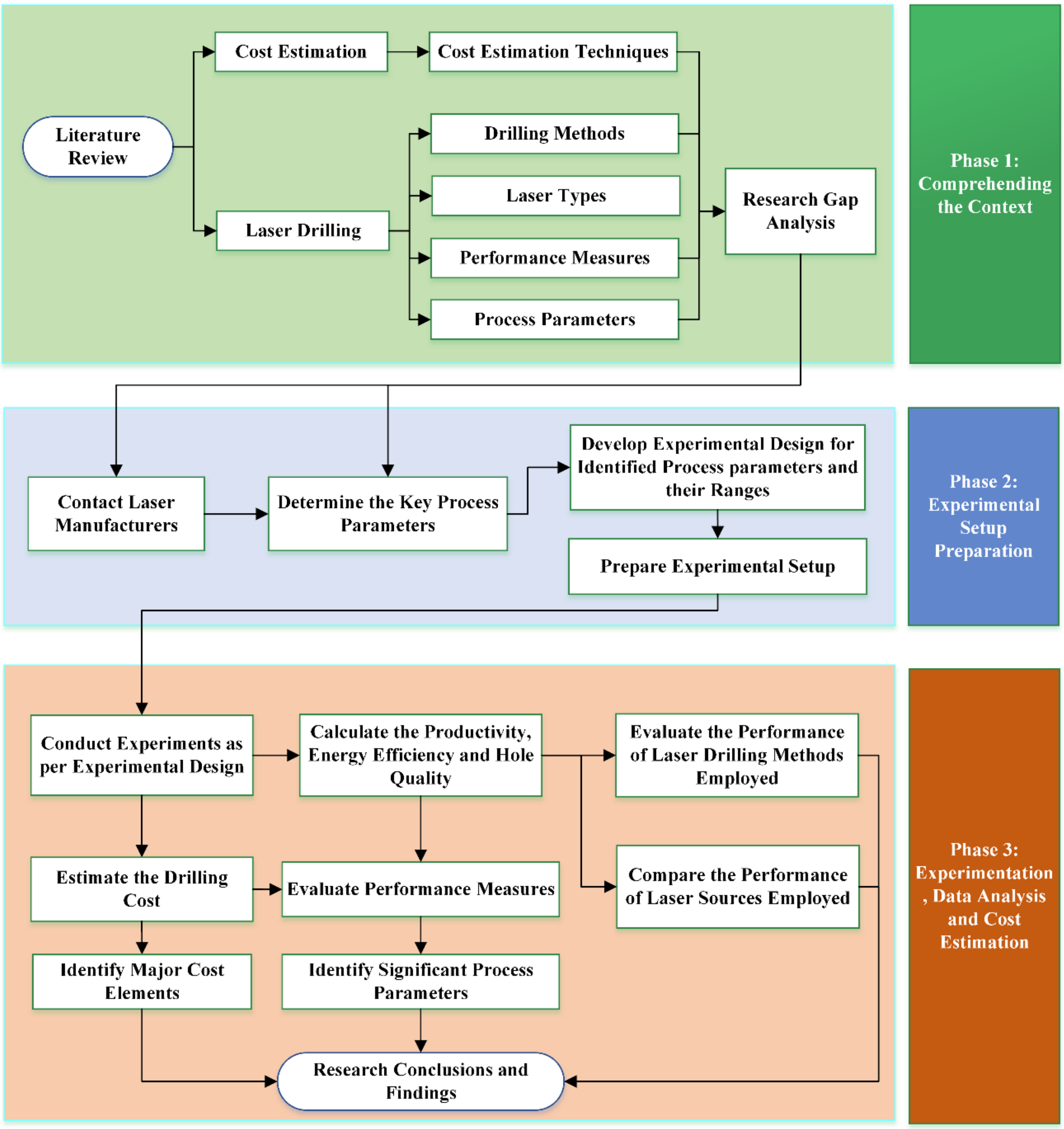


Figure 3-2 Research methodology

Phase 2: Experimental Setup Preparation

This research phase focused on the preparation of an experimental setup. Firstly, the key process parameters were determined through research gap analysis and by approaching different laser manufacturers. Secondly, an effort was made to develop the experimental design for the identified process parameters and ranges. Thirdly, an experimental setup was prepared to proceed with the experimentation. It is important to mention that two laser drilling setups were prepared using different laser sources. Details of the developed experimental setups are provided in the next chapter.

Phase 3: Experimentation, Data Analysis and Cost Estimation

The third phase involves experimentation, analysis of data and cost estimation. Experimentation was conducted as per design of experiments. Material removal rate, specific energy consumption and hole quality were evaluated for each experiment. A comprehensive analysis was performed to understand and analyse the effects of the process parameters on the response variables. Additionally, significant process parameters were identified for the mentioned performance measures. A comparison was also made of the laser drilling methods used and laser sources employed.

At the end of this phase, cost estimation was performed for the laser drilling process. This was done in two stages. In the first stage, a detailed cost analysis was performed to estimate the laser drilling process cost and identify the major cost elements of the laser drilling process. In the second stage, impacts of the laser drilling process parameters on the manufacturing cost were investigated. Finally, research conclusions and findings were delivered along with their contribution to knowledge.

3.8 Summary

This chapter covers the different research methods (research purpose, research design, research strategy and data collection approaches) that have been considered appropriate to achieve the research aim and objectives. A justification of the selected research methods has also been provided. Finally, the methodology adopted for this research is explained which consists of three stages including “comprehending the context”, “experimental setup preparation” and “experimentation, data analysis and cost estimation”.

The following chapter presents the experimental setups prepared for this study. It also describes the procedures used to calculate the responses.

4 EXPERIMENTAL SETUP AND PROCEDURES

4.1 Introduction

This chapter highlights the significance of the material selected for experimentation. Two different laser drilling setups were developed to perform the laser drilling operation using a Quasi-CW fibre laser and a flashlamp-pumped Nd:YAG laser. Details of these experimental setups are provided along with specifications of the lasers. The method of cleaning of samples after the experimentation is explained. Moreover, the procedure and calculations used to measure productivity, energy efficiency and hole quality are described in detail. Details of the experimental methodology are also mentioned in each respective experimental chapter.

4.2 Material Selection

Aircraft engine components usually run under elevated temperature (above 1000°C) and high-pressure conditions (more than 1MPa) (Li et al., 2015). Material with outstanding thermo-mechanical properties is required for effective performance in such hot-sections of an aeroengine. Superalloys are ideal candidates for use in such extreme operating conditions because of excellent corrosion and wear resistance, and high creep strength properties (Reed, 2008). Superalloys are majorly classified into four categories, (Ni) nickel-based, (Ti) titanium-based, (Co) cobalt-based and (Fe) iron-based alloys, as depicted in Figure 4-1. A significant portion (70%) of superalloys is used by aerospace industries (see Figure 4-2) and approximately 50% of the aerospace components are manufactured by using Ni-based superalloys (Ganji and Rajyalakshmi, 2020).

Inconel 718 (Ni-based superalloy) is one of the most acceptable alloys in the aerospace industry. This superalloy consists of different elements which include nickel, molybdenum, chromium, titanium, iron and other distinctive elements. Nickel protects the components from the attack of any organic or inorganic compound; chromium prevents corrosion in oxidizing media and molybdenum provides resistance to pitting attack (Donachie and Donachie, 2002). The characteristics of high strength, excellent thermal and fatigue resistivity enable these alloys to be used in a wide range of applications such as aeroengine components, space shuttles, nuclear reactors and toolings.

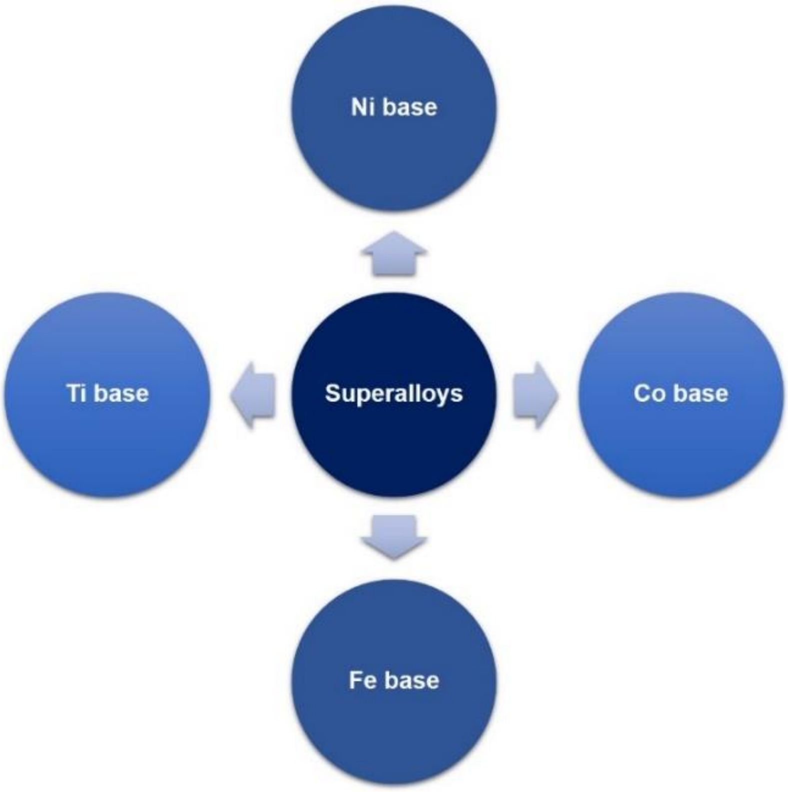


Figure 4-1 Major classification of superalloys

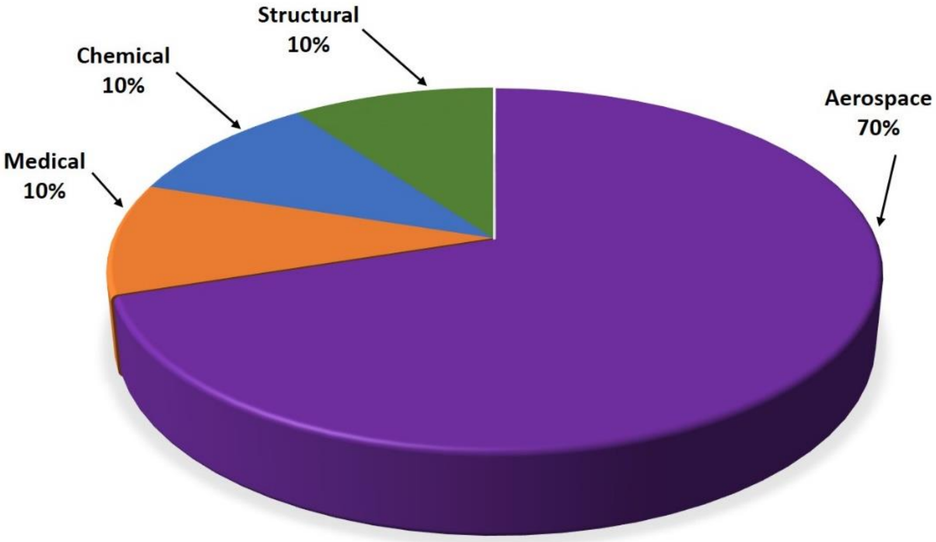


Figure 4-2 Use of superalloys in industries (Ganji and Rajyalakshmi, 2020)

Inconel® alloy 718 sheets were used for the experimentation. These sheets were supplied from Goodfellow, UK. The chemical composition of the material was validated via optical emission spectroscopy, the results of which are provided in Table 4-1.

Table 4-1 Chemical composition of Nickel (IN 718) superalloy

Ni	Cr	Mo	Mn	Ti	Nb	Fe	Al	Si
52.56	19	3.05	0.18	0.9	5.13	18.5	0.5	0.18

4.3 Laser Drilling Setup

Two laser drilling setups were developed to perform the drilling operation. The details of these setups are mentioned below.

Quasi-CW fibre laser

This drilling facility was provided by IPG Photonics Corporation at the company site. A Quasi-CW fibre laser (YLS-200/20000-QCW model, IPG Photonics, UK) was used for this setup. The experimental setup and its schematic diagram are presented in Figure 4-3 and Figure 4-4, respectively. The specifications of the laser system are given in Table 4-2. The laser beam was directed at the workpiece material using a 140 mm collimator lens and a focusing lens of 200 mm focal length. The laser beam distribution was of top-hat profile. The diameter of fibre used and laser beam spot size was 0.2 mm and 285 µm, respectively. The lens was equipped with a gas nozzle co-axially to deliver the assist gas and get protection from the flushing material.

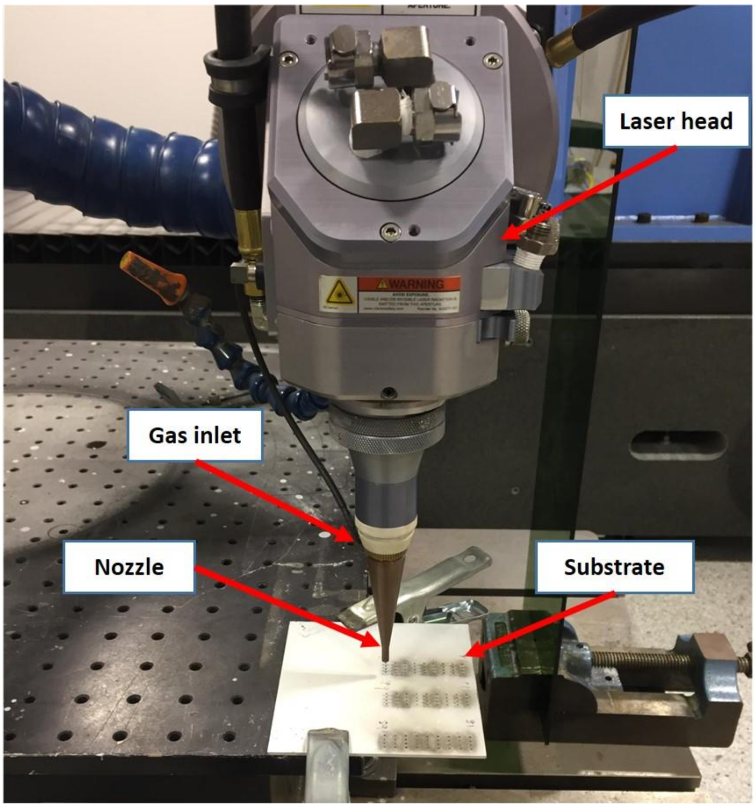


Figure 4-3 Laser drilling experimental setup (QCW fibre laser)

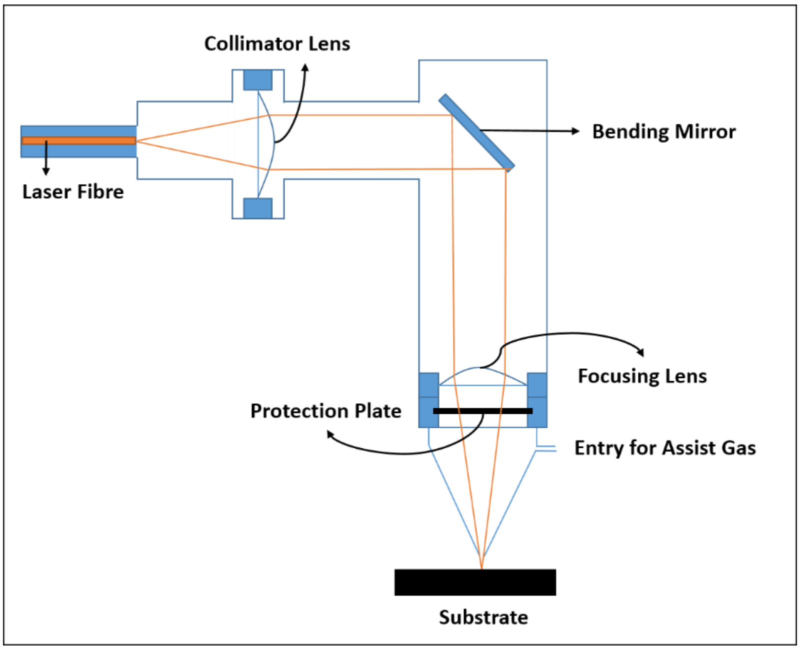


Figure 4-4 Schematic representation of laser drilling setup

Table 4-2 Laser system specifications (QCW fibre laser)

Specifications	Values
Wavelength	1070 nm
Peak power*	20,000 kW
Pulse duration	0.2 – 10 ms
Average power*	2000 W
Pulse energy*	200 J
Pulse frequency*	2000 Hz
* Maximum values	

Flashlamp-pumped Nd:YAG laser

This experimental setup was prepared in the lab at Cranfield University using flashlamp-pumped Nd:YAG laser (JK300HPS model, JK Lasers, UK). Laser system specifications are presented in Table 4-3. An optical fibre of 0.3 mm diameter was used to deliver the laser beam. The focal length of the optical lens used was 300 mm, giving a spot diameter of 0.9 mm. The laser beam profile distribution was Gaussian with TEM_{00}. Conical nozzle with a diameter of 2.0 mm was used to deliver the assist gas, and the distance between the nozzle tip and the substrate was fixed at 3.0 mm. The laser drilling setup prepared for the experiments is shown in Figure 4-5.

Table 4-3 Laser system specifications (Nd:YAG laser)

Specifications	Values
Wavelength	1064 nm
Peak power*	9 kW
Pulse duration	0.2 – 20 ms

Specifications	Values
Average power*	300 W
Pulse energy*	56 J
Pulse frequency*	1000 Hz
* Maximum values	

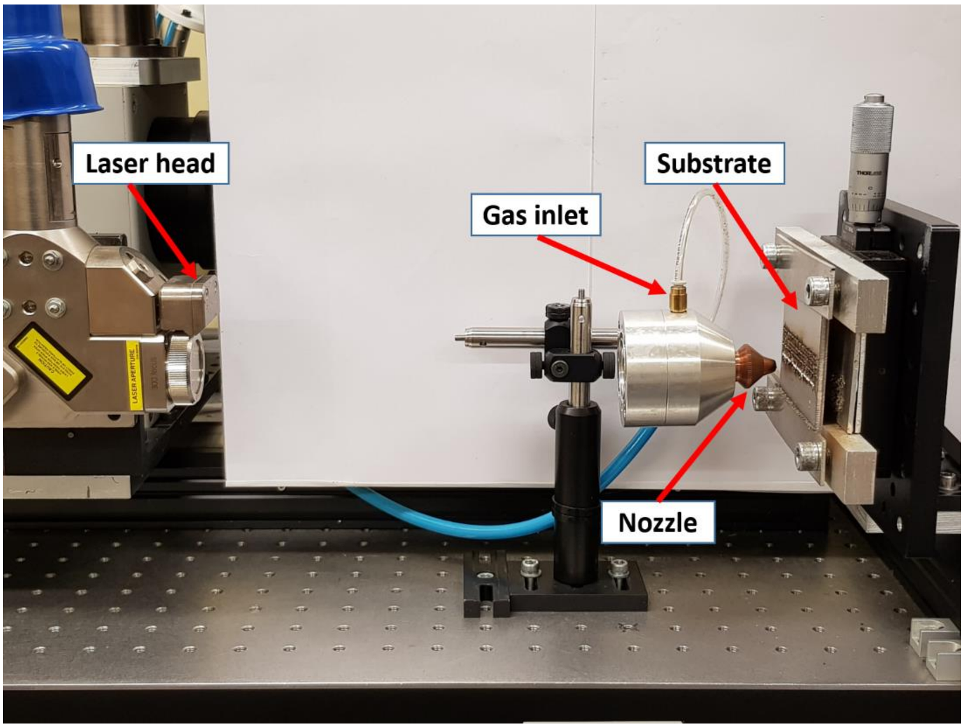


Figure 4-5 Laser drilling experimental setup (Nd:YAG laser)

All experiments were performed at a laser beam incidence angle of 90° to the material surface and the focal position of the laser beam was maintained at the workpiece surface. The hole pitch was set at 5 mm to prevent potential effects from adjacent holes.

4.4 Samples Preparation

After performing the drilling experiments, all samples were cleaned using a series of 240, 1200 and 2500 grade silicon carbide papers to make sure that debris from the surface of the specimen have been removed. Figure 4-6 shows an example of a specimen before and after cleaning.

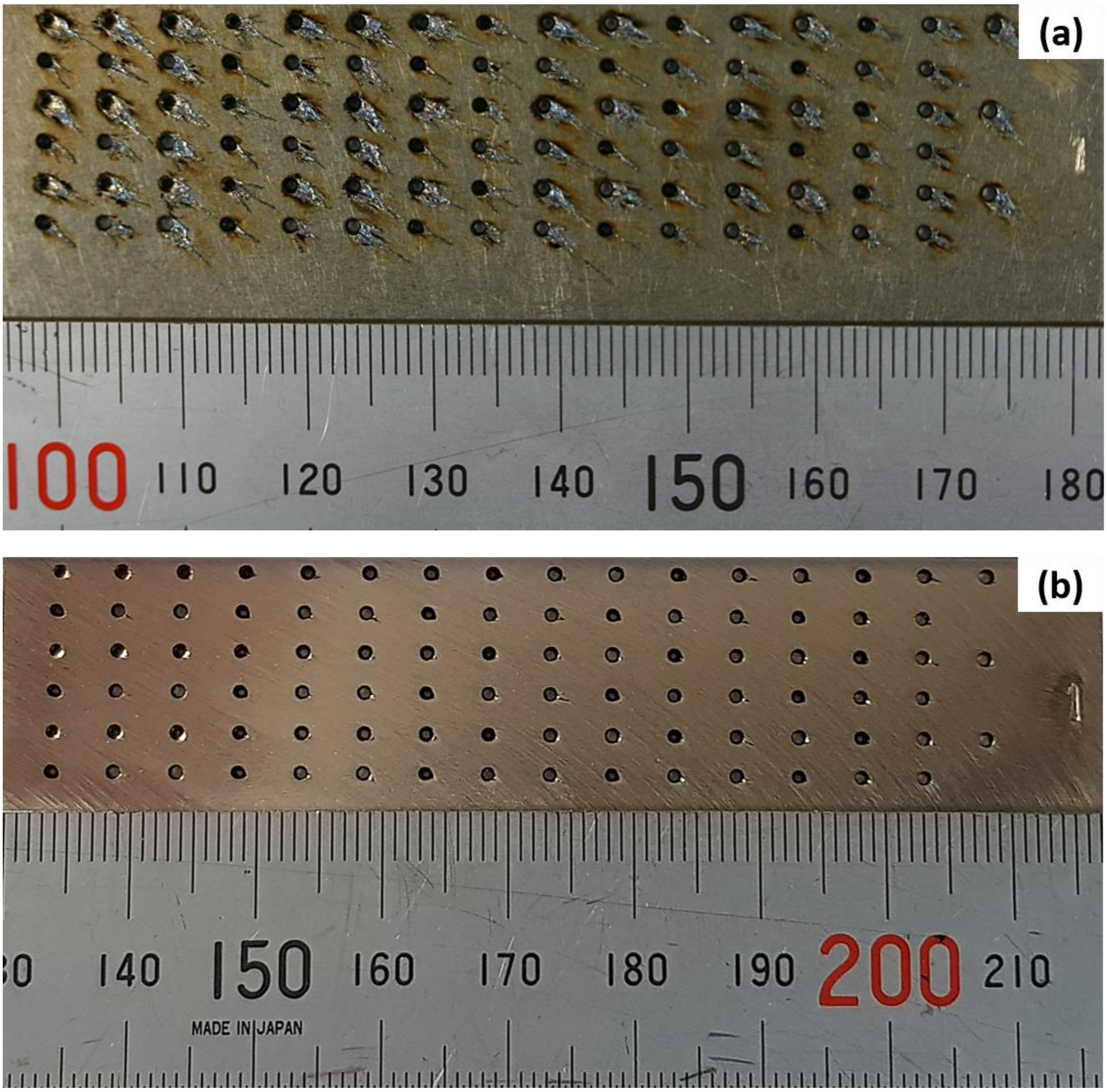


Figure 4-6 Laser drilling specimen (a) before cleaning (b) after cleaning

4.5 Measurements of the Responses

Each experimental run was performed three times and the average value was considered to minimise the error defects during experimentation and measurements. The method of measuring the responses is described in the following sections.

4.5.1 Productivity

The productivity of the laser drilling process was determined by the material removal rate, which specifies the amount of material removed per unit time. For the employed drilling techniques, MRR was determined using equation (4-1) (Sarfraz et al., 2019b).

$$MRR = \frac{V}{T} \tag{4-1}$$

where:

MRR = material removal rate (mm^3/s)

V = volume of material removed (mm^3)

T = drilling time per hole (s)

In this study, the final geometry of drilled holes was assumed as a frustum of the cone because of hole taper (see Figure 4-7), therefore the volume of material removed (V) was computed using equation (4-2) (Mishra and Yadava, 2013c).

$$V = \frac{1}{3}\pi t(R_{ent}^2 + R_{ent}^2 R_{ex}^2 + R_{ex}^2) \tag{4-2}$$

where:

t = workpiece thickness (mm)

R_{ent} = entry side radius of the drilled hole (mm)

R_{ex} = exit side radius of the drilled hole (mm)

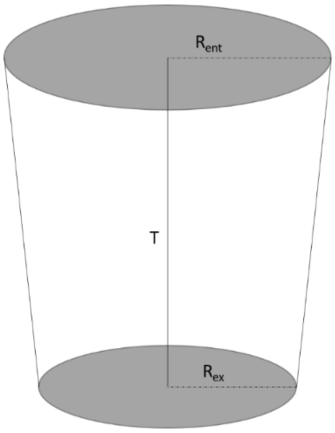


Figure 4-7 Schematic of hole taper

For each hole, a total of seven measurements were recorded for both entry and exit diameters ensuring coverage of minimum, maximum and average values (Figure 4-8). The arithmetic mean of these measurements was calculated to get an average value of the hole diameter for both entry and exit sides. These measurements were taken using an optical microscope (LEICA CTR6000, Leica, Germany), as shown in Figure 4-9.

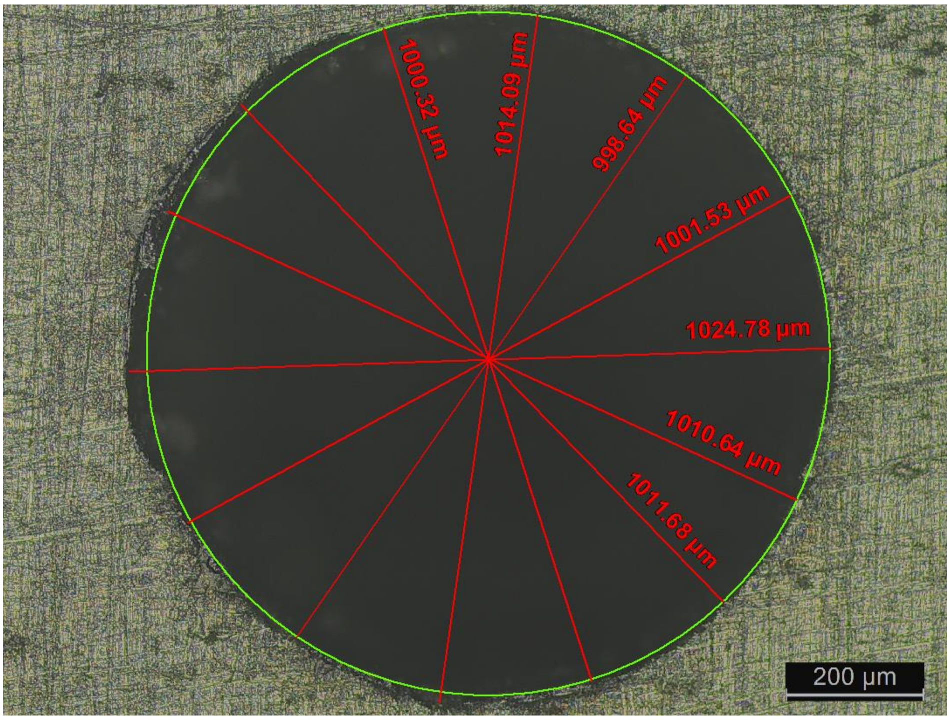


Figure 4-8 Measurement of the hole diameter produced by single-pulse drilling using Nd:YAG laser (P_e = 20 J, P_d = 6 ms, t = 1.0 mm, assist gas = compressed air)

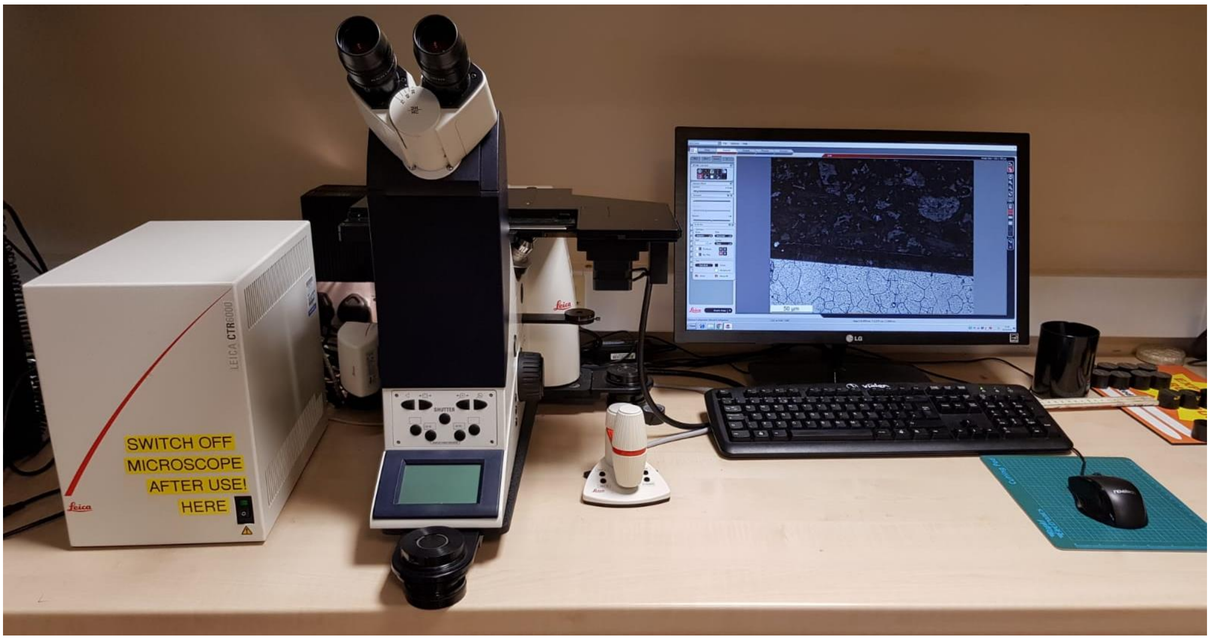


Figure 4-9 Leica optical microscope

4.5.2 Energy Efficiency

Specific energy consumption determines the energy consumed to remove a unit volume of material. SEC shows how efficiently the material is removed in terms of energy utilization, and it depicts the energy efficiency of the laser drilling process. For the single-pulse drilling method, equation (4-3) was used to calculate the value of SEC, while equations (4-4) and (4-5) were used for percussion and trepanning methods, respectively (Fysikopoulos et al., 2012; Franco et al., 2016). The expression used for average power calculation is also provided in equation (4-6).

$$SEC_{single-pulse\ drilling} = \frac{P_e}{V} \tag{4-3}$$

$$SEC_{percussion} = \frac{NOP \times P_e}{V} \tag{4-4}$$

$$SEC_{trepanning} = \frac{P_{avg}}{MRR} \tag{4-5}$$

$$P_{avg} = P_e \times P_f \tag{4-6}$$

where:

SEC = specific energy consumption (J/mm^3)

P_e = applied pulse energy (J)

NOP = number of pulses

P_{avg} = average laser power (W)

P_f = pulse frequency (Hz)

4.5.3 Hole Quality

The quality of the produced hole was specified by the hole taper, which depicts the ratio of the difference between the entry and exit hole diameter, and the plate thickness. The taper angle was measured in degrees. The following relation (equation (4-7)) was used to determine the hole taper angle (Sarfraz et al., 2019b).

$$HT\ (^\circ) = \tan^{-1}\left(\frac{D_{ent} - D_{ex}}{2 \times t}\right) \tag{4-7}$$

where:

HT = hole taper (degree)

D_{ent} = entry side diameter of the drilled hole (mm)

D_{ex} = exit side diameter of the drilled hole (mm)

The method of measuring the hole diameters is the same as explained in section 4.5.1.

4.6 Summary

Inconel 718 superalloy was used as workpiece material in this study because of its significant applications in the aerospace industry. Two different lasers were used for the experimentation including Quasi-CW fibre laser and flashlamp-pumped Nd:YAG laser. The purpose was to compare the performance of the laser drilling process while using different laser sources. After performing the experiments, all samples were cleaned to remove the spatter and/or debris from the workpiece surface. This helped in precise measurements of drilled hole dimensions. Both the entrance and exit hole dimensions were used to calculate the responses. The method of measuring hole dimensions and computation of responses is also briefly explained. The impacts of process parameters on the measured responses for single-pulse, percussion and trepanning drilling are discussed in the following chapter.

5 IMPACT OF PROCESS PARAMETERS ON LASER DRILLING PERFORMANCE

5.1 Introduction

Performance of the laser drilling process depends on the applied process parameters. At the same time, there are different laser drilling methods available that can be used to conduct laser drilling operations and each of them has different associated levels of performance. The selection of an appropriate laser drilling method and process parameter for a required performance level is a challenging task which is essential to understand for the user. Therefore, this chapter aims to deliver a clear understanding of the impacts of laser drilling process parameters on productivity (material removal rate), energy efficiency (specific energy consumption) and hole quality (hole taper) taking into consideration three different laser drilling methods i.e. single-pulse, percussion and trepanning.

A Quasi-CW fibre laser was used to drill holes in IN 718 superalloy using single-pulse, percussion and trepanning drilling. Effects of process parameters on material removal rate, specific energy consumption and hole taper have been discussed in accordance with the results obtained through experimentation. For each drilling method, key process parameters have been determined in relation to material removal rate, specific energy consumption and hole taper. The performance of laser drilling methods has also been examined based on the measured responses.

5.2 Process Parameters Selection

In the laser drilling process, material removal rate, specific energy consumption and hole quality depend on the selected process parameters. This research focuses on three different laser drilling processes i.e. single-pulse drilling, percussion and trepanning as these are the most widely used laser drilling methods in the industry. For evaluating the performance of single-pulse drilling, two process parameters were selected namely pulse energy and pulse duration. For percussion, the process parameters used were pulse energy, pulse duration and number of pulses. Pulse energy, pulse duration, pulse frequency and trepan speed were chosen as process parameters for the trepanning drilling process. These process parameters were selected because of their significant impact on material removal rate, hole quality and specific energy consumption, as reported by laser manufacturers' experts. Furthermore, the significance of these process parameters is enumerated in Chapter 2.

Based on an extensive literature review and trial experiments values of process parameters were selected so that drilling of holes gives better hole quality and material removal rate with minimum energy consumption. The process parameters with levels for the employed drilling methods are provided in Table 5-1. However, some of the parameters were kept constant during the entire experimentation and are listed in Table 5-2.

Table 5-1 Process parameters and their values

Drilling method(s)	Process parameters	Values
Single-pulse	Pulse energy (P_e)	20, 30, 40 (J)
	Pulse duration (P_d)	2, 3, 4 (ms)
Percussion	Pulse energy	5, 6, 7 (J)
	Pulse duration	0.5, 1, 1.5 (ms)
	Number of pulses per hole (NOP/hole)	5, 10, 15
Trepanning	Pulse energy	5, 6, 7 (J)
	Pulse duration	0.5, 1, 1.5 (ms)
	Pulse frequency (P_f)	20, 30, 40 (Hz)
	Trepan speed (T_s)	30, 40, 50 (mm/min)

Table 5-2 Values of the fixed parameters

Parameters	Values
Frequency (percussion)	10 (Hz)
Programmed radius (trepanning)	0.125 (mm)
(Assist) gas pressure	100 (psi)
Assist gas	Compressed air

5.3 Experimental Procedure

Laser drilling of 1 mm thick IN 718 superalloy sheet was performed using single-pulse drilling, percussion and trepanning. The selected material thickness represents the typical wall thickness of aeroengine components (see Table 2-1). A Quasi-CW fibre laser was used for this study. The laser specifications and experimental setup are given in Chapter 4. For each method, nine experiments in total were designed using a Taguchi L9 orthogonal array. The reason for using a Taguchi array was to evaluate the impact of the process parameters with a reduced number of experiments (Roy, 2010). Material removal rate, specific energy consumption and hole taper were calculated for each experimental run; the observed values are tabulated in Tables 5-3 – 5-5.

Table 5-3 Experimental design matrix and observed responses (single-pulse drilling)

Exp. No.	Process parameters		Responses		
	P_e (J)	P_d (ms)	MRR (mm^3/s)	SEC (J/mm^3)	HT (°)
1	20	2	98.85	101.16	7.56
2	20	3	58.93	113.12	6.87
3	20	4	41.05	121.8	6.51
4	30	2	124	120.97	10.04
5	30	3	67.77	140.57	7.57
6	30	4	46.78	156.34	6.24
7	40	2	143.15	139.71	11.34
8	40	3	83.13	160.38	9.11
9	40	4	55.92	178.81	7.2

Table 5-4 Experimental design matrix and observed responses (percussion)

Exp. No.	Process parameters			Responses		
	P_e (J)	P_d (ms)	NOP/hole	MRR (mm^3/s)	SEC (J/mm^3)	HT (°)
1	5	0.5	5	0.433	115.53	7.18
2	5	1	10	0.210	281.06	6.61
3	5	1.5	15	0.097	441.96	5.81
4	6	0.5	10	0.265	269.96	6.65
5	6	1	15	0.123	488.6	6.02
6	6	1.5	5	0.328	176.26	6.23
7	7	0.5	15	0.153	427.87	6.38
8	7	1	5	0.391	185.09	6.26
9	7	1.5	10	0.237	415.92	5.54

Table 5-5 Experimental design matrix and observed responses (trepanning)

Exp. No.	Process parameters				Responses		
	P_e (J)	P_d (ms)	P_f (Hz)	T_s (mm/min)	MRR (mm^3/s)	SEC (J/mm^3)	HT (°)
1	5	0.5	20	30	0.125	734.93	4.24
2	5	1	30	40	0.147	1016.87	3.42
3	5	1.5	40	50	0.165	1196.94	3.29
4	6	0.5	30	50	0.189	961.19	3.81
5	6	1	40	30	0.120	2058.46	2.31
6	6	1.5	20	40	0.132	918.92	2.97
7	7	0.5	40	40	0.165	1790.3	2.66
8	7	1	20	50	0.174	760.48	3.36
9	7	1.5	30	30	0.106	2036.91	1.75

5.4 Investigation of Process Parameters' Impact on the Responses

An analysis of the data was performed using statistical software (Design-Expert®version10). This included an examination of the influence of laser drilling process parameters on the measured responses as well as the identification of significant process parameters for the mentioned laser drilling methods.

The impact of process parameters (single-pulse drilling: pulse energy and pulse duration; percussion: pulse energy, pulse duration, and number of pulses per hole; trepanning: pulse energy, pulse duration, pulse frequency, and trepan speed) on MRR, SEC, and HT for single-pulse, percussion, and trepanning were examined using 3D response surface graphs. Analysis of variance (ANOVA) was performed at a 95% confidence interval to determine the significance level of the process parameters for each drilling method with respect to the measured responses. The results are discussed below in detail.

5.4.1 Single-Pulse Drilling

Figure 5-1 shows the material removal rate achieved during single-pulse drilling for different pulse energies at the three different pulse durations used. It is observed that MRR is more sensitive to a change in pulse duration compared to pulse energy. Furthermore, MRR increases with an increase in pulse energy. This is due to the fact that high pulse energy increases the melt surface temperature which in turn enhances recoil pressure (see Figure 2-3). This ultimately results in a high MRR. On the other hand, higher MRR is observed at low values of pulse duration because peak power of the laser beam is higher when a short pulse duration is employed. This helps in penetration during the laser drilling operation and results in an increase in the material removal rate. Similar results were noted by Yang et al. (2016) and Sarfraz et al. (2019b).

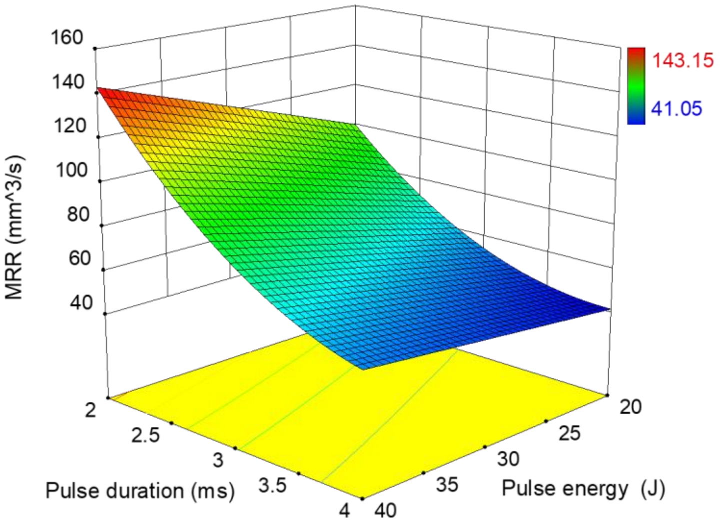


Figure 5-1 Response surface plot for MRR vs. P_e and P_d (single-pulse drilling)

The impacts of pulse energy and pulse duration on specific energy consumption are presented in Figure 5-2. An increasing trend is observed with an increment in pulse energy and pulse duration. The graph demonstrates that while keeping the pulse duration constant, a significant increase in the SEC value is observed with an increase in pulse energy because of the high energy consumed during the process (Franco et al., 2016). It is also evident that keeping the pulse energy constant, SEC increases with the increase in pulse duration because of lower peak power at longer pulse duration, which consumes more energy to penetrate into the workpiece material.

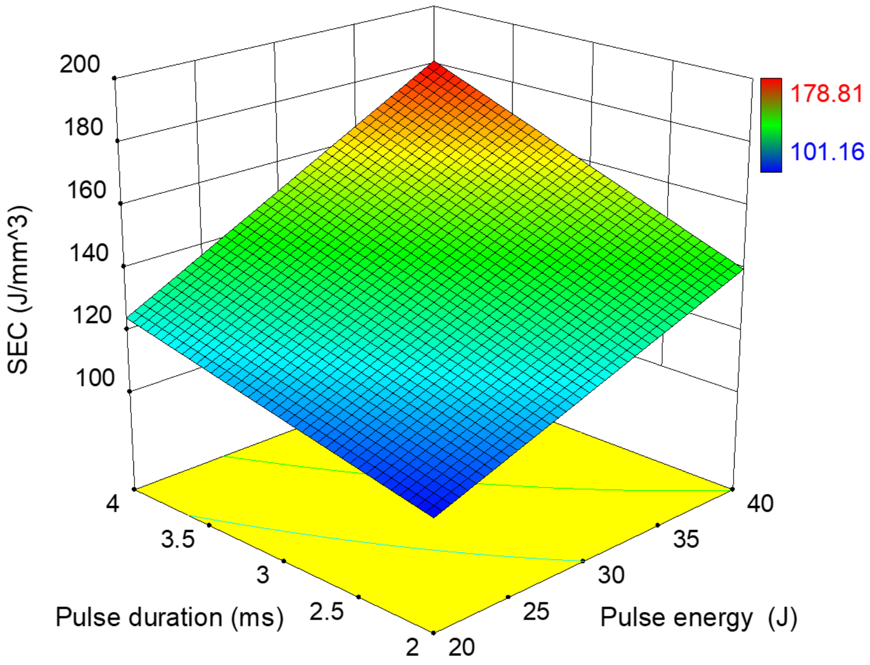


Figure 5-2 Response surface plot for SEC vs. P_e and P_d (single-pulse drilling)

Figure 5-3 depicts the effects of pulse energy and pulse duration on hole taper. This graph demonstrates that there is a substantial decrease in the value of hole taper when the pulse duration is increased from 2 ms to 4 ms because it permits enough interaction time between the workpiece and laser beam to allow the expulsion of molten material from the hole (bottom side) more effectively. On the other hand, a small increase in hole taper value is observed when pulse energy is changed from 20 J to 40 J. When a laser beam with high pulse energy interacts with the top side of the workpiece, it melts and vaporizes the material instantly and increases the mean (entrance) hole diameter; however, the intensity of the laser beam decreases as it passes through the thickness, which results in a small exit hole diameter, and produces a high hole taper. This variation is consistent with the findings of Chatterjee et al. (2018a) and Sarfraz et al. (2019b).

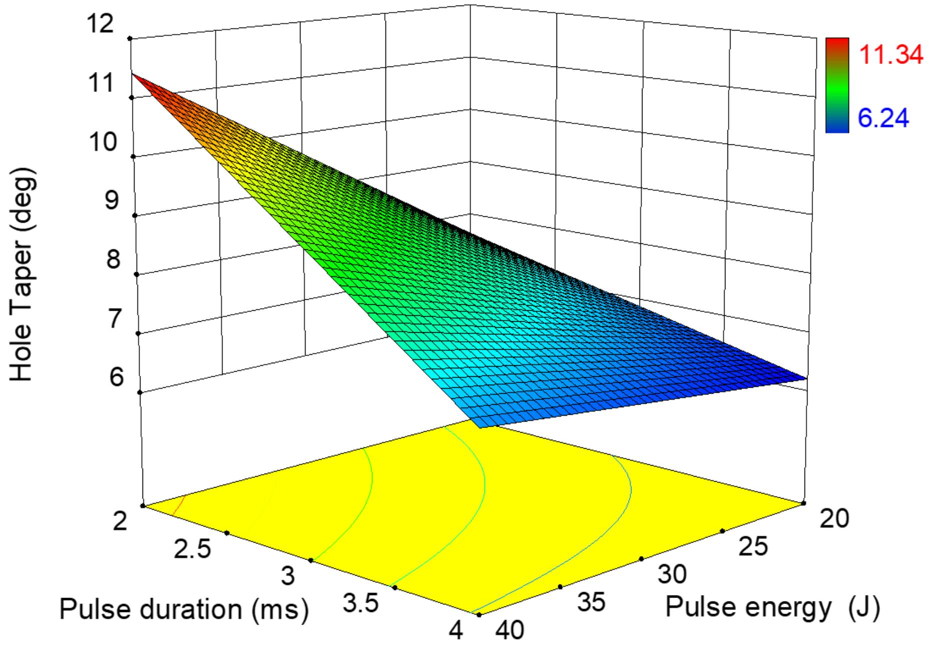


Figure 5-3 Response surface plot for HT vs. P_e and P_d (single-pulse drilling)

For single-pulse drilling, the results of ANOVA depicting significant process parameters along with their percentage contribution with respect to material removal rate, specific energy consumption and hole taper are summarised in Table 5-6. Both pulse energy and pulse duration were found to be significant process parameters for all responses with P values < 0.05. The highest F value of 164.05 and percentage contribution of 67.57% clearly indicate pulse energy as the most significant parameter for SEC. On the other hand, pulse duration was revealed to be the most significant parameter affecting the MRR and HT.

Table 5-6 ANOVA results for MRR, SEC and HT (single-pulse drilling)

Source	**df**	**SS**	**MS**	**F value**	**P value**	**Contribution (%)**
For MRR						
P_e	1	1158.57	1158.57	10.04	0.0193	11.49
P_d	1	8232.51	8232.51	71.38	0.002	81.65
Residual	6	692.04	115.34	-	-	6.86
Total	8	10083.11	-	-	-	100
For SEC						
P_e	1	3399.59	3399.59	164.05	<0.0001	67.57
P_d	1	1507.65	1507.65	72.75	0.0001	29.96
Residual	6	124.34	20.72	-	-	2.47
Total	8	5031.58	-	-	-	100
For HT						
P_e	1	7.50	7.50	7	0.0093	31.07
P_d	1	13.47	13.47	14.22	0.0023	55.8
Residual	6	3.17	0.53	25.52	-	13.13
Total	8	24.14	-	-	-	100
df: Degree of freedom, SS: Sum of squares, MS: Mean square						

5.4.2 Percussion

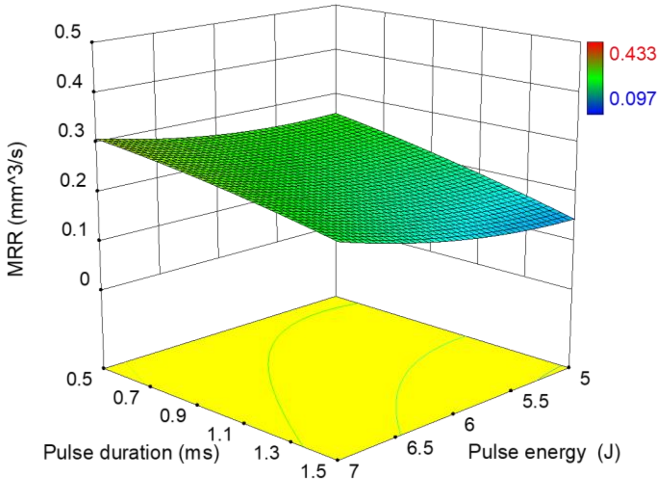
The response of pulse energy and pulse duration on MRR and SEC for percussion are presented in Figures 5-4 (a) and 5-5 (a), respectively. Similar effects have been observed for pulse energy and pulse duration on MRR and SEC as in the case of single-pulse drilling; however, this process is a multi-pulse process where each pulse contributes to produce a hole. Therefore, the influence of process parameters on hole taper is slightly different; this is described later in this section.

Figure 5-4 (b) shows the impacts of pulse energy and NOP per hole on MRR. It is noted that MRR decreases with an increase in NOP per hole and increases with an increase in pulse energy. It is also revealed that a combination of minimum NOP and high pulse energy results in maximum MRR. This is due to the fact that lower NOP need less time for drilling. On the other hand, high pulse energy increases the transfer rate of heat energy into the substrate, resulting in a rapid increase in melt volume and this eventually results in higher MRR.

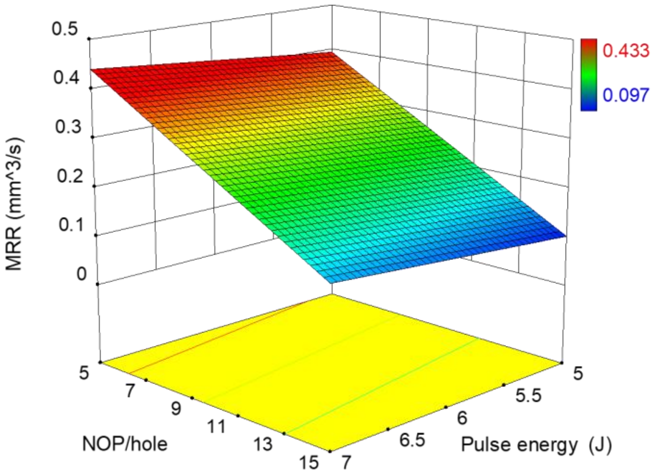
The surface plot (Figure 5-4 (c)) presents the inverse effect of pulse duration and NOP per hole on MRR. It can also be observed that MRR is affected more by NOP than pulse duration.

Figure 5-5 (b) depicts the impacts of pulse energy and NOP per hole on the SEC. The figure indicates that SEC increases with the increment in pulse energy and NOP. It can also be noted that SEC is affected more by NOP than pulse energy. Both pulse energy and NOP have a direct relation with SEC and therefore results in higher SEC value, as reported by Bandyopadhay et al. (2002).

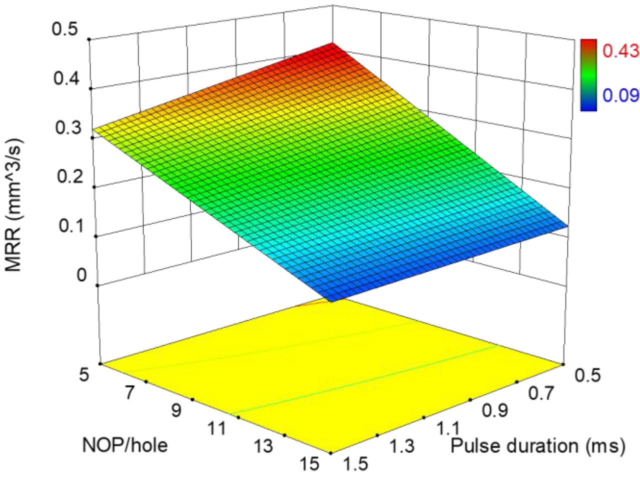
The effects of pulse duration and NOP per hole on SEC have been provided in Figure 5-5 (c). The SEC is maximum at higher values of pulse duration and NOP per hole. It is also evident that the impact of NOP on SEC is higher as compared to pulse duration. The decrease in peak power at higher pulse duration levels is the main reason for the rise in SEC value.



(a) Response surface plot for MRR vs. P_e and P_d

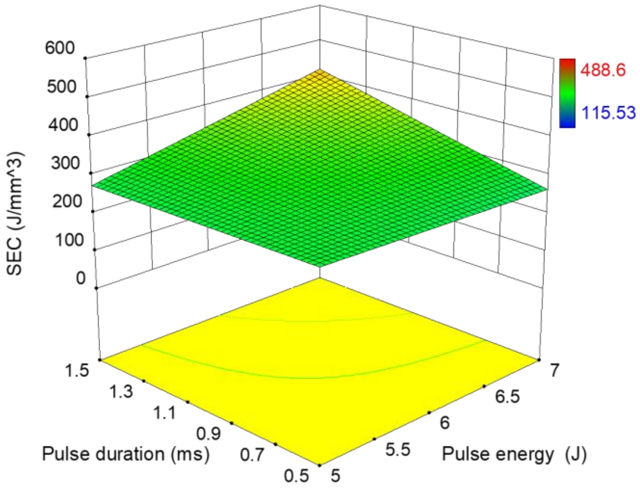


(b) Response surface plot for MRR vs. P_e and NOP/hole

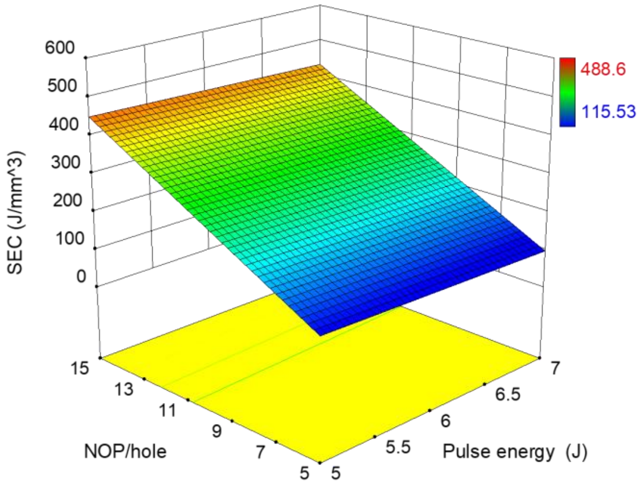


(c) Response surface plot for MRR vs. P_d and NOP/hole

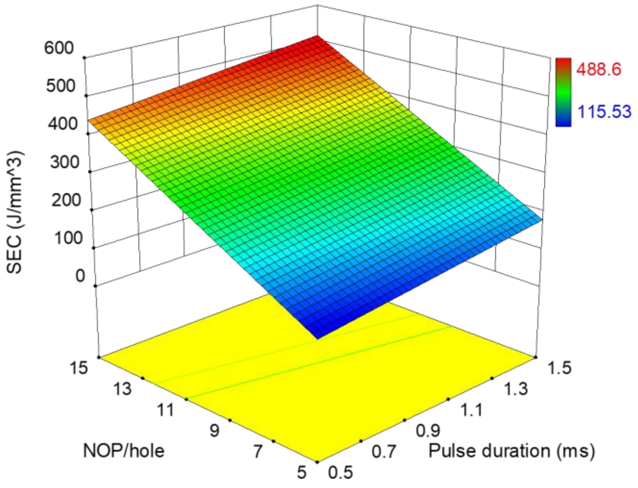
Figure 5-4 Effects of process parameters on MRR for percussion



(a) Response surface plot for SEC vs. P_e and P_d



(b) Response surface plot for SEC vs. P_e and NOP/hole



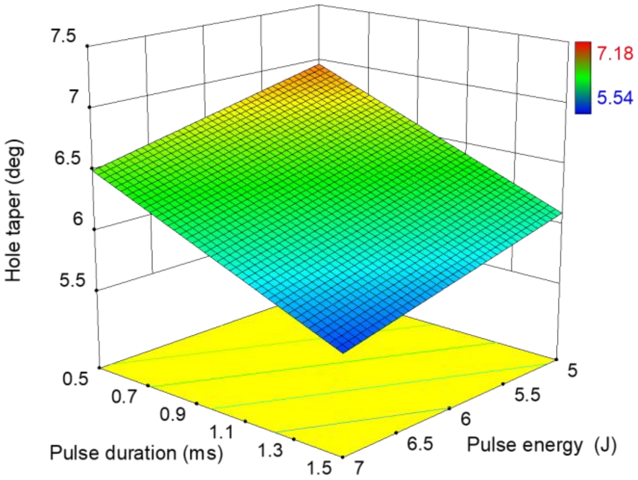
(c) Response surface plot for SEC vs. P_d and NOP/hole

Figure 5-5 Effects of process parameters on SEC for percussion

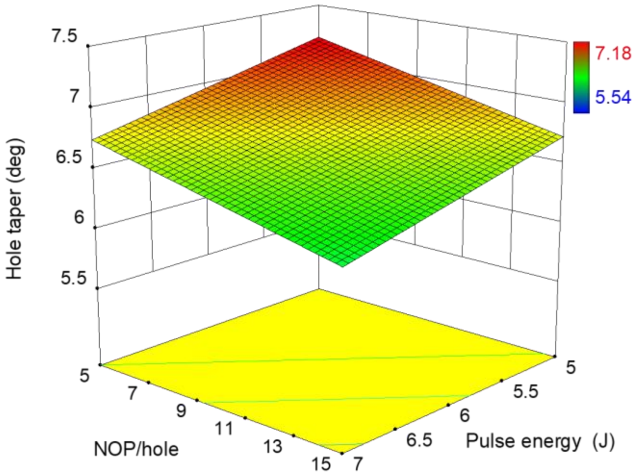
Figure 5-6 (a) demonstrates the impacts of pulse energy and pulse duration on hole taper for percussion drilling. It is clear that the hole taper is less sensitive to variation in pulse energy as compared to pulse duration. Furthermore, hole taper decreases with the increase in values of both parameters. The reason is that at high pulse energy the intensity of the laser beam is enough to remove sufficient material from the hole exit side (Thawari et al., 2005) and the application of higher pulse duration provides sufficient laser beam-workpiece interaction time that leads to a fair reduction in hole taper.

The impacts of pulse energy and NOP per hole on hole taper are presented in Figure 5-6 (b). It can be observed that the hole taper decreases with the increase in pulse energy and NOP per hole. The decrease in hole taper at higher NOP value is the result of additional laser pulses that assist in removing material from the hole on the bottom side after the formation of the through-hole, thereby enlarging the exit hole diameter, which eventually produces lower hole taper (Ghoreishi et al., 2002b). It is also evident that the effect of NOP on the hole taper is large as compared to pulse energy.

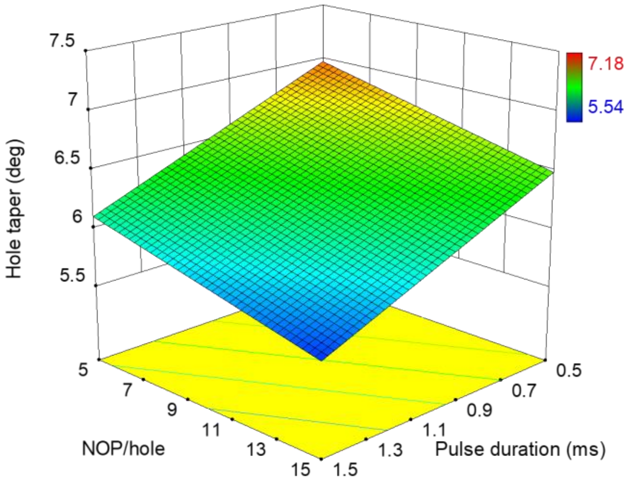
The 3D relationship of pulse duration and NOP per hole on hole taper is illustrated in Figure 5-6 (c). It is noted that the minimum hole taper can be obtained at high levels of pulse duration and NOP per hole. Moreover, hole taper is more sensitive to variation in pulse duration as compared to NOP per hole. This behaviour is because of an increase in interaction time between the workpiece and laser beam as explained above.



(a) Response surface plot for HT vs. P_e and P_d



(b) Response surface plot for HT vs. P_e and NOP/hole



(c) Response surface plot for HT vs. P_d and NOP/hole

Figure 5-6 Effects of process parameters on HT for percussion

The ANOVA results for all the measured responses for percussion drilling are provided in Table 5-7. It is clearly evident that all the process parameters are significant with P values less than 0.05 for the mentioned responses. Number of pulses per hole was noted as the most significant process parameter for MRR and SEC with a contribution of 93% and 87.42% respectively. For HT, pulse duration was indicated as the most influencing parameter among all other process parameters with a contribution of 60.48%.

Table 5-7 ANOVA results for MRR, SEC and HT (percussion)

Source	df	SS	MS	F value	P value	Contribution (%)
For MRR						
P_e	1	0.001949	0.001949	4.84	0.0425	1.95
P_d	1	0.004161	0.004161	13.70	0.0140	4.16
NOP/hole	1	0.093	0.093	307.20	<0.0001	93
Residual	5	0.00089	0.000178	-	-	0.89
Total	8	0.100	-	-	-	100
For SEC						
P_e	1	6037.58	6037.58	6.75	0.0484	4.08
P_d	1	8123.97	8123.97	9.08	0.0296	5.48
NOP/hole	1	129500	129500	144.81	<0.0001	87.42
Residual	5	4472.03	894.41	-	-	3.02
Total	8	148133.58	-	-	-	100
For HT						
P_e	1	0.33	0.33	29.85	0.0028	17.51
P_d	1	1.14	1.14	103.75	0.0002	60.48
NOP/hole	1	0.36	0.36	32.46	0.0023	19.1
Residual	5	0.055	0.011	-	-	2.92
Total	8	1.885	-	-	-	100

5.4.3 Trepanning

Figures 5-7 (a) and 5-8 (a) illustrate the impacts of pulse energy and pulse duration on MRR and SEC for trepanning. The trends are similar to single pulse and percussion drilling.

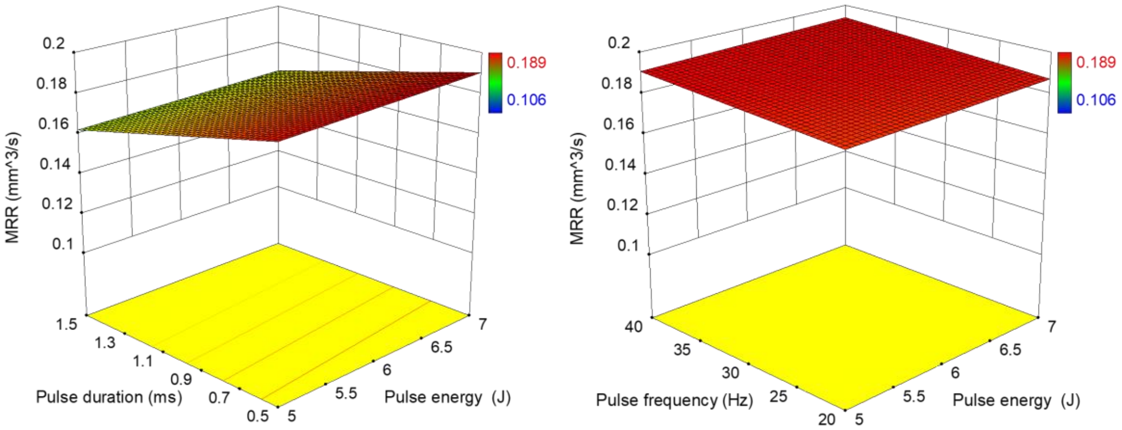
Figure 5-7 (b) shows the direct influence of pulse energy and pulse frequency on MRR. It can be observed that a combination of maximum pulse frequency and pulse energy results in a high MRR value. This is because high pulse frequency and pulse energy values result in a short time gap between pulses and allow more energy to enter into the workpiece material. Consequently, more amount of material is removed. Similar findings have been reported by Mishra and Yadava (2013a).

The 3D response surface plot shown in Figure 5-7 (c) presents the direct influence of pulse energy and trepan speed on MRR. This is because pulse energy has a direct relation with heat flow and increase in pulse energy allows a large amount of heat to enter into the material that subsequently increases the melt front temperature to produce a large-melt volume. Furthermore, the increase in trepan speed removes the material faster, which eventually results in a higher MRR. It can also be observed that the MRR is affected more by trepan speed than pulse energy.

The impacts of pulse duration and pulse frequency on MRR show that MRR decreases by increasing pulse duration (Figure 5-7 (d)). On the contrary, a positive trend is noticed with the increase in pulse frequency. It is also clear that MRR is more sensitive to pulse duration in comparison with pulse frequency.

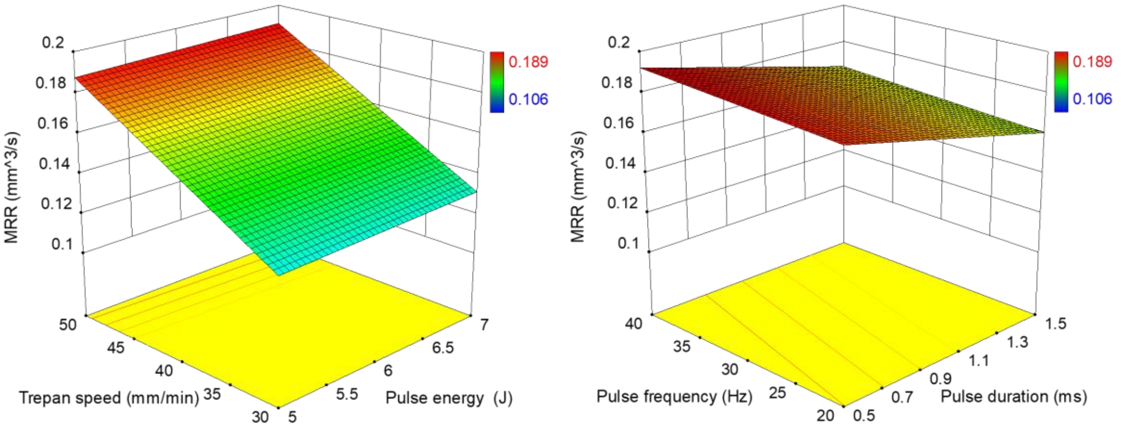
Figure 5-7 (e) describes the influence of pulse duration and trepan speed on MRR. It is evident from the graph that pulse duration has less effect on MRR as compared to trepan speed. Moreover, maximum MRR is achieved at a lower level of pulse duration and a higher level of trepan speed. This is because at fast trepan speed laser beam overlap increases, this removes the material more effectively (Marimuthu et al., 2019a), and high peak power at low pulse duration also contributes in material removal, thus higher MRR is achieved.

The 3D relationship between the MRR and pulse frequency and trepan speed is presented in Figure 5-7 (f). The combination of minimum pulse frequency and trepan speed results in a lower MRR value. MRR increases with the increase in pulse frequency and trepan speed because of high laser power availability and large beam overlap.



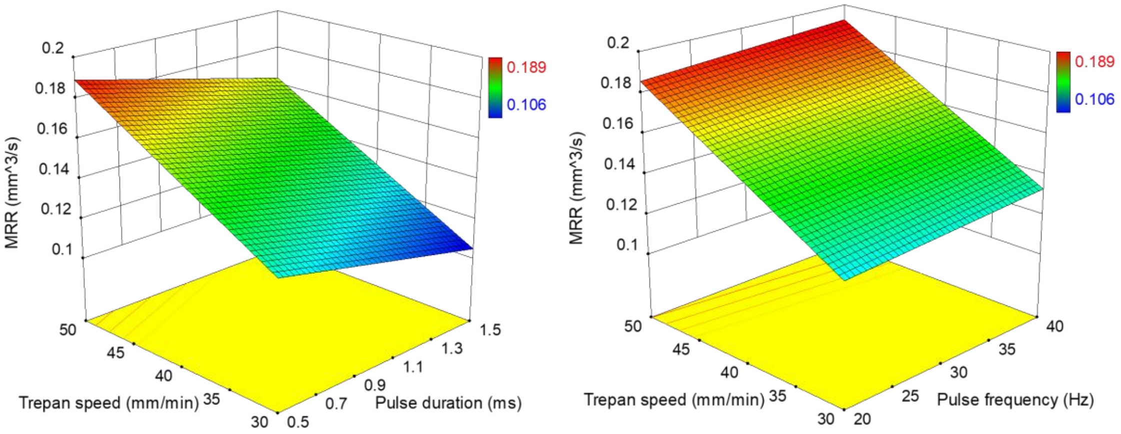
(a) Response surface plot for MRR vs. P_e and P_d

(b) Response surface plot for MRR vs. P_e and P_f



(c) Response surface plot for MRR vs. P_e and T_s

(d) Response surface plot for MRR vs. P_d and P_f



(e) Response surface plot for MRR vs. P_d and T_s

(f) Response surface plot for MRR vs. P_f and T_s

Figure 5-7 Effects of parameters on MRR for trepanning

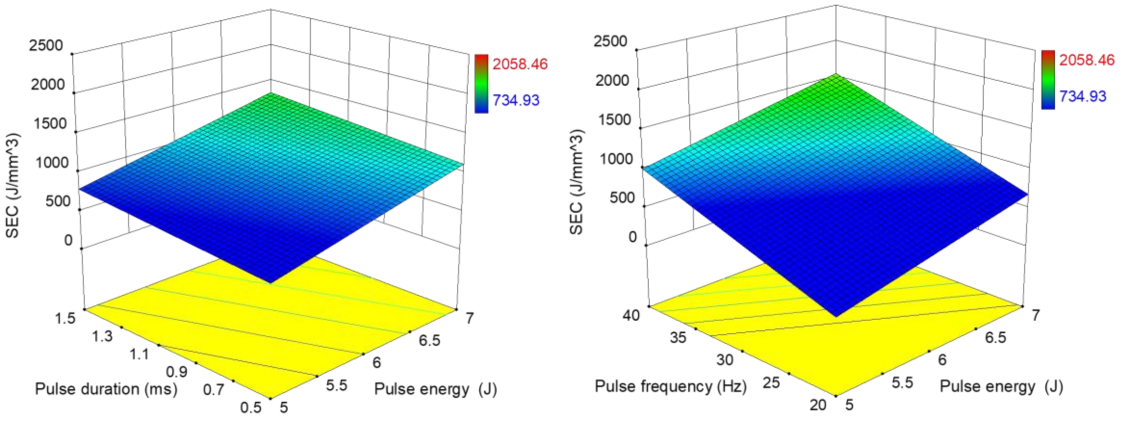
The impacts of pulse energy and pulse frequency on SEC show that SEC increases by increasing pulse energy (Figure 5-8 (b)). A similar trend is observed with the increment in pulse frequency. This is due to the fact that the average power of a laser increases at higher values of pulse energy and pulse frequency and, therefore, consumes more energy (Franco et al., 2016).

Figure 5-8 (c) depicts the effects of pulse energy and trepan speed on SEC. The surface plot shows a direct influence of pulse energy on SEC. On the contrary, a negative trend is observed with an increase in trepan speed. An increase in the trepan speed can contribute to high material removal volume, which eventually reduces the SEC value.

The 3D response surface plot shown in Figure 5-8 (d) presents the effects of pulse duration and pulse frequency on SEC. It can be identified that the SEC value increases with an increase in pulse duration and pulse frequency. It is also clear that pulse frequency influences SEC more than pulse duration. The reason for this is that at higher pulse frequency the laser consumes more power (Fysikopoulos et al., 2012).

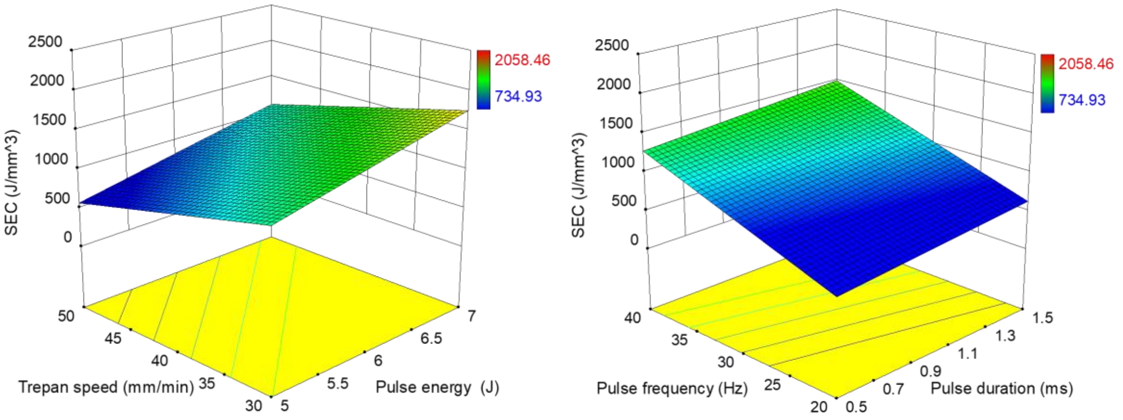
Figure 5-8 (e) describes the influence of pulse duration and trepan speed on SEC. It is clear from the surface plot that pulse duration has less effect on SEC as compared to trepan speed. Moreover, minimum SEC is achieved at a lower level of pulse duration.

The response surface plot in Figure 5-8 (f) describes the effects of pulse frequency and trepan speed on SEC. The graph demonstrates that SEC is minimum at low levels of pulse frequency and high levels of trepan speed. Furthermore, SEC is found to be more sensitive to variation in pulse frequency as compared to the trepan speed.



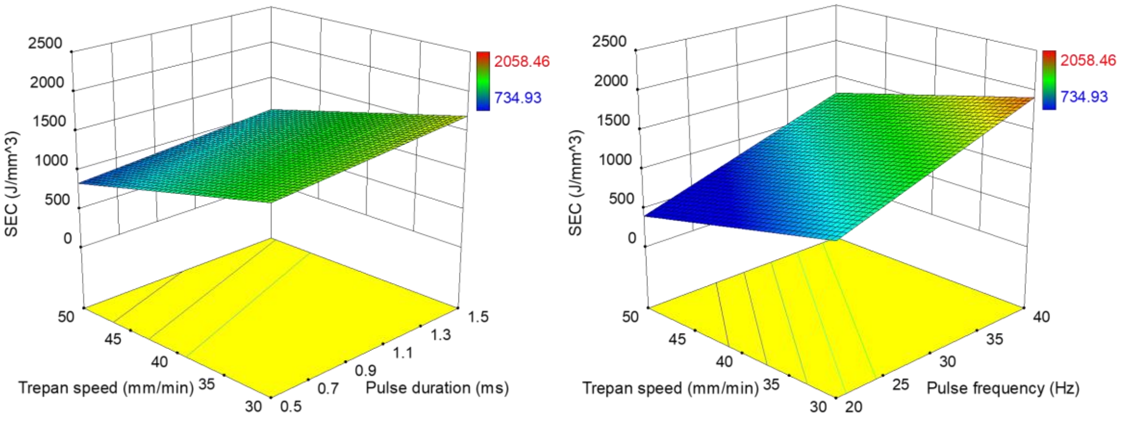
(a) Response surface plot for SEC vs. P_e and P_d

(b) Response surface plot for SEC vs. P_e and P_f



(c) Response surface plot for SEC vs. P_e and T_s

(d) Response surface plot for SEC vs. P_d and P_f



(e) Response surface plot for SEC vs. P_d and T_s

(f) Response surface plot for SEC vs. P_f and T_s

Figure 5-8 Effects of parameters on SEC for trepanning

The impact of pulse energy and pulse duration on hole taper for trepanning are presented in Figure 5-9 (a). Similar trends have been found as in the case of percussion drilling.

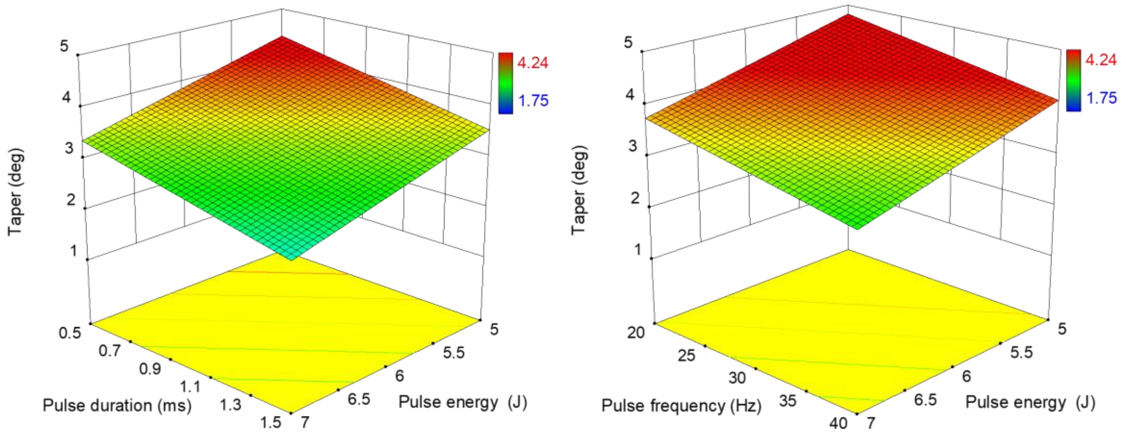
Figure 5-9 (b) represents the effects of pulse energy and pulse frequency on hole taper. A decreasing trend is observed with an increase in pulse energy and pulse frequency. Laser power increases at higher values of pulse frequency, which imparts more heat into the substrate material and therefore results in efficient melting (removal) of material, particularly on the exit side of a hole. As a result, the difference between entry and exit hole diameters decreases and lower hole taper is produced (Mishra and Yadava, 2013a).

The impact of pulse energy and trepan speed on hole taper show that hole taper decreases by increasing pulse energy (Figure 5-9 (c)). On the contrary, an increase in the trepan speed results in increased hole taper. It is also evident that hole taper is less sensitive to trepan speed as compared to pulse energy. The reason for this behaviour is that an increase in trepan speed does not provide enough time to distribute the required heat into the work material and eventually results in higher hole taper.

The effects of pulse duration and pulse frequency on hole taper have been described in Figure 5-9 (d). It can be identified that minimum hole taper is observed at the maximum level of pulse duration and pulse frequency because of high laser power availability.

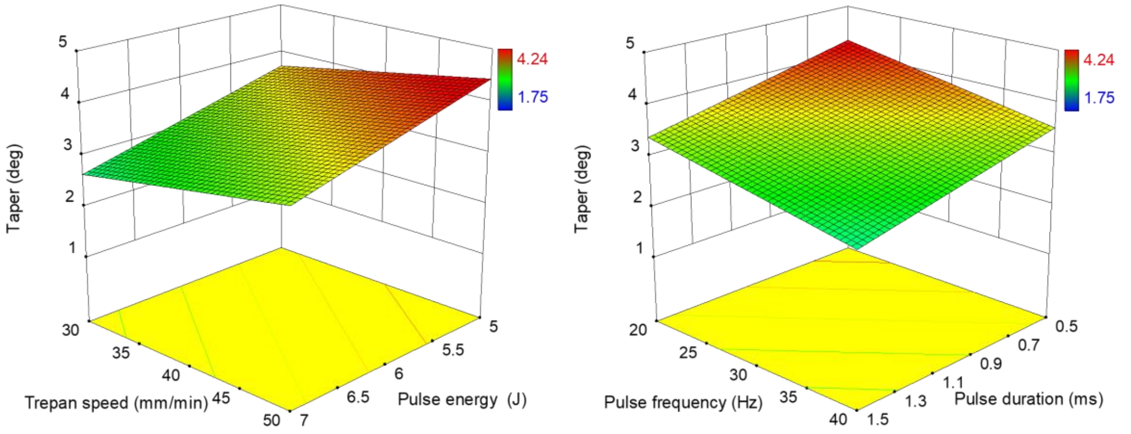
Figure 5-9 (e) depicts the influence of pulse duration and trepan speed on hole taper. It is clearly seen that a combination of maximum pulse duration and minimum trepan speed results in a smaller hole taper value.

Figure 5-9 (f) shows the effects of pulse frequency and trepan speed on hole taper. At a low level of trepan speed, hole taper increases with an increase in pulse frequency. A similar effect is observed at high levels of trepan speed.



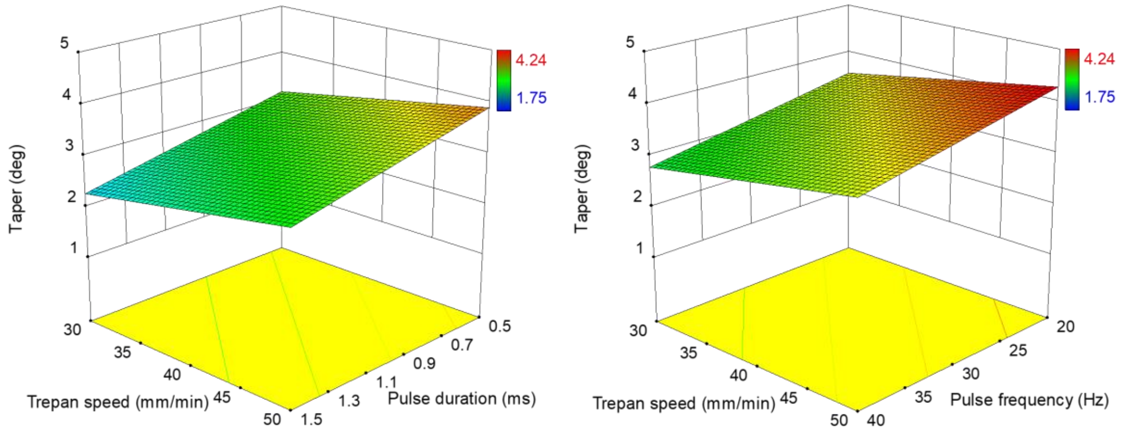
(a) Response surface plot for HT vs. P_e and P_d

(b) Response surface plot for HT vs. P_e and P_f



(c) Response surface plot for HT vs. P_e and T_s

(d) Response surface plot for HT vs. P_d and P_f



(e) Response surface plot for HT vs. P_d and T_s

(f) Response surface plot for HT vs. P_f and T_s

Figure 5-9 Effects of parameters on HT for trepanning

Table 5-8 presents the results of ANOVA for trepanning method in relation to MRR, SEC and HT. P values (<5) specify that all process parameters have a statistically significant effect on the mentioned responses. As shown in Table 5-8, trepan speed is a significant parameter affecting the material removal rate with the highest F value of 5481.89 and percentage contribution of 83.57%, while pulse energy shows the least effect on the MRR. Pulse frequency (49.87%) contributed significantly for SEC followed by trepan speed (26.32%), pulse energy (19.35%) and pulse duration (3.2%). In the case of HT, both the F value and percentage contribution value showed pulse energy as the most significant process parameter.

Table 5-8 ANOVA results for MRR, SEC and HT (trepanning)

Source	df	SS	MS	F value	P value	Contribution (%)
For MRR						
P_e	1	1.09×10^{-5}	1.09×10^{-5}	11.48	0.0276	0.18
P_d	1	9.53×10^{-4}	9.53×10^{-4}	1000.06	<0.0001	15.24
P_f	1	5.95×10^{-5}	5.95×10^{-5}	62.50	0.0014	0.95
T_s	1	5.22×10^{-3}	5.22×10^{-3}	5481.89	<0.0001	83.57
Residual	4	3.81×10^{-6}	9.52×10^{-7}	-	-	0.06
Total	8	6.25×10^{-3}	-	-	-	100
For SEC						
P_e	1	4.48×10^{5}	4.48×10^{5}	60.82	0.0015	19.35
P_d	1	74003.72	74003.72	10.05	0.0338	3.2
P_f	1	1.15×10^{6}	1.15×10^{6}	156.78	0.0002	49.87
T_s	1	6.09×10^{5}	6.09×10^{5}	82.75	0.0008	26.32
Residual	4	29443.40	7360.85	-	-	1.27
Total	8	2.31×10^{6}	-	-	-	100
For HT						
P_e	1	1.70	1.70	68.74	0.0012	36.26
P_d	1	1.22	1.22	49.61	0.0021	26.02
P_f	1	0.89	0.89	36.05	0.0039	18.98
T_s	1	0.78	0.78	31.81	0.0049	16.63
Residual	4	0.099	0.025	-	-	2.11
Total	8	4.69	-	-	-	100

5.5 Performance Comparison of Single-Pulse, Percussion and Trepanning Drilling

One of the objectives of this research was to compare the performance of single-pulse, percussion, and trepanning drilling; therefore, the effectiveness of each method in terms of maximum values of MRR and minimum values of SEC and hole taper has been summarized, as shown in Figure 5-10. Single-pulse drilling was taken as a reference to compare the corresponding values of different drilling methods. The increment and decrement in corresponding drilling method values from single-pulse drilling are presented with positive and negative percentages. It is evident from the figure that the performance of single-pulse drilling is better in case of MRR as the MRR reduces by 99.70% when using percussion drilling and 99.87% when trepanning was employed. SEC increases by 14.20% and 626.50% when using percussion and trepanning, respectively, indicating that single-pulse drilling outperformed the others with minimum SEC value. In the case of hole taper, trepanning yields better results by decreasing it by 72.92%, whereas percussion gives the second best value with 11.22% reduction.

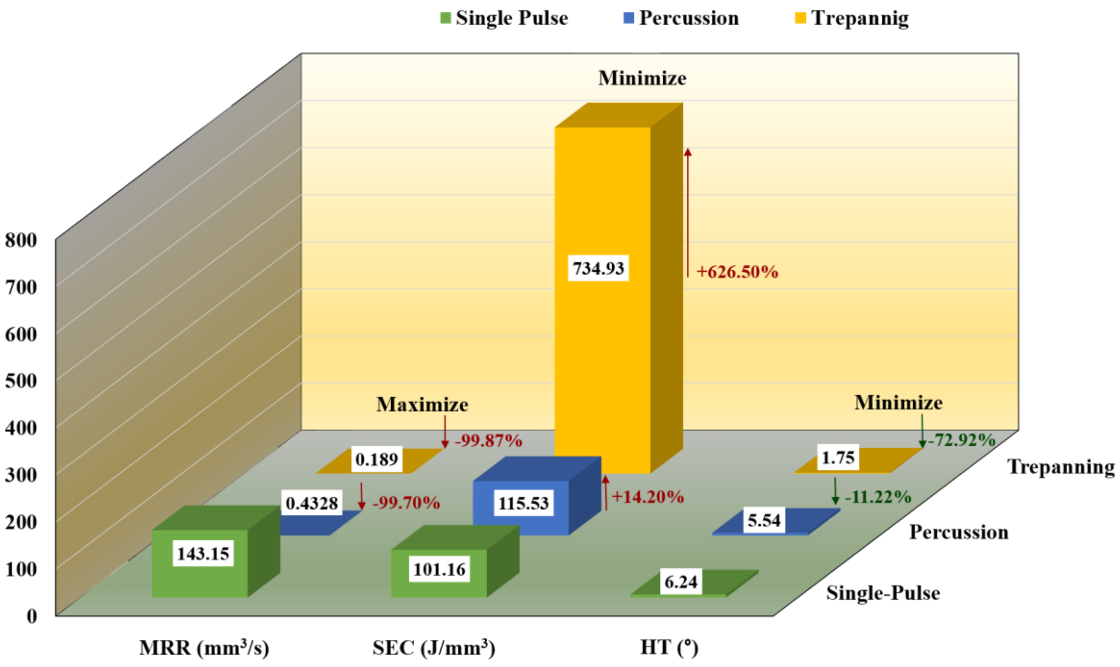


Figure 5-10 Comparison plot of single-pulse, percussion and trepanning for MRR, SEC, and HT

5.6 Summary

This chapter presents an analysis of material removal rate, specific energy consumption and hole taper based on the experimental results. The selection of process parameters and their levels along with the experimental procedure has been discussed. 3D response surface plots have been developed to investigate the individual and simultaneous influence of process parameters on the measured responses for single-pulse, percussion and trepanning drilling methods. Significant process parameters have been identified through ANOVA results. Table 5-9 summarizes the results of process parameters variations and their effects on the performance characteristics.

Moreover, the performance of different laser drilling methods has been evaluated in terms of productivity, energy efficiency and hole quality. The results obtained from this study show the single-pulse drilling method as the best option if the productivity and energy efficiency are given priority over quality. On the contrary, the trepanning method gives the highest hole quality but productivity and energy efficiency were found to be very low.

Table 5-9 Significant process parameters and their effects on different performance characteristics

Sr. No.	Performance characteristics (PC)	Significant process parameters	Variation of process parameters to achieve the best value of PC
1	MRR	Pulse energy	High (SP, Per, Tre)
		Pulse duration	Low (SP, Per, Tre)
		Number of pulses	Low (Per)
		Pulse frequency	High (Tre)
		Trepan speed	High (Tre)
2	SEC	Pulse energy	Low (SP, Per, Tre)
		Pulse duration	Low (SP, Per, Tre)
		Number of pulses	Low (Per)
		Pulse frequency	Low (Tre)
		Trepan speed	High (Tre)

Sr. No.	Performance characteristics (PC)	Significant process parameters	Variation of process parameters to achieve the best value of PC
3	HT	Pulse energy	Low (SP), High (Per, Tre)
		Pulse duration	High (SP, Per, Tre)
		Number of pulses	High (Per)
		Pulse frequency	High (Tre)
		Trepan speed	Low (Tre)
SP: Single-pulse, Per: Percussion, Tre: Trepanning			

In order to compare the laser drilling performance for different laser sources, another set of experimentation was performed using flashlamp-pumped Nd:YAG laser and the results are discussed in the following chapter.

6 COMPARISON OF FIBRE LASER DRILLING AND FLASHLAMP-PUMPED LASER DRILLING

6.1 Introduction

Traditionally laser drilling has been performed using flashlamp-pumped Nd:YAG laser but this laser has limited efficiency and beam quality, and needs high maintenance. Nowadays, most of the flashlamp-pumped Nd:YAG lasers are being replaced by fibre lasers that have higher efficiency, zero maintenance and better beam quality. However, the capital cost of a fibre laser is very high compared to Nd:YAG laser. The performance of laser drilling needs to be investigated under the above mentioned laser sources. Therefore in this chapter, the author presents a comparison of fibre laser drilling and flashlamp-pumped laser drilling.

Single-pulse drilling was employed to drill holes in IN 718 superalloy using flashlamp-pumped Nd:YAG laser. Material removal rate, specific energy consumption and hole taper were evaluated for the applied process parameters and the results were compared with the values of performance measures achieved through Quasi-CW fibre laser drilling.

6.2 Process Parameters Selection

The process parameters selected for flashlamp-pumped Nd:YAG laser drilling were the same as those chosen for Quasi-CW fibre laser drilling. It is important to mention that the operating levels of pulse energy were also the same but due to limitations of the laser system the applied pulse duration was a bit higher. The process parameters and their operating levels are shown in Table 6-1.

Table 6-1 Operating levels of the process parameters

Process parameters	Levels
Pulse energy	20, 30, 40 (ms)
Pulse duration	6, 11, 16 (ms)
(Assist) gas pressure	100 (psi)
Assist gas	Compressed air

6.3 Experimental Procedure

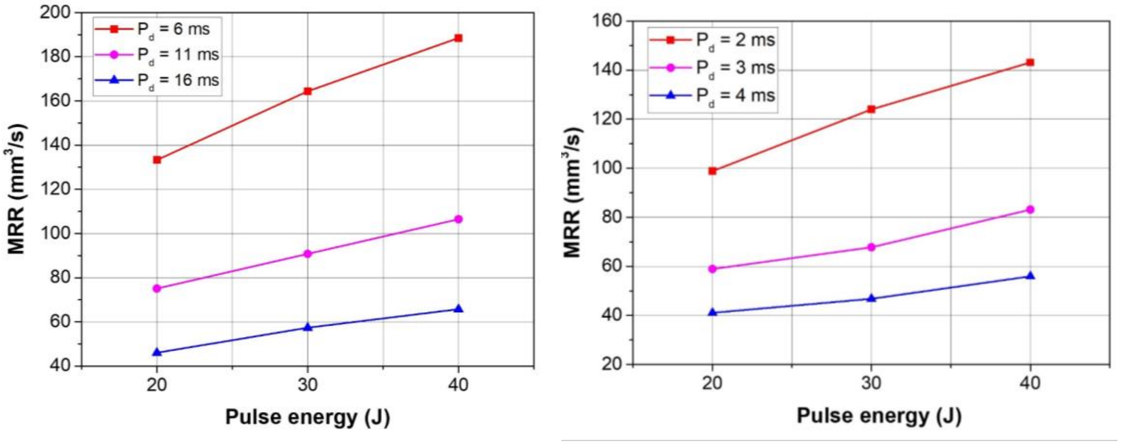
Samples of IN 718 plates of 100 mm × 100 mm × 1.0 mm dimensions were used for the experiments. The drilling operation was performed using a flashlamp-pumped Nd:YAG laser. Compressed air was employed as an assist gas. The details of the experimental setup and important specifications of the Nd:YAG laser system are provided in Chapter 4. Experiments were performed using Taguchi L9 orthogonal array. The experimental runs with the observed response values are provided in Table 6-2.

Table 6-2 Experimental results for Nd:YAG laser drilling

Exp. No.	**Process parameters**		**Responses**		
	P_e (J)	**P_d (ms)**	**MRR (mm^3/s)**	**SEC (J/mm^3)**	**HT (°)**
1	20	6	133.29	23.88	15.16
2	20	11	75.06	26.15	12.6
3	20	16	46	28.27	9.53
4	30	6	164.38	29.14	18.7
5	30	11	90.76	32.1	15.13
6	30	16	57.37	34.62	11.01
7	40	6	188.48	34.4	20.65
8	40	11	106.46	37.97	16.67
9	40	16	65.73	40.97	14.19

6.4 Investigation of Laser Sources Performance

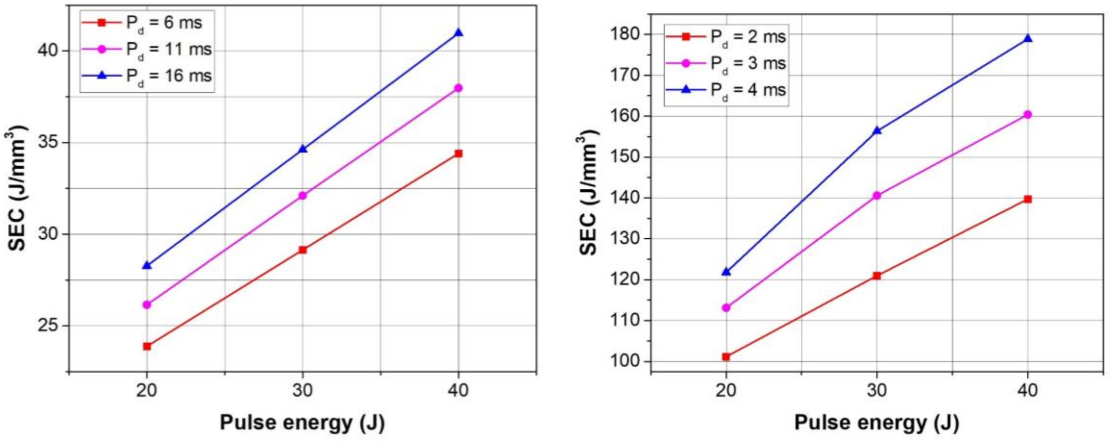
The performance of Nd:YAG laser drilling was analysed in terms of material removal rate, specific energy consumption and hole taper. The results of material removal rate for both Nd:YAG laser and fibre laser drilled holes are shown in Figure 6-1 (a,b). It is found that the trends are the same for both lasers. Maximum value of MRR is observed at higher values of pulse energy and lower pulse duration levels. This is because the combination of minimum pulse duration and maximum pulse energy results in high power intensity availability which promotes vaporisation and as a result enhances the material removal phenomenon (Sarfraz et al., 2019a). From Figure 6-1 (a), it is also evident that the material removal rate ranges between 46 and 188.48 mm^3/s for Nd:YAG laser drilling. On comparison with fibre laser drilling (Figure 6-1 (b)), higher values of MRR are observed in Nd:YAG laser drilling. This can be explained by the fact that the laser beam spot size of the fibre laser was smaller which means high power density is available per pulse. This helps in efficient removal of material and reduces hole taper (Tu et al., 2014). In this case, lower hole taper depicts that the same hole depth can be achieved but with less material to be removed and therefore results in lower material removal rate. The comparison of hole taper between Nd:YAG laser and fibre laser is shown in Figure 6-3.



(a) **(b)**

Figure 6-1 Variation in MRR at varying pulse energy and pulse duration using (a) Nd:YAG laser (b) fibre laser

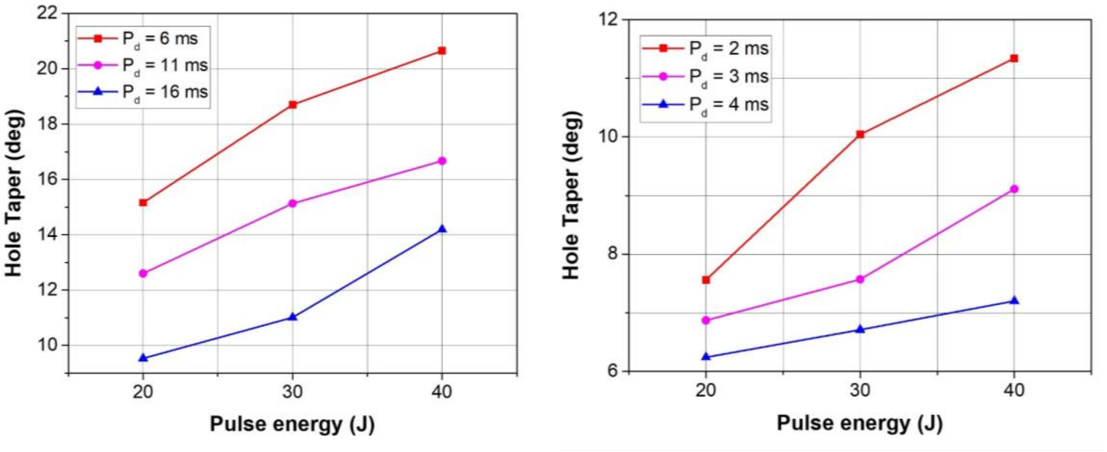
The effects of pulse energy and pulse duration on specific energy consumption for Nd:YAG laser drilling have been described in Figure 6-2 (a). It can be identified that specific energy consumption value increases with the increase in pulse energy and pulse duration. Similar trends have been noted for fibre laser drilling (Figure 6-2 (b)). It is also clear that the values of specific energy consumption are lower when Nd:YAG laser drilling was applied. With Nd:YAG laser drilling, the maximum noted value of specific energy consumption was 40.97 J/mm^3 which is almost four times less than fibre laser drilling. Although the pulse energy used in both cases is the same but different specific energy consumption values are possible due to the difference in beam spot size and laser specifications.



(a) **(b)**

Figure 6-2 Variation in SEC at varying pulse energy and pulse duration using (a) Nd:YAG laser (b) fibre laser

Hole taper as a function of pulse energy for different pulse durations during Nd:YAG laser drilling and fibre laser drilling is presented in Figure 6-3 (a,b). Same trends are found for both lasers. For a given pulse duration the hole taper is proportional to pulse energy. On the other hand, hole taper decreases as the pulse duration increases. It can be observed from the figure that the fibre laser provides good quality holes with lower hole taper (6.24°) compared to the Nd:YAG laser although higher levels of pulse duration were employed during Nd:YAG laser drilling. This is due to the difference in laser beam spot size as described above. Also, the beam quality of fibre laser is better i.e. less diverging laser beam which contributes to producing fine hole quality with reduced tapering at the side walls (Rihakova and Chmelickova, 2017).



(a) **(b)**

Figure 6-3 Variation in hole taper at varying pulse energy and pulse duration using (a) Nd:YAG laser (b) fibre laser

6.5 Summary

This chapter reports on the experimental work carried out to compare the laser drilling performance between two different laser sources i.e. Quasi-CW fibre laser and flashlamp-pumped Nd:YAG laser. The impacts of process parameters on the performance measures were observed for Nd:YAG laser drilled holes. The trends were found similar as noted for fibre laser drilled holes.

From the operating envelope of Quasi-CW fibre laser drilling and flashlamp-pumped Nd:YAG laser drilling, higher material removal rate was observed with lower values of specific energy consumption when flashlamp-pumped Nd:YAG laser was employed. The difference in these values is expected due to different beam spot sizes, laser power densities and laser specifications.

On the other hand, Quasi-CW fibre laser generated high quality holes with lower hole taper values because of lower beam spot size and higher beam quality associated with the fibre laser. It gives a clear indication to use fibre lasers when high quality holes are desired. However, the purchasing cost of a fibre laser is high as compared to Nd:YAG laser. Cost estimation of the laser drilling process has been performed in the next chapter to investigate the potential cost drivers and major cost elements involved in the process. Moreover, integrated analysis is performed to study the impacts of laser drilling process parameters on material removal rate, hole taper and drilling cost and to find out the optimal drilling conditions.

7 INTEGRATED ANALYSIS OF PRODUCTIVITY, HOLE QUALITY AND COST OF LASER DRILLING

7.1 Introduction

The laser drilling process is complex as the drilling operation can be performed with different combinations of process parameters which all affect hole quality, material removal rate and specific energy consumption of the process. This has been shown for two different lasers in Chapters 5 and 6. In the current chapter, the cost of laser drilling has been estimated. As reported in Chapter 2, process parameters affecting the performance of the laser drilling process also have a substantial impact on cost. Therefore the impacts of process parameters on the drilling cost have also been analysed and discussed.

This experimental study was performed to fundamentally investigate the effects of laser drilling process parameters on productivity, hole quality and drilling cost altogether. Due to the contrasting effects of process parameters on productivity, hole quality and drilling cost, multi-objective optimisation was performed using grey relational analysis to identify the optimal drilling conditions aiming to maximise the MRR while minimising hole taper and drilling cost.

7.2 Process Parameters Selection

In order to investigate the influence of process parameters on the material removal rate, hole taper and drilling cost (C_d), four laser drilling process parameters were selected, namely pulse energy, pulse duration, gas pressure and gas flow rate. These process parameters were chosen based on their significant influence on the material removal rate, hole taper and drilling cost, as mentioned by laser manufacturers’ experts. The importance of selected process parameters is also explained in Chapter 2. The selection of limits and their levels was based on screening experiments and a literature review. Table 7-1 shows the controlled parameters along with the selected levels.

Table 7-1 Levels of the process parameters

Process parameters	**Levels**
Pulse energy	20, 30, 40 (ms)
Pulse duration	6, 11, 16 (ms)
(Assist) gas pressure	50, 75, 100 (psi)
(Assist) gas flow rate	30, 35, 40 (l/min)

7.3 Experimental Procedure

The experimental procedure used in this study was the same as reported in Chapter 6. However, it is important to mention that in these experiments the assist gas pressure and gas flow rate were controlled through a gas regulator and gas flow meter installed on the cylinder. A series of experiments was performed using the Box-Behnken experimental design technique. Overall 27 experiments were conducted with four process parameters and three centre points (Montgomery, 2017). The number of experiments can be determined using the following equation (7-1).

$$\mathrm{z} = 2^{l} + 2l + y \tag{7-1}$$

where:

z = total number of experiments

l = number of input parameters

y = number of centre points

Each experimental run was replicated three times to assure the reproducibility and reliability of the experimental procedure. Figure 7-1 shows a photograph of the different experiments conducted; both the entry and exit sides of drilled holes are presented, where each row represents a repetition of the experiments. Experimental runs with the observed response values are provided in Table 7-2. The detailed cost analysis is explained in the following section.

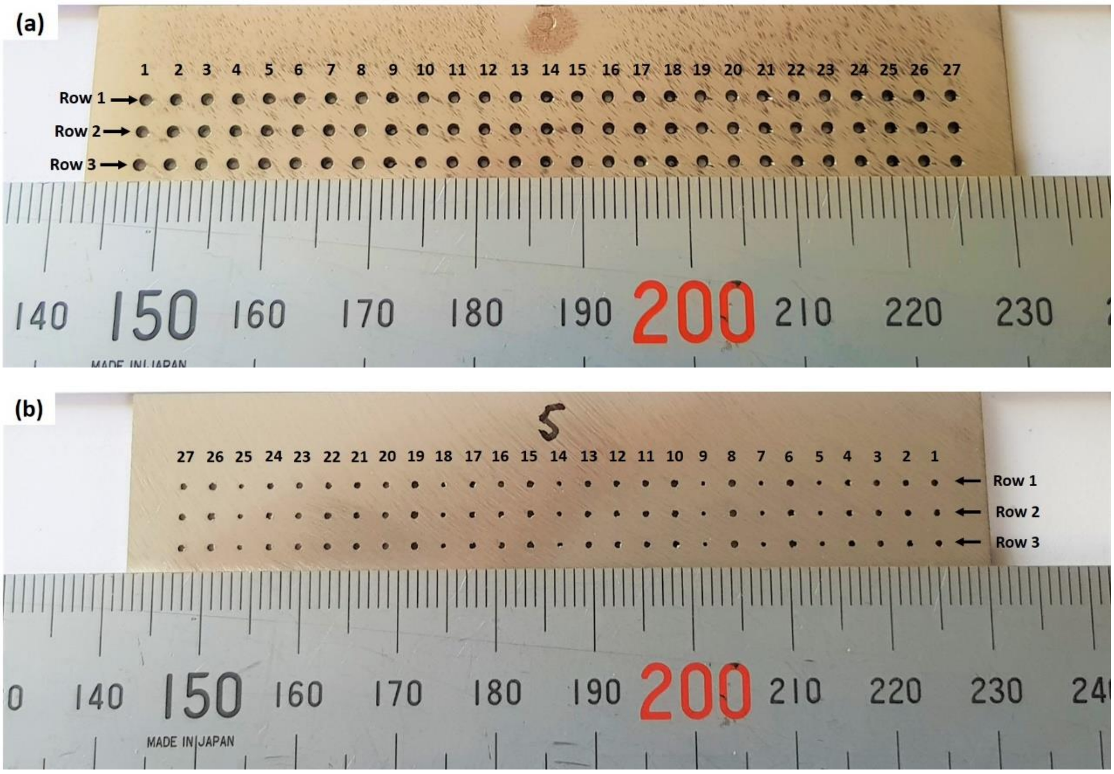


Figure 7-1 Arrays of holes after drilling (a) entry side (b) exit side

Table 7-2 Experimental layout and results

Exp. No.	Process parameters				Responses		
	P_e (J)	P_d (ms)	G_p (psi)	G_{fr} (l/min)	MRR (mm^3/s)	HT (°)	C_d^* (£)
1	30	11	50	30	105.4	17.22	0.01353
2	30	11	50	40	110	7.29	0.01473
3	30	6	50	35	127.6	11.94	0.00779
4	30	16	50	35	89.3	8.41	0.02709
5	20	11	50	35	94.6	12.71	0.01453
6	40	11	50	35	108.1	18.27	0.01667
7	20	6	75	35	118.2	7.91	0.00818
8	40	6	75	35	171.7	13.47	0.01233
9	20	16	75	35	100.9	8.38	0.02495

Exp. No.	Process parameters				Responses		
	P_e (J)	P_d (ms)	G_p (psi)	G_{fr} (l/min)	MRR (mm^3/s)	HT (°)	C_d* (£)
10	40	16	75	35	104	11.94	0.02442
11	30	11	75	35	122.9	11.15	0.01574
12	30	11	75	35	125.2	11.81	0.01384
13	30	11	75	35	128	11.93	0.01512
14	20	11	75	30	107.1	12.86	0.01163
15	40	11	75	30	133.4	18.42	0.01550
16	30	6	75	30	140.1	14.1	0.01128
17	30	16	75	30	111	12.56	0.01844
18	20	11	75	40	110.6	5.89	0.01492
19	40	11	75	40	141.4	10.74	0.02016
20	30	6	75	40	157	9.12	0.01138
21	30	16	75	40	106.8	5.59	0.03282
22	30	11	100	30	131.7	12.4	0.01492
23	30	6	100	35	145.5	7.77	0.01357
24	30	16	100	35	113	6.24	0.02633
25	20	11	100	35	115.4	8.54	0.01244
26	40	11	100	35	148.2	14.1	0.01628
27	30	11	100	40	133.1	5.07	0.01930

* Cost is multiplied by a factor of 100

7.4 Cost Estimation

Manufacturing cost estimation is an essential activity for companies targeting to become successful in the current competitive scenario. For this purpose, this research intends to provide a detailed cost analysis for the laser drilling process considering single-pulse drilling. Process-based cost estimation method was used to estimate the cost. The total cost was divided into different cost components and the cost associated with each component was calculated in accordance with the related process steps, described below in detail.

One of the important tasks of cost estimation is to establish a work breakdown structure (WBS). The main purpose of a WBS is to provide a uniform structure, incorporating all the elements of the process that will be specified by the cost estimate, where each element represents the cost required to execute that process. When a WBS includes all the cost information, it may serve directly as a cost breakdown structure (NASA, 2015). The operating costs breakdown structure of the laser drilling process is presented in Figure 7-2. This has been validated with the experts' opinion.

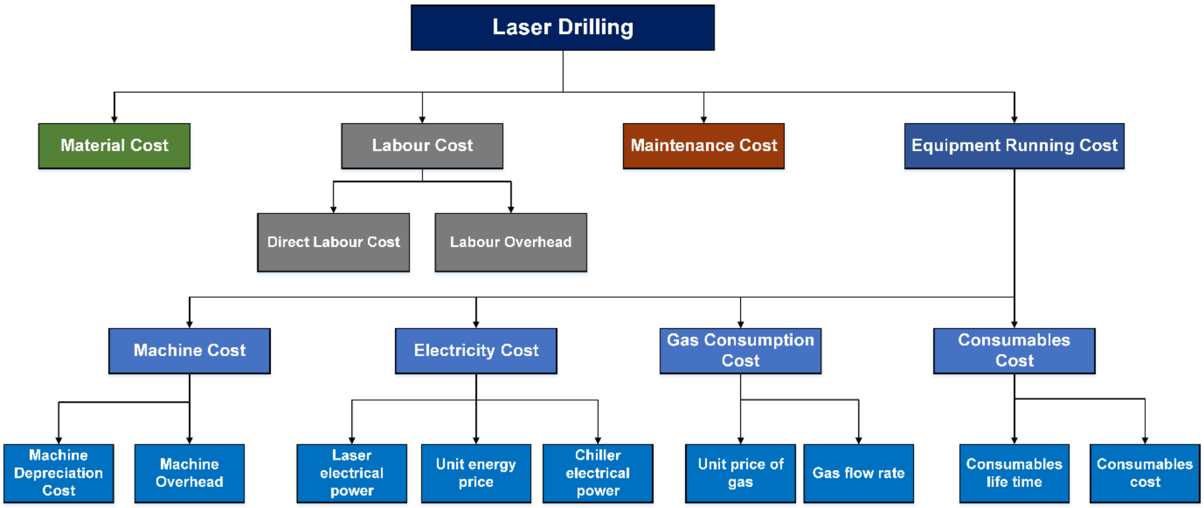


Figure 7-2 Cost breakdown structure

Cost estimation requires the identification of cost drivers i.e. those factors which significantly influence cost. The total cost changes with a small modification to a single cost driver. It is possible to generate a comprehensive cost estimate for a particular process only if all of its cost drivers are identified (NASA, 2015).

The main cost drivers relevant to the laser drilling process have been determined through experts' opinion and literature review (see Table 7-3). Equipment running cost, maintenance, material and labour costs are the key cost drivers in laser drilling cost estimation. After a comprehensive study, it was identified that equipment running cost further includes equipment depreciation, electrical (power) consumption, components replacement, gas consumption, component handling and overhead costs. When all cost drivers are finalised, a cost is allocated to each driver and the total process cost can be calculated.

Table 7-3 Cost drivers of the laser drilling process

Cost drivers	**(Yeo et al., 1994)**	**(Basiev and Powell, 2004)**	**(Ion, 2005)**	**(Dahotre and Harimkar, 2008)**	**(Sarfraz et al., 2018b)**
Equipment running cost	Equipment depreciation	Equipment depreciation	Equipment depreciation	Equipment depreciation	Equipment depreciation
	Electrical consumption	Electrical consumption	Electrical consumption	Electrical (power) consumption	Electrical consumption
	Replaceable components (lenses, flash lamp, filters)	Replaceable components (lenses, laser pumps)	Replaceable components (lenses, flash lamps)		Replaceable components (lenses, flash lamp, filters, nozzle)
	Gas consumption		Gas consumption		Gas consumption
		Component handling		Component handling	Component handling
		Overhead	Overhead	Overhead	Overhead
Maintenance		Equipment maintenance	Equipment maintenance		Equipment maintenance
Material				Material cost	Material cost
Labour		Labour (operator) cost	Labour (laser operators and engineers) cost	Labour cost	Labour cost
			Overhead		

7.4.1 Laser Drilling Cost Estimation

The total cost of laser drilling per hole (C_{ld}) depends on different cost components including material cost, labour cost (C_{lr}), maintenance cost (C_{main}) and equipment running cost. Material cost was classified as a fixed cost since the focus of this study was to evaluate the process cost. The equipment running cost further consists of machine cost (C_{me}), electricity cost (C_{ey}), gas consumption cost (C_{gc}), consumables cost (C_{con}) and component handling cost. A simple motorised linear stage was used to control the movement of the substrate, therefore component handling cost was neglected. The total drilling cost in cumulative form can be represented as the equation (7-2).

$$C_{ld} = C_{lr} + C_{me} + C_{ey} + C_{gc} + C_{con} + C_{main} \qquad (7\text{-}2)$$

Labour Cost

Labour cost per hole (C_{lr}) is comprised of direct labour cost and labour overhead, as shown in equation (7-3). Direct labour cost (C_{dl}) is calculated based on the wage rate of the operator, the number of operators required for the process and the drilling time. Labour's overhead (H_{lo}) includes training cost, medical and fringe benefits (D'Urso et al., 2017). This is estimated as 40% of the direct labour cost. The total labour cost is expressed as equation (7-4).

$$C_{lr} = Direct\ labour\ cost\ (C_{dl}) + Labour\ overhead\ (H_{lo}) \qquad (7\text{-}3)$$

$$C_{lr} = (C_{hl} \times L_r \times \frac{T}{3600}) + [0.4(C_{hl} \times L_r \times \frac{T}{3600})] \qquad (7\text{-}4)$$

where:

C_{hl} = hourly cost of labour (£/hr)

L_r = total number of labours involved

T = drilling time per hole (s).

Each hole has a specific drilling time, changing drilling parameters vary the drilling time per hole. In single-pulse drilling, drilling time was estimated equal to the applied pulse duration.

Machine Cost

Machine cost per hole includes the machine depreciation cost and machine overhead as shown in equation (7-5). The machine depreciation cost (C_{md}) is based on equipment useful life, its purchase cost and salvage value, production hours per year and the drilling time. The salvage value of a laser machine is very limited; therefore, this factor is omitted. Machine overhead (H_{mo}) includes lighting/HVAC and floor space cost i.e. 30% of machine depreciation cost (Shehab and Abdalla, 2002).

The machine cost (C_{me}) is estimated using equation (7-6),

$$C_{me} = Machine\ depreciation\ cost\ (C_{md}) + Machine\ overhead\ (H_{mo}) \tag{7-5}$$

$$C_{me} = \left(\frac{C_{ep}}{L_{ep} \times H_y} \times \frac{T}{3600}\right) + [0.3\left(\frac{C_{ep}}{L_{ep} \times H_y} \times \frac{T}{3600}\right)] \tag{7-6}$$

where:

C_{ep} = purchase cost of equipment (laser & chiller) in £

L_{ep} = equipment useful life (years)

H_y = production hours per year

Cost of Electricity

Electricity cost comprises energy consumed by the equipment, the unit price of energy and the drilling time. Four factors were taken into consideration for the electrical energy consumption of equipment i.e. electrical power of the chiller, electrical power of the laser, utilised laser power and the maximum power achieved by the laser. The cost of electricity (C_{ey}) per hole is represented by equation (7-7).

$$C_{ey} = [C_{up} \times \left(\left(\frac{P_l \times P_{ut}}{P_{max}} \right) + P_{ch} \right)] \times \frac{T}{3600} \tag{7-7}$$

where:

C_{up} = unit price of electricity (£/kWh)

P_l = electrical power of the laser (kW)

P_{max} = maximum power achieved by the laser (kW)

P_{ch} = electrical power of the chiller (kW)

P_{ut} = utilised laser power in kW

Utilised laser power is the used output (average) power of the laser. In single-pulse drilling, it is the product of applied pulse energy and pulse frequency ($P_e \times P_f = J \times \frac{1}{s}$).

Cost of Gas Consumption

The cost of gas consumption per hole (C_{gc}) depends on the gas flow rate, the unit price of the gas and drilling time. Equation (7-8) represents the calculations used for the gas consumption cost.

$$C_{gc} = G_{fr} \times G_{up} \times 60 \times \frac{T}{3600} \tag{7-8}$$

where:

G_{fr} = flow rate of gas (l/min)

G_{up} = unit price of gas (£/l)

Gas flow rate can be measured easily using the gas flow metre installed on the cylinder.

Cost of Consumables

Consumable laser components (filters, flash lamps, nozzle tip, lens cover glass) have a limited lifetime and need regular replacement. The consumables cost per hole (C_{con}) can be calculated based on the price of consumable components and their useful lifetime, and drilling time. Equation (7-9) can be used to estimate the consumables cost.

$$C_{con} = [\left(\frac{C_{fs}}{T_{fs}}\right) + \left(\frac{C_{fl}}{T_{fl}}\right) + \left(\frac{C_{nt}}{T_{nt}}\right) + \left(\frac{C_{ls}}{T_{ls}}\right)] \times \frac{T}{3600} \tag{7-9}$$

where:

C_{fs} = price of filters (£)

T_{fs} = (expected) lifetime of filters (hrs)

C_{fl} = price of flash lamps (£)

T_{fl} = (expected) lifetime of flash lamps (hrs)

C_{nt} = price of nozzle tip (£)

T_{nt} = (expected) lifetime of nozzle tip (hrs)

C_{ls} = price of lens cover glass (£)

T_{ls} = (expected) lifetime of lens cover glass (hrs)

Cost of Maintenance

Pulsed Nd:YAG laser requires periodic maintenance and service. The maintenance cost depends on the hourly cost of maintenance labour, maintenance time required, available working time of the machine and drilling time per hole, as shown in equation (7-10).

$$C_{main} = C_{lab-main} \times \frac{T_{main}}{T_{mac-work}} \times \frac{T}{3600} \tag{7-10}$$

where:

C_{main} = maintenance cost per hole (£)

$C_{lab-main}$ = cost of labour for maintenance experts (£/hr)

T_{main} = time required for maintenance (hrs)

$T_{mac-work}$ = (expected) available working time of the machine before breakdown (hrs)

7.4.2 Total Drilling Cost

Labour cost C_{lr}, machine cost C_{me}, electricity cost C_{ey} (laser & chiller), gas consumption cost C_{gc}, consumables cost C_{con} and maintenance cost C_{main} are added to calculate the total drilling cost. The operating cost calculations are provided in Table 7-4. It is essential to mention that these calculations did not consider extraordinary maintenance and equipment breakdown, and all cost components data has been acquired from the industry.

Table 7-4 Operating costs breakdown

Cost elements	Calculations	Drilling cost (£/hr)
Labour cost	(1.4)(£ 15/hr)(1)	21
Machine cost (laser & chiller)	(1.3)(£ 61050)/(12 years)(240 days/year)(8 hrs/day)	3.445
Laser power consumption	(£ 0.14/kWh)(10 kW)*P_{ut}/(0.3 kW)	4.6* P_{ut}
Chiller power consumption	(£ 0.14/kWh)(3.8 kW)	0.532
Gas consumption	G_{fr}*(£ 0.00390/litre)(60 min/hr)	0.23382*G_{fr}
Laser maintenance	(£ 300/hr)(8 hrs)/(1920 hrs)	1.25
Consumables (filters, flash lamp, nozzle tip, lens cover glass)	(£300/2000 hrs) + (£ 500/1200 hrs) + (£ 14/200 hrs) + (£ 39/200 hrs)	0.832
Total operating cost per hour	27.059 + 4.6*P_{ut} + 0.23382*G_{fr}	

The total approximated drilling cost per hole is given by equations (7-11). It is evident that laser drilling cost is a function of utilised laser power, gas flow rate and drilling time.

$$Drilling\ cost\ (£/hole) = (27.059 + (4.6 \times P_{ut}[kW]) + \Big(0.23382 \times G_{fr}\left[\frac{litre}{min}\right]\Big)) \times \Big(\frac{T[sec]}{3600\left[\frac{sec}{hr}\right]}\Big) \quad (7\text{-}11)$$

The percentage contribution of all cost components under low, medium and high levels of process parameters is provided in Figures 7-3 – 7-5. At the low level of parameters, labour cost was a maximum of 61% followed by gas consumption cost of 21%, machine cost of 10%, maintenance cost of 4%, electricity cost of 2% and consumable cost of 2% in the total drilling cost respectively (Figure 7-3). A similar contribution of cost components was observed at medium and high levels of process parameters (Figure 7-4, Figure 7-5). For the laser cutting process, Riveiro et al. (2016) reported similar findings that showed gas consumption, machine (laser/chiller) cost and electricity cost as major cost components ignoring the labour cost.

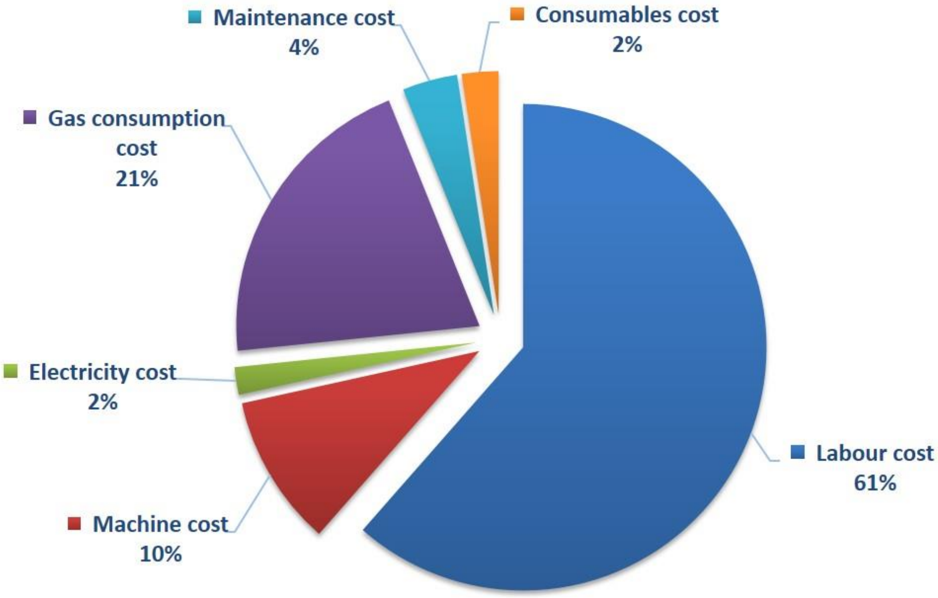


Figure 7-3 Percentage contribution of cost components in the total drilling cost at low level of process parameters (P_e = 20 J, P_d = 6 ms, G_p = 50 psi, G_{fr} = 30 mm^3/s)

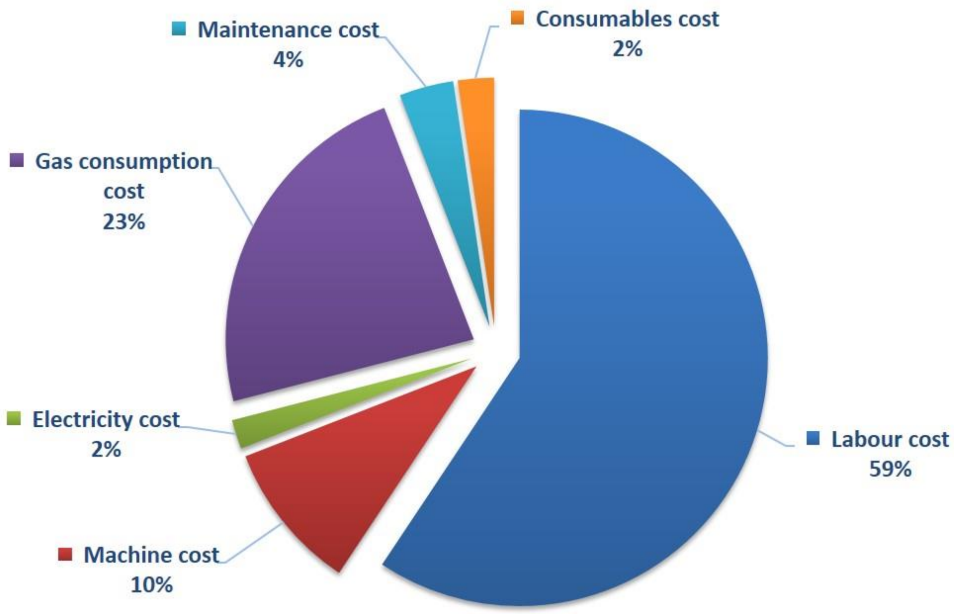


Figure 7-4 Percentage contribution of cost components in the total drilling cost at medium level of process parameters (P_e = 30 J, P_d = 11 ms, G_p = 75 psi, G_{fr} = 35 mm^3/s)

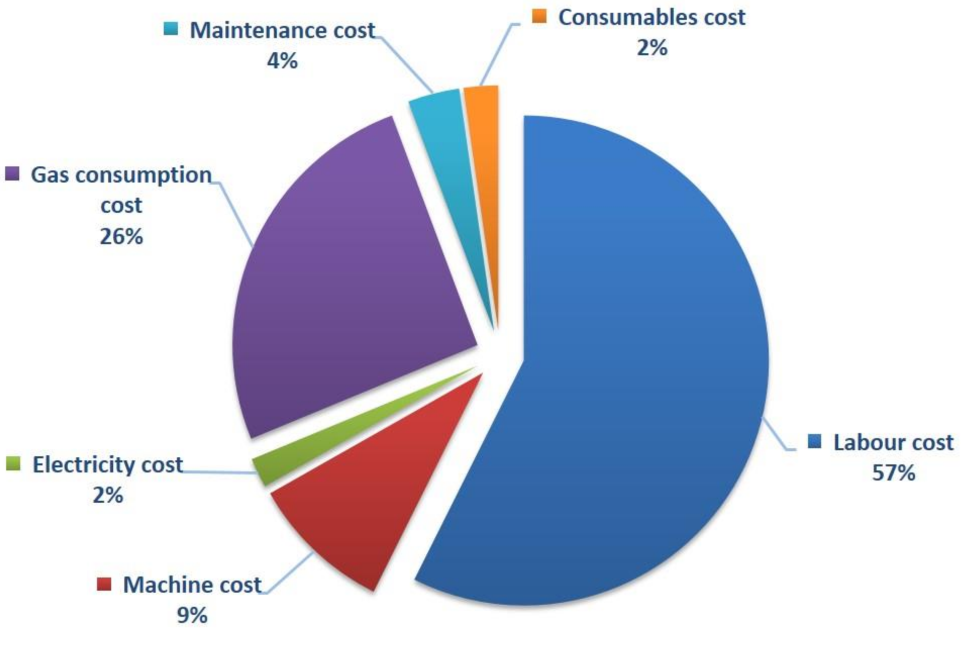


Figure 7-5 Percentage contribution of cost components in the total drilling cost at high level of process parameters (P_e = 40 J, P_d = 16 ms, G_p = 100 psi, G_{fr} = 40 mm^3/s)

7.5 Investigation of Process Parameters Impact on the Responses

To examine the individual and simultaneous influence of input process parameters on material removal rate, hole taper and drilling cost, 3D surface plots were drawn which are provided below. The effects of pulse energy and pulse duration on MRR and hole taper were found to be the same as discussed in Chapter 5 and Chapter 6. Therefore, for MRR and hole taper the influence of gas pressure and gas flow rate is only discussed below.

7.5.1 Influence of gas pressure and gas flow rate on MRR

The surface plot of MRR (Figure 7-6) based on gas pressure and gas flow rate shows that MRR is maximum at high level of gas flow rate. Because higher gas flow rate provides additional thermal energy to support the heating phenomena due to the oxidising nature of compressed air. MRR is found increasing with the increase in gas pressure because higher the pressure greater the kinetic force of gas that efficiently expels the molten material outside the hole cavity. Panda et al. (2011) and Pattanayak and Panda (2018) reported similar results. It is also evident that MRR is influenced more by gas pressure than the gas flow rate.

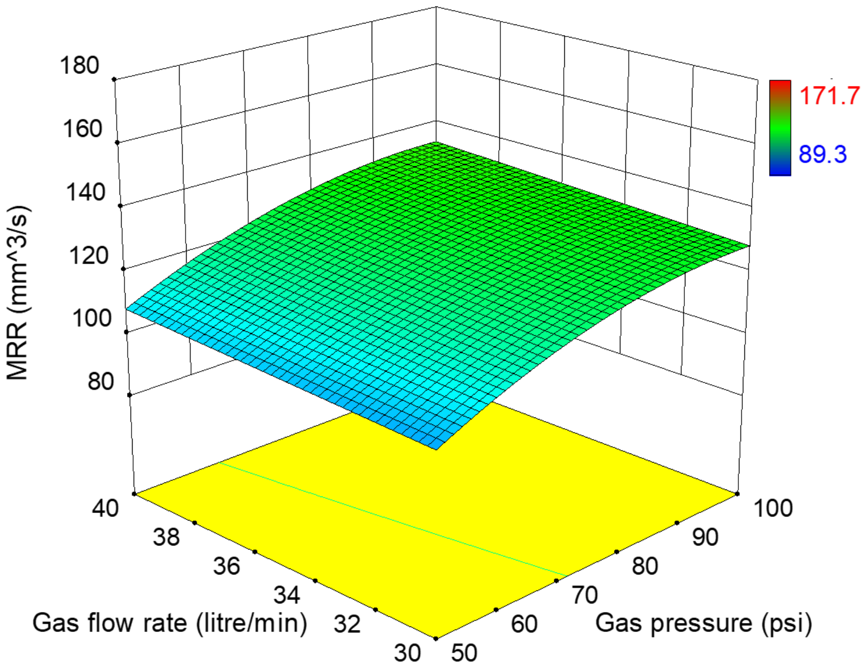


Figure 7-6 Response surface plot for MRR vs. G_p and G_{fr}

7.5.2 Influence of gas pressure and gas flow rate on hole taper

The effects of gas pressure and gas flow rate on hole taper are revealed in Figure 7-7. Hole taper decreases with the increase in gas pressure. This is because higher gas pressure properly removes the molten metal from the material (top) surface. Moreover, an increase in pressure does not permit the molten metal to set down inside the hole cavity. Thus, hole taper reduces when higher gas pressure is used which is in accordance with the findings of Chatterjee et al. (2018a). A similar trend has been observed with the increase in gas flow rate because higher compressed air flow rate increases the localized temperature due to its combustible supportability and results in efficient removal of the material from the hole exits which results in lower hole taper, as stated by Nawaz et al. (2020).

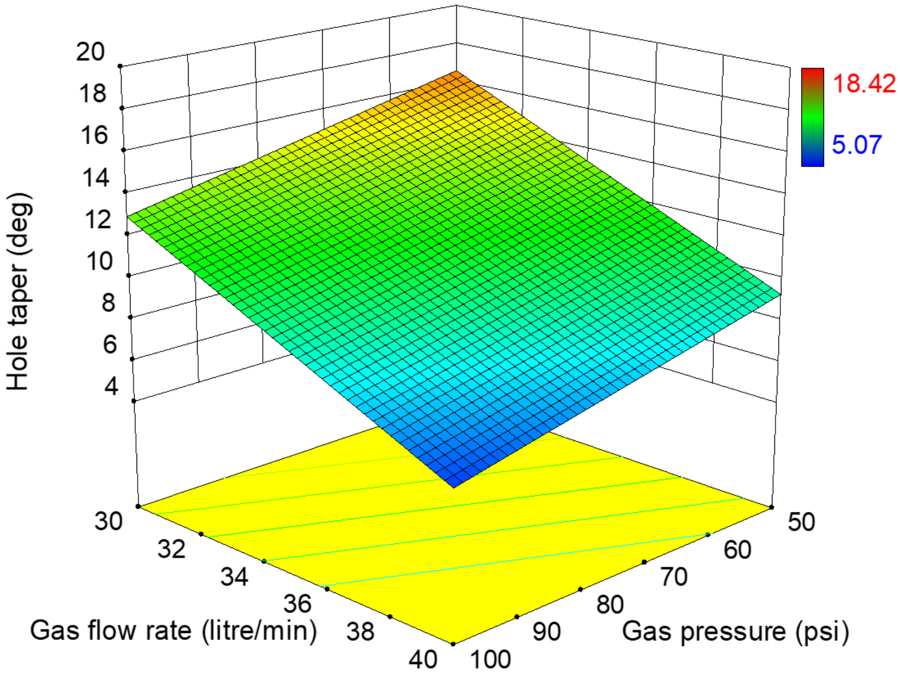


Figure 7-7 Response surface plot for hole taper vs. G_p and G_{fr}

7.5.3 Influence of pulse energy and pulse duration on drilling cost

Figure 7-8 illustrates the response of pulse energy and pulse duration on drilling costs. The lowest value of drilling cost is observed at minimum values of pulse duration and pulse energy. The increase in drilling cost at higher pulse duration and pulse energy values results from an increase in drilling time and power consumption respectively (Eltawahni et al., 2012). The response graph also indicates that pulse duration has more influence on drilling cost than pulse energy.

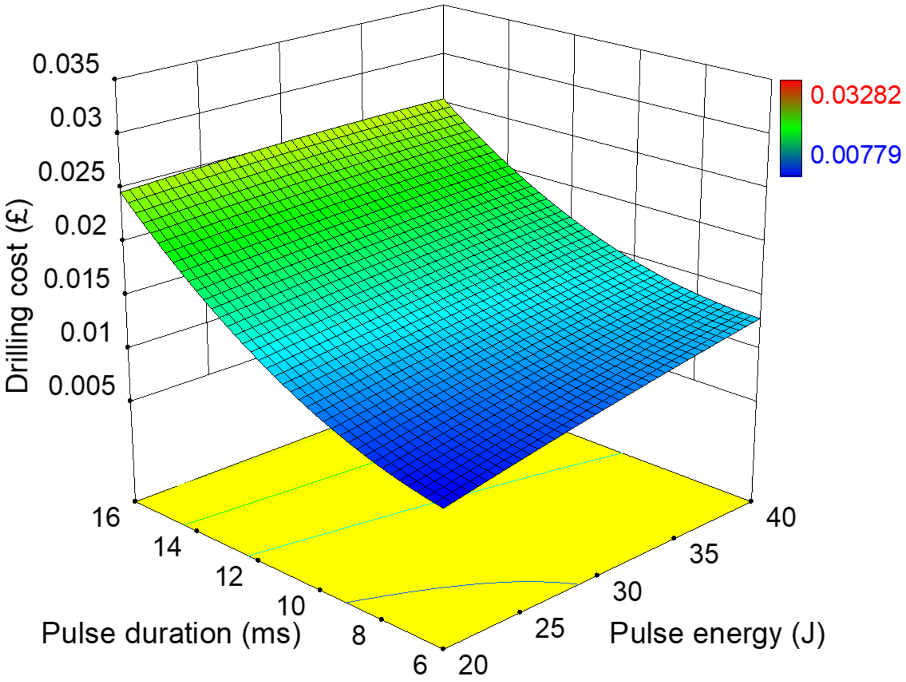


Figure 7-8 Response surface plot for drilling cost vs. P_e and P_d

7.5.4 Influence of gas pressure and gas flow rate on drilling cost

The effects of gas pressure and gas flow rate on drilling costs are described in Figure 7-9. An increase in gas flow rate shows a noticeable increase in drilling cost, whereas no prominent effect is observed from gas pressure. Higher gas flow rate results in more gas consumption, which ultimately increases drilling cost. Eltawahni et al. (2012) and Riveiro et al. (2016) noticed the same results for the CO_2 laser cutting process.

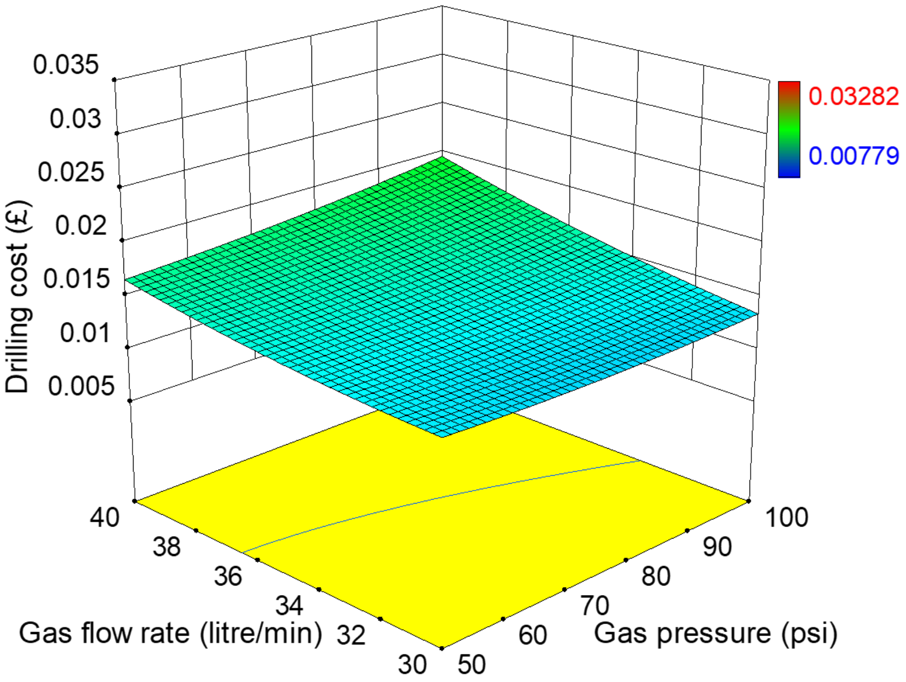


Figure 7-9 Response surface plot for drilling cost vs. G_p and G_{fr}

7.6 Optimisation

For the manufacturing industries, optimum levels of process parameters are very important aimed at maximising productivity and quality while minimising the cost. However, these performance measures are conflicting. For instance, lower hole taper is achieved with high pulse duration and high gas flow rate but increase in pulse duration and higher gas flow rate affect the drilling cost. Similarly, high pulse energy increases the MRR but the hole taper and drilling cost are affected. To mitigate this problem, grey rational analysis (GRA) was used to perform multi-objective optimisation aiming to maximise the MRR while minimising hole taper and drilling cost.

In GRA, the first step is “grey relational generating,” where normalisation is carried out on the measured responses to develop the range between 0 and 1. According to the desired target for the responses, such as MRR (maximisation in target), cost and hole taper (minimisation in target) relations are defined. For MRR, “larger-the-better” is the desirable target, so the following relation (equation (7-12)) is used:

$$x_i(y) = \frac{x_i^0(y) - min(x_i^0(y))}{\max(x_i^0(y)) - min(x_i^0(y))} \tag{7-12}$$

Here, $x_i(y)$ is the grey relational generation value and $x_i^0(y)$ is the yth response value collected for the ith experiment, where i = 1, 2, 3, …., l and y = 1, 2, …., m with l = 27 and m = 3 .

However, "smaller-the-better" is the desired target for cost and hole taper. That is why the desired target is defined in the following relation (equation (7-13)):

$$x_i(y) = \frac{\max(x_i^0(y)) - x_i^0(y)}{\max(x_i^0(y)) - min(x_i^0(y))} \tag{7-13}$$

Here, $\max(x_i^0(y))$ is the maximum value and $min(x_i^0(y))$ is the minimum value of the particular response.

In the second step, grey relational coefficients (GRC) are determined to develop a relationship between real experimental normalised values and the desirable data. The grey-relational coefficient is defined by equation (7-14):

$$a_i(y) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(y) + \zeta\Delta_{max}} \tag{7-14}$$

Here, $a_i(y)$ is the GRC value, $\Delta_{0i}(y)$ is the normalised response value, Δ_{min} and Δ_{max} are the minimum and maximum absolute differences. Zeta (ζ) is a distinguish coefficient restricted between 0-1. The principal objective of applying ζ is to lower the effect of Δ_{max}. When the value of Δ_{max} is too big it significantly affects the GRC. In this study, zeta (ζ) is selected as 0.5 to fit the practical needs (Panda et al., 2011).

The grey relational grade (GRG) is then determined as the weighted sum of GRC. Finally, GRG is calculated using equation (7-15).

$$\gamma_i = \sum_{y=1}^{n} \omega_y a_i(y) \tag{7-15}$$

Here γ_i is the final GRG value of each experiment, n denotes the number of responses (MRR, cost, hole taper) and ω_y is the normalised weight of response y. The highest GRG depicts the best parameter combination for the desired targets.

Based on the conflicting responses, grey relation entropy method was used to assign weights to each response to avoid human-made assumptions. In this way a realistic weight calculation method is used systematically. This method assigns weight based on the influence of the process parameters on the response, where higher weight is allocated to the response with a higher variation (Khan et al., 2019).

Firstly, the mean value of GRC was calculated at each level of the process parameter associated with the individual response (Table 7-5). For example, at level 1 of pulse energy, the mean value of GRC for MRR was determined as 0.394. The maximum and minimum values of the mean of GRC were then used to calculate the range, as shown in equation (7-16).

$$R_{i,j} = max\{Q_{i,j,1}, Q_{i,j,2}, \dots\ Q_{i,j,u}\} - min\{Q_{i,j,1}, Q_{i,j,2}, \dots\ Q_{i,j,u}\} \qquad (7\text{-}16)$$

where $R_{i,j}$ is the range of mean value of GRC ($Q_{i,j}$) for the response i, process parameter j with level u.

The value of weight ω for each response is calculated using equation (7-17).

$$\omega_i = \sum\nolimits_{i=1}^{c} R_{i,j} \,/ \sum_{i=1}^{c} \sum_{j=1}^{p} R_{i,j} \qquad (7\text{-}17)$$

Where c is the number of responses and p is the number of process parameters.

Table 7-5 Weight assignment using the grey relation entropy method

Parameters	**MRR**				**HT**				**C_d**			
	Level 1	**Level 2**	**Level 3**	**R**	**Level 1**	**Level 2**	**Level 3**	**R**	**Level 1**	**Level 2**	**Level 3**	**R**
P_e	0.394	0.477	0.584	0.189	0.641	0.618	0.428	0.213	0.695	0.621	0.578	0.118
P_d	0.639	0.461	0.381	0.258	0.566	0.547	0.680	0.132	0.824	0.632	0.420	0.404
G_p	0.390	0.505	0.518	0.128	0.511	0.566	0.687	0.176	0.660	0.629	0.595	0.065
G_{fr}	0.461	0.482	0.503	0.042	0.420	0.562	0.789	0.368	0.671	0.634	0.569	0.102
$\sum R$				0.617				0.890				0.689
Weight				0.281				0.405				0.314

Table 7-6 depicts the normalised, grey relational coefficients and grey relational grade values for the corresponding responses. It is evident that test no. 7 depicts the highest value of GRG. Therefore, the seventh experiment gives the optimum condition (P_e1-P_d1-G_p2-$G_{fr}2$) for higher MRR with lower hole taper and cost.

Table 7-6 Response table for normalised, GRC and GRG values

Exp. No.	Normalised values			GRC			GRG
	MRR	HT	C_d	MRR	HT	C_d	
1	0.195	0.771	0.805	0.383	0.355	0.686	0.497
2	0.251	0.723	0.749	0.4	0.75	0.643	0.609
3	0.465	1	0.535	0.483	0.493	1	0.695
4	0	0.229	1	0.333	0.667	0.393	0.462
5	0.064	0.731	0.936	0.348	0.466	0.65	0.508
6	0.228	0.645	0.772	0.393	0.336	0.585	0.453
7	0.351	0.984	0.649	0.435	0.702	0.97	0.735
8	1	0.819	0	1	0.443	0.734	0.717
9	0.141	0.314	0.859	0.368	0.669	0.422	0.484
10	0.178	0.336	0.822	0.378	0.493	0.429	0.435
11	0.408	0.683	0.592	0.458	0.523	0.612	0.541
12	0.436	0.758	0.564	0.47	0.498	0.674	0.561
13	0.47	0.707	0.53	0.485	0.493	0.631	0.547
14	0.216	0.847	0.784	0.389	0.461	0.765	0.564
15	0.535	0.692	0.465	0.518	0.333	0.619	0.501
16	0.617	0.861	0.383	0.566	0.425	0.782	0.609

Exp. No.	Normalised values			GRC			GRG
	MRR	HT	C_d	MRR	HT	C_d	
17	0.263	0.574	0.737	0.404	0.471	0.54	0.480
18	0.258	0.715	0.742	0.403	0.891	0.637	0.651
19	0.632	0.506	0.368	0.576	0.541	0.503	0.535
20	0.822	0.857	0.178	0.737	0.623	0.777	0.717
21	0.212	0	0.788	0.388	0.928	0.333	0.535
22	0.515	0.715	0.485	0.507	0.477	0.637	0.550
23	0.682	0.769	0.318	0.611	0.712	0.684	0.672
24	0.288	0.259	0.712	0.412	0.851	0.403	0.546
25	0.317	0.814	0.683	0.423	0.658	0.729	0.621
26	0.715	0.661	0.285	0.637	0.425	0.596	0.554
27	0.532	0.54	0.468	0.516	1	0.521	0.670

Further, the mean value of GRG was also calculated for each level of the drilling parameter and is provided in Table 7-7. Moreover, the total mean of GRG for all experiments is calculated as 0.572 (Table 7-7). Each row presents the process parameter and its levels. The level of corresponding process parameter with the highest value of GRG is presented in bold form. The optimum parameter levels for higher MRR and lower hole taper and cost are P_e1-P_d1-G_p3-$G_{fr}3$.

Table 7-7 GRG response table at each level of process parameters

Process parameters	**GRG**		
	Level 1	**Level 2**	**Level 3**
Pulse energy	**0.594**	0.580	0.532
Pulse duration	**0.691**	0.557	0.491
Gas pressure	0.537	0.574	**0.602**
Gas flow rate	0.534	0.569	**0.620**
Total mean value of GRG = 0.572			

The ANOVA was performed for GRG to evaluate the significance of each process parameter. The results are provided in Table 7-8. It is clearly evident that all the process parameters are significant with P values less than 0.05. The percentage contribution of each process parameter in GRG was also computed. Pulse duration was found as the most significant parameter with a 60% contribution that affects the MRR, hole taper, and cost followed by gas flow rate (11%), gas pressure (6.5%) and pulse energy (5.5%).

Table 7-8 ANOVA for GRG

Source	**df**	**SS**	**MS**	**F value**	**P value**	**Contribution (%)**
P_e	1	0.011	0.011	8.26	0.0088	5.5
P_d	1	0.12	0.12	88.32	<0.0001	60
G_p	1	0.013	0.013	9.24	0.0060	6.5
G_{fr}	1	0.022	0.022	16.25	0.0006	11
Residual	22	0.030	0.001365			15
Total	26	0.20				100

7.6.1 Confirmatory Test

A confirmation test has been done for verification of improvement in the responses. The levels of process parameters selected for the confirmation test are shown in Table 7-9. The initial drilling conditions represent test No. 7 (optimum parameters from Table 7-6) and the optimal drilling conditions represent the optimum parameter levels from Table 7-7. The estimated value of GRG for optimal drilling condition (γ_{es}) was determined using equation (7-18).

$$\gamma_{es} = \gamma_x + \sum_{i=1}^{q} (\gamma_o - \gamma_x) \tag{7-18}$$

where γ_x is the total mean value of GRG, γ_o is the mean value of GRG at optimal drilling condition and q denotes the number of process parameters. Table 7-9 shows a 7.6% improvement in GRG when optimal drilling conditions are considered. This table also indicates a considerable improvement in the values of MRR and hole taper at the expense of minor cost increase because of the higher levels of gas pressure and gas flow rate used. Therefore, it can be postulated that the conflicting responses in laser drilling are improved by using GRA.

Table 7-9 Confirmatory test results

Conditions	**Initial drilling conditions**	**Optimal drilling conditions**
Levels	P_e1-P_d1-G_p2-$G_{fr}2$	P_e1-P_d1-G_p3-$G_{fr}3$
MRR (mm^3/s)	118.2	130.4
HT (deg)	7.91	4.52
C_d (£)	0.00818	0.00921
GRG	0.735	0.791
Improvement in GRG value	0.056	
% improvement in GRG	7.62%	

7.7 Summary

In this chapter, the author presents an experimental analysis of productivity, quality and process cost for single-pulse laser drilling of IN 718 superalloy. The impacts of pulse energy, pulse duration, gas pressure and gas flow rate have been examined on the selected performance measures. A detailed cost analysis has been performed to explore the economic implications of the laser drilling process. In addition, optimum levels of process parameters have been determined using multi-objective optimisation to achieve higher productivity and hole quality at the minimum possible cost.

The outcome from this chapter contributes to providing the potential cost drivers involved in the laser drilling process. At the same time, major cost elements of the laser drilling process have been identified. Also, the findings from the analysis revealed the optimal drilling conditions while improving material removal rate and hole quality, and minimising drilling cost.

The research findings as a result of this thesis are discussed in the next chapter along with the conclusions and future work recommendations.

8 DISCUSSION AND CONCLUSIONS

8.1 Introduction

This chapter aims to provide a discussion on the key themes of this research work. The major conclusions derived from this research work are also highlighted. Additionally, to further extend this study, a brief overview of potential future work directions in the field of laser drilling is presented.

This chapter is divided into seven sections. Section 8.1 introduces the aim of this chapter. The key findings of this research are described in Section 8.2. Section 8.3 presents an account of how the research findings fulfilled the objectives of this research. In Section 8.4, the key research contributions are revealed. Section 8.5 identifies the limitations of this research. A set of conclusions from this research is illustrated in Section 8.6. Finally, Section 8.7 covers the recommendations for possible future work directions.

8.2 Discussion of Key Research Findings

The key findings of this research are reviewed and discussed in this section. The sequence of discussion is the same as adopted in the presentation of the thesis.

8.2.1 Literature Review

A comprehensive literature review was conducted covering two main areas i.e. laser drilling and cost estimation. Concerning the first one, the literature review revealed emerging applications of laser drilling in the aerospace industry. Different laser drilling methods are available, each one of them has different associated performance levels of productivity, efficiency and quality. However, there is a lack of research in characterising laser drilling methods in terms of the mentioned performance measures. The laser source is an important component of the laser drilling setup which affects the cost efficiency of the laser drilling process. It was identified that there is a need to evaluate laser drilling performance for the available laser sources.

A literature review executed in the area of cost estimation indicated that cost estimation has been performed for different manufacturing processes. However, no effort has been reported which discusses cost of the laser drilling process. At the same time, it was discovered that laser drilling process parameters also influence drilling cost which needs to be addressed as well.

8.2.2 Research Methodology

The research methodology adopted for this study is detailed in Chapter 3. The main challenge of this study was the limited data available on the performance of the laser drilling process. To mitigate this challenge, quantitative research approach was adopted with experimental research strategy. This helped to collect real-time data and explore the relationship between different variables of the laser drilling process.

The selection of process parameters for experimentation and cost analysis was also a major issue in this research. Therefore, the researcher adopted different activities of data collection. These activities involved literature review of journal papers, dissertations, research and review reports. In addition, video calls and telephone interviews were organised with laser manufacturers to improve objectivity.

8.2.3 Experimental Setup and Procedures

Lucrative properties of Inconel 718 have made it the best candidate material for the aerospace industry owing to its high strength, wear and fatigue resistance at elevated temperatures. A significant application involves the use of IN 718 in aeroengine components used in high-temperature applications. Therefore, IN 718 was used as workpiece material in this study.

The experimentation was performed using two different laser drilling setups. The main difference between these two setups was the use of different laser sources. Some error defects are always associated with experimentation due to the uncontrollable parameters involved. To minimise these defects, each experimental run was performed three times and the average value was considered.

The productivity of the laser drilling process was defined by the material removal rate which specifies the amount of material removed per unit time. Energy efficiency was determined by specific energy consumption which depicts the energy consumed to remove a unit volume of material. Hole taper was selected to identify the quality of the drilled holes as hole taper is one of the most important quality attributes desired in aeroengine components.

8.2.4 Impact of Process Parameters on Material Removal Rate, Specific Energy Consumption and Hole Quality

One of the most important findings from the literature is the lack of characterisation of laser drilling methods in terms of productivity, energy efficiency and quality. Chapter 5 presents an experimental investigation of material removal rate, specific energy consumption and hole quality for three different laser drilling processes namely, single-pulse, percussion and trepanning. The effect of process parameters on the performance measures for each drilling method was evaluated to identify significant process parameters and their relationship with the mentioned performance measures. Moreover, a comparison plot was produced to highlight the performance levels of the employed laser drilling methods. These findings will permit laser operators to select suitable process parameters and drilling method, maximising productivity and efficiency while ensuring quality requirements.

8.2.5 Comparison of Fibre Laser Drilling and Flashlamp-Pumped Laser Drilling

A comparison of fibre laser drilling and flashlamp-pumped laser drilling has been performed in this research. The goal was to demonstrate the advantages and limitations of the Quasi-CW fibre laser and flashlamp-pumped Nd:YAG laser. Material removal rate, specific energy consumption and hole taper were analysed against the applied process parameters and the results were compared for the mentioned laser sources. It was identified that the best hole quality can be achieved with Quasi-CW fibre laser. However, high capital cost is associated with a fibre laser as compared to an Nd:YAG laser.

8.2.6 Integrated Analysis of Productivity, Hole Quality and Cost of Laser Drilling

An integrated analysis was carried out to study the impact of the laser drilling process parameters on productivity, hole quality and drilling cost altogether. To estimate the drilling cost all potential cost drivers were identified through literature review and experts' opinion. Labour cost, machine cost, electricity cost, gas consumption cost, consumables cost and maintenance cost were determined as the key cost drivers of the laser drilling process. After acquiring all cost components data the total drilling cost was calculated. An analysis of the process parameters' impact on the material removal rate, hole taper and drilling cost revealed the contrasting effects of the process parameters. Therefore grey relational analysis (GRA) was used to perform multi-objective optimisation aiming to achieve optimal drilling conditions while maximising material removal rate and minimising the hole taper and drilling cost. The research results can be used as guiding principles for the laser drilling of IN 718 superalloy specifically for the aerospace industry.

8.3 Fulfilment of Research Aim and Objectives

This section illustrates how the main objectives of this research have been achieved. A description is provided below for each research objective:

1. **Identify key process parameters and their influence on productivity, energy efficiency and hole quality.**

   In order to accomplish this objective, an experimental setup was prepared using a Quasi-CW fibre laser aiming to study the impact of laser drilling process parameters on productivity, energy efficiency and hole quality. First of all, a comprehensive literature review was carried out which helped to understand the significance of the different laser drilling process parameters. It also helped to select process parameters for experimentation. To proceed with the experimentation, trial experiments were conducted which assisted in selecting the ranges of the process parameters. Based on the observed response values, 3D response surface graphs were plotted to explore the relationship between the applied laser drilling process parameters and performance measures. Also, an analysis of variance was performed to determine the significant process parameters along with their percentage contribution values in relation to the selected performance measures.

2. **Demonstrate the capability of laser drilling methods in terms of productivity, energy efficiency and hole quality.**

   This objective is linked with the first objective. During the experimentation, it was ensured that three different laser drilling methods are applied i.e. single-pulse, percussion and trepanning. For each drilling method, the best possible values of material removal rate, specific energy consumption and hole taper were selected and a comparison graph was plotted. The graph indicated the performance levels of the applied drilling methods.

3. **Provide the insight of the process characteristics of laser drilling while using flashlamp-pumped Nd:YAG laser and Quasi-CW fibre laser.**

   For the accomplishment of this objective, another laser drilling setup was prepared using flashlamp-pumped Nd:YAG laser. Experimentation was conducted using this drilling setup and the impacts of the process parameters on material removal rate, specific energy consumption and hole taper were observed. The values of performance measures achieved through flashlamp-pumped Nd:YAG laser drilling were then compared with Quasi-CW fibre laser drilling.

4. **Determine the impact of process parameters on drilling cost and identify major cost elements of the laser drilling process.**

   To achieve this objective, the researcher performed another set of experiments. The goal was to investigate the impact of different laser drilling process parameters on the drilling cost. First of all, the drilling cost was calculated following a determination of the cost drivers involved in the laser drilling process. The cost drivers were identified through a literature review and by contacting the experts from accessible laser manufacturers. The percentage contribution of each cost component was then computed to reveal the major cost elements of the laser drilling process. Finally, the influence of laser drilling process parameters was studied to determine their impact on the drilling cost.

5. **Obtain optimal drilling conditions with taken into consideration productivity, quality and cost.**

   This objective was achieved by incorporating the material removal rate and hole taper as responses with the drilling cost in the experimentation carried out for the accomplishment of the fourth objective. It was concluded that the laser drilling process parameters have contrasting effects on productivity, hole quality and drilling cost. Therefore, multi-objective optimisation was performed using grey relational analysis that revealed the optimal drilling conditions for maximum material removal rate and minimum hole taper and drilling cost.

   The research aim was achieved after the successful fulfilment of research objectives which were to investigate the productivity, energy efficiency, quality and cost for the laser drilling process.

8.4 Research Contribution to Knowledge

This research delivers a significant contribution to enhance the understanding of the performance of the laser drilling process within the context of productivity, energy efficiency, quality and cost. A thorough investigation has been performed to examine the effects of laser drilling process parameters on the productivity, energy efficiency, hole quality and cost taking into consideration different laser drilling methods and laser sources.

In accordance with the research gaps presented in Section 2.13, the main contributions of this research are provided as follows:

- This research has characterised laser drilling methods by evaluating their performance in terms of productivity, energy efficiency and quality. It enables the users to select a suitable laser drilling method for the required performance level.
- This research has provided a comparison of laser drilling performance for two different laser sources (Quasi-CW fibre laser and flashlamp-pumped Nd:YAG laser) that supports the practitioners in selecting the laser source for an appropriate laser drilling setup.

- Significant process parameters have been identified along with their relationship with productivity (MRR), energy efficiency (SEC), quality (hole taper) and drilling cost. This serves as a guide for the practitioners to determine the appropriate process parameters and their levels for laser drilling operations.
- An effort has been made in this research to estimate the cost of the laser drilling process. The key cost drivers and major cost elements of the laser drilling process have been identified that assist manufacturing industries in providing complete cost information related to the laser drilling process.
- An optimal combination of laser drilling parameters has been found for improved productivity and hole quality, and reduced drilling cost.

8.5 Research Limitations

This research focused on an investigation of productivity, energy efficiency, quality and cost for the laser drilling process. However, there are some limitations associated with this research which are listed as follows:

- This research was limited to IN 718 samples, assisted by compressed air. A broad range of materials such as composites and ceramics with different types of assist gases can be included for further analysis. Moreover, other process parameters including nozzle diameter, nozzle stand-off distance and laser beam focal position can also be considered.
- One quality attribute of the laser drilling process (hole taper) has been considered in this work because of time restrictions. It is necessary to analyse the surface integrity of laser-drilled holes along with other response variables such as heat-affected zone, recast layer thickness, surface roughness and circularity to improve drilling performance.
- Due to the availability of laser sources, this research focused only on the performance evaluation of Quasi-CW fibre laser and flashlamp-pumped Nd:YAG laser. However, these are the most commonly used laser sources for drilling in the aerospace industries.
- In the current study, the cost analysis has been performed taking into consideration single-pulse drilling and Nd:YAG laser. The analysis can be

explored further considering other laser drilling methods and laser sources.

8.6 Conclusions

In conclusion, it can be stated that this study has achieved its main aim and defined objectives of investigating the productivity, energy efficiency, quality and cost for the laser drilling process. The main conclusions of this study are summarised as follows:

- Laser drilling is a complex process as there are several parameters involved which affect the performance of the process. Therefore, it is necessary to study the process for the selection of the optimal process parameters. In this way, the operators and companies can plan the process more accurately and productively.
- There are always some assumptions involved in simulation work, hence experimental work is necessary that can represent the real behaviour of a process.
- Productivity, energy efficiency and quality have been experimentally investigated for single-pulse, percussion and trepanning drilling methods. With maximum material removal rate and lower specific energy consumption value, single-pulse drilling method was found as the preferable choice for drilling if the productivity and energy efficiency are given priority over quality. On the other hand, the best hole quality can be obtained with trepanning drilling method but at the expense of higher energy consumption and lower material removal rate. The most influential parameters affecting the material removal rate (productivity), specific energy consumption (energy efficiency) and hole taper (quality) have also been identified and discussed in Chapter 5.
- By comparing the performance of fibre laser drilling and Nd:YAG laser drilling it is confirmed that high-quality holes can be achieved using a fibre laser. However, the capital cost of a fibre laser is higher compared to an Nd:YAG laser.

- An integrated analysis of productivity, hole quality and drilling cost showed a significant influence of process parameters on the drilling cost apart from productivity and hole quality. From the analysis, the optimal combination of drilling parameters was found to be a pulse energy of 20 J, pulse duration of 6 ms, gas pressure of 100 psi and a gas flow rate of 40 mm^3/s.
- A detailed cost analysis revealed that labour cost, gas consumption and machine costs are the major cost elements of the laser drilling process.

8.7 Future Work Recommendations

This section focuses on proposing the possible aspects that can be considered to further extend or improve this research work in the future, and are explained below:

- Both the horizontal and vertical experimental setups should be investigated in terms of laser drilling.
- A comparative study can be performed to evaluate the performance of the laser drilling process in contrast to other non-conventional machining processes such as EDM and ECM.
- The environmental aspects of sustainability should be evaluated using laser drilling and comparing different laser sources.
- Using a knowledge-based system, efforts can be directed towards the development of a tool for linking laser drilling process parameters with productivity, energy efficiency, quality and cost.
- Other heuristics techniques, such as (non-dominated sorting genetic algorithm) NSGA-II, artificial bee colony (ABC) and particle swarm optimisation can also be used for the analysis and the results can be compared.
- Further efforts are needed to explore the laser drilling process in the digital manufacturing paradigm. One of the opportunity is to enable automatic program generation by making use of the semantic element of a model-based definition (MBD).

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APPENDICES

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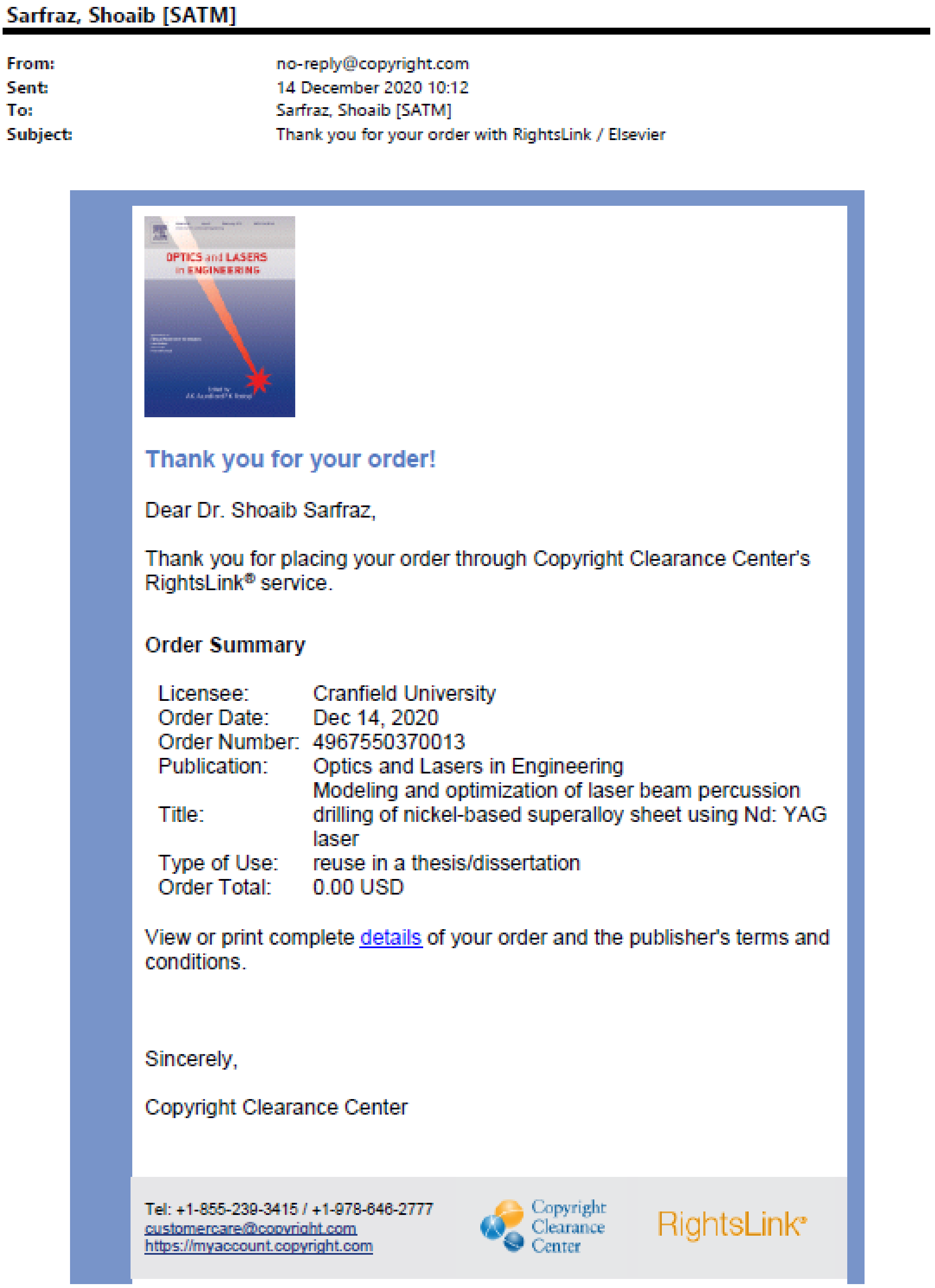
A.1 Figure 2-2 Hole formation physical mechanism in the laser drilling process



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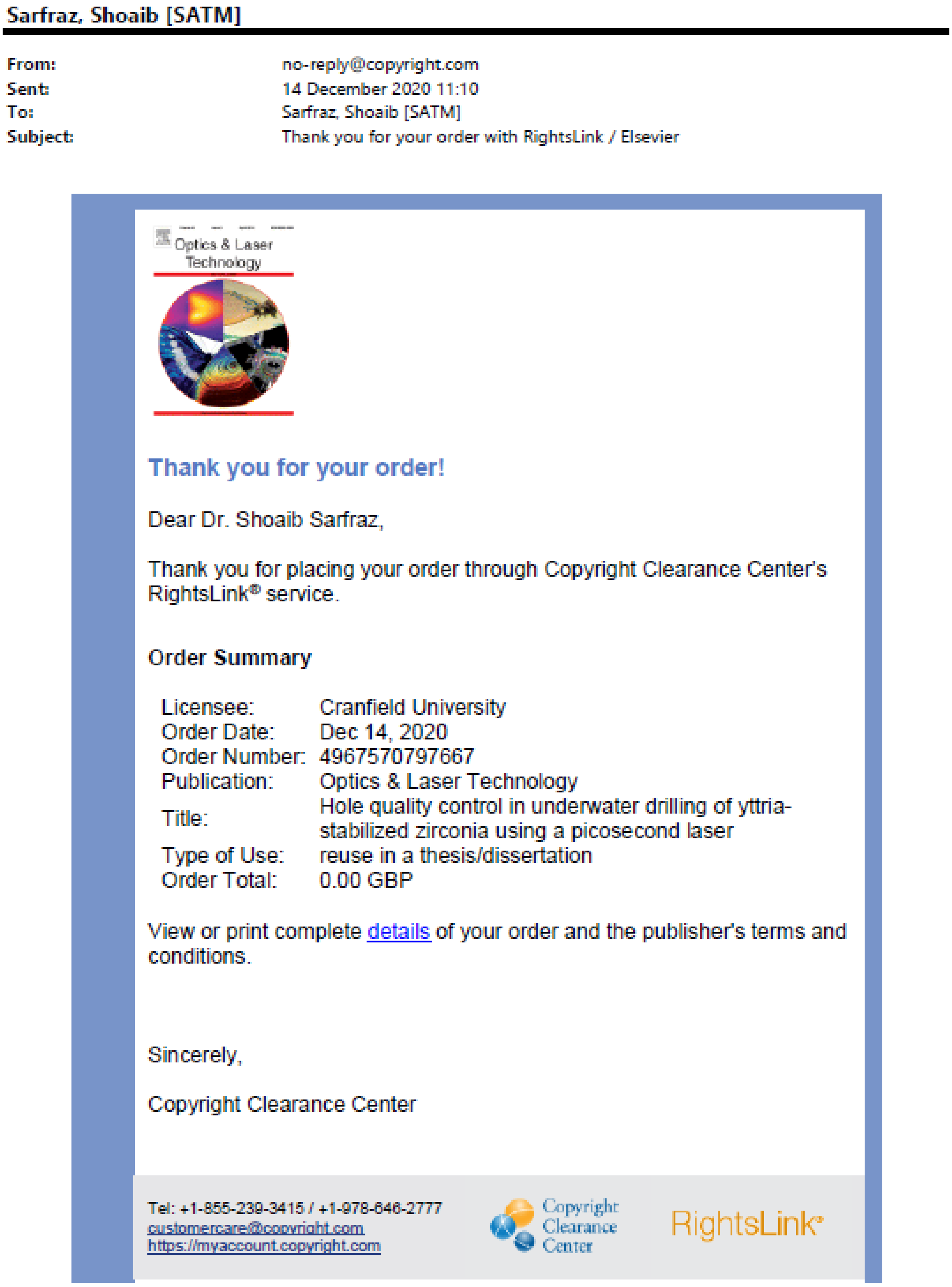
A.2 Figure 2-9 Microcracks formation around the drilled hole (0.5 mm thick yttria-stabilized zirconia)



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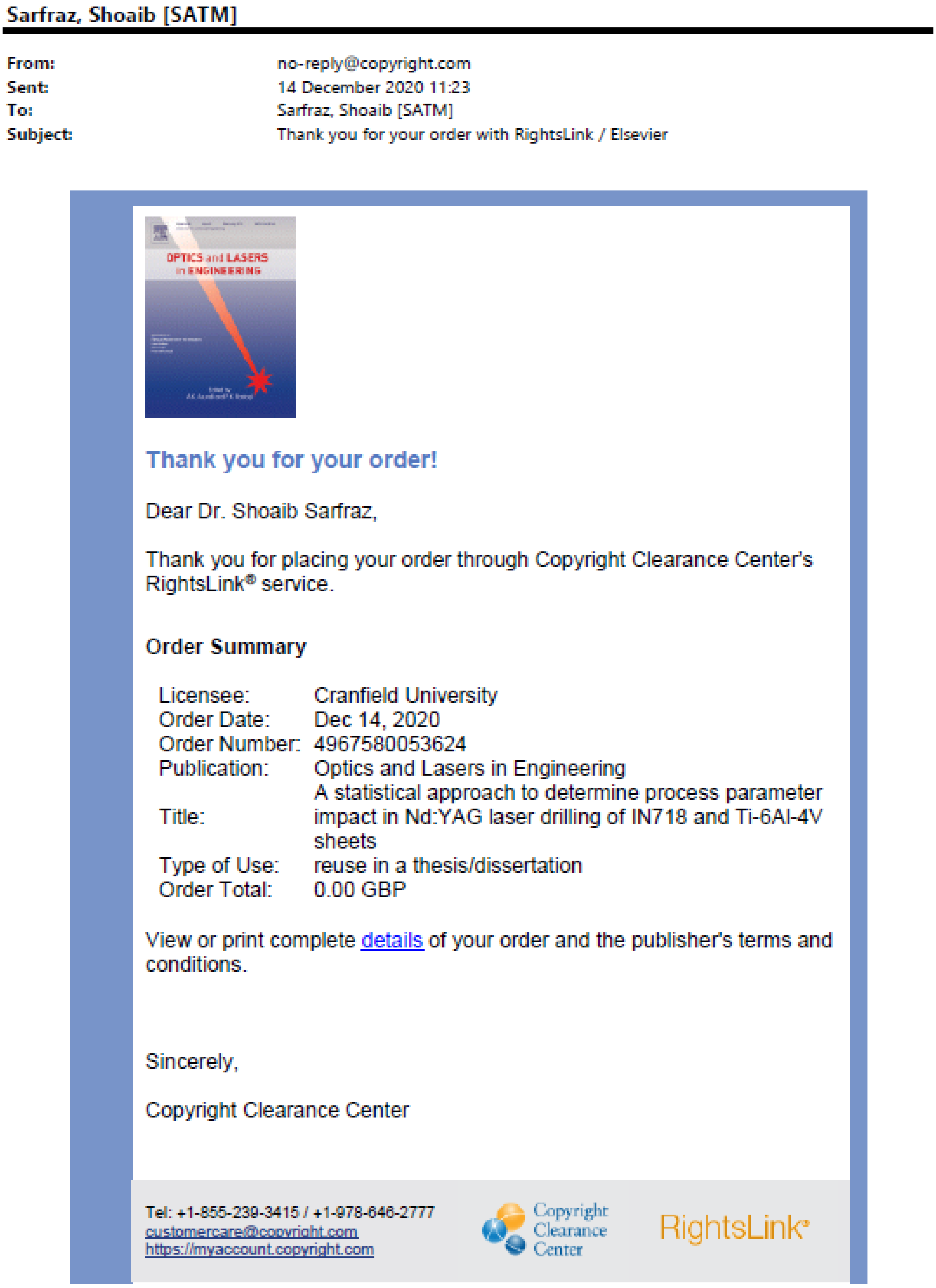
A.3 Figure 2-10 Recast layer in a percussion drilled hole (4 mm thick IN 718)



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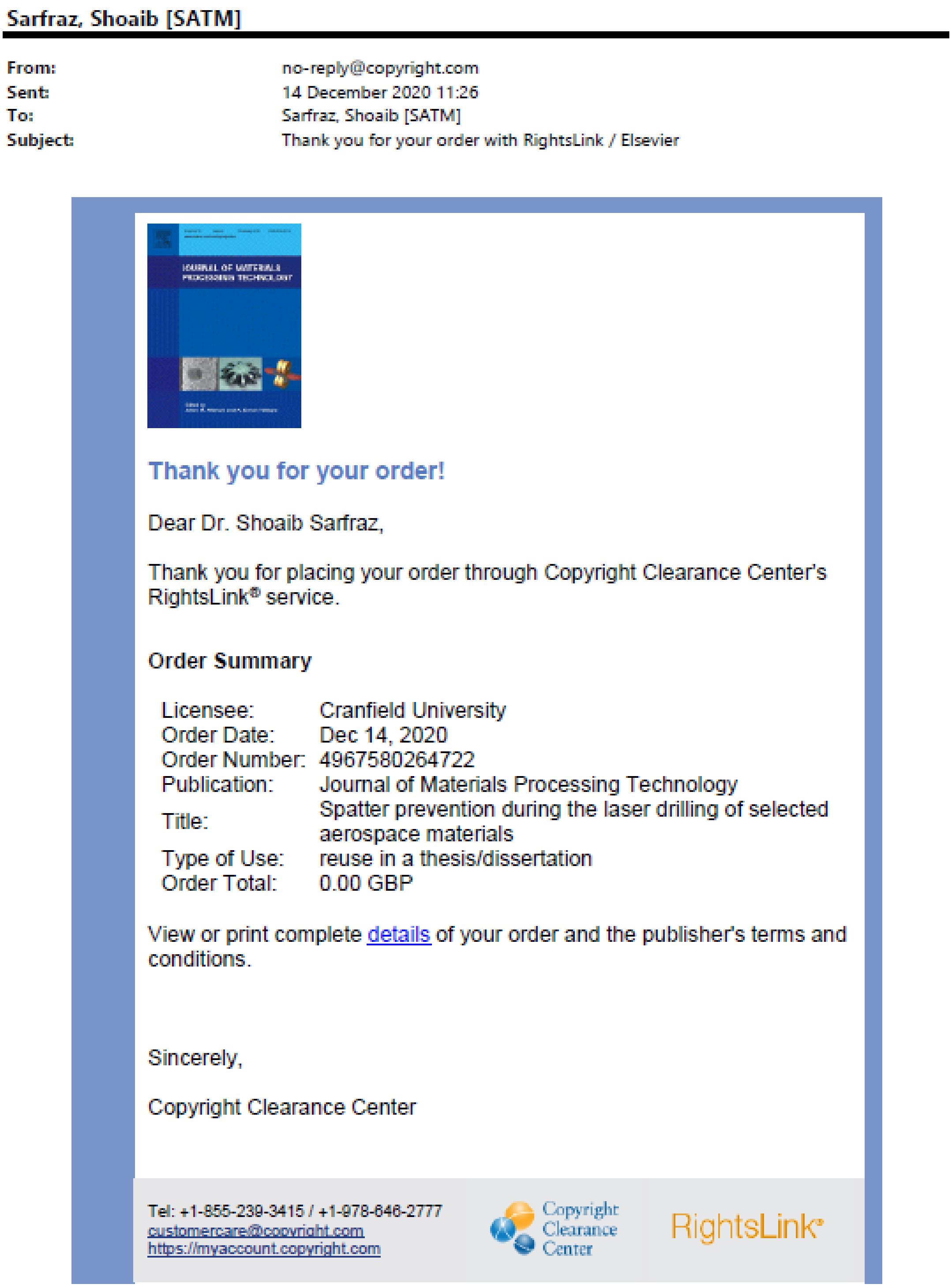
A.4 Figure 2-11 SEM image of spatter deposited over the periphery of the hole (2.05 mm thick Nimonic PK 33)



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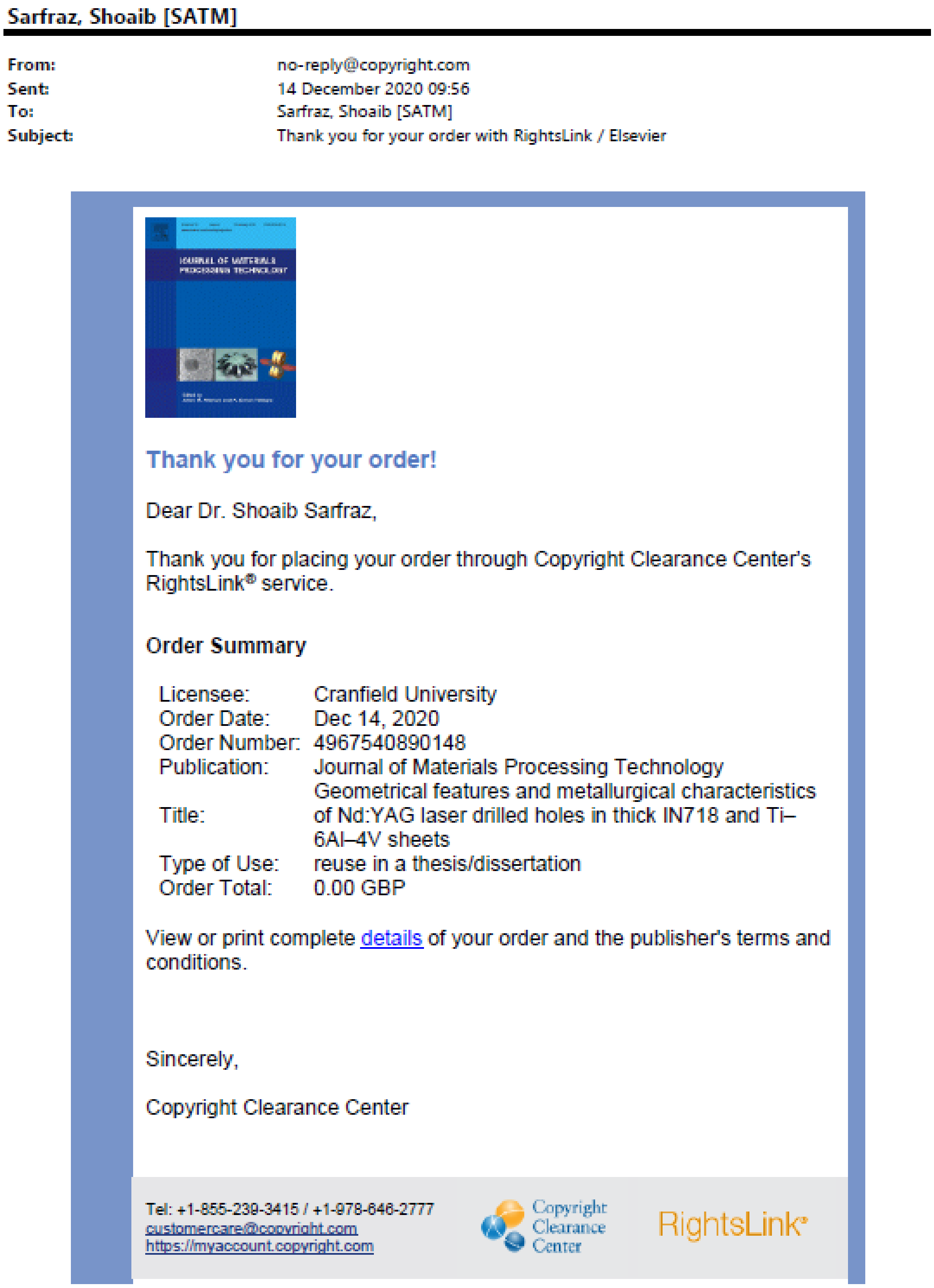
A.5 Figure 2-12 HAZ and recast layer in laser drilled hole (8.0 mm thick IN 718)



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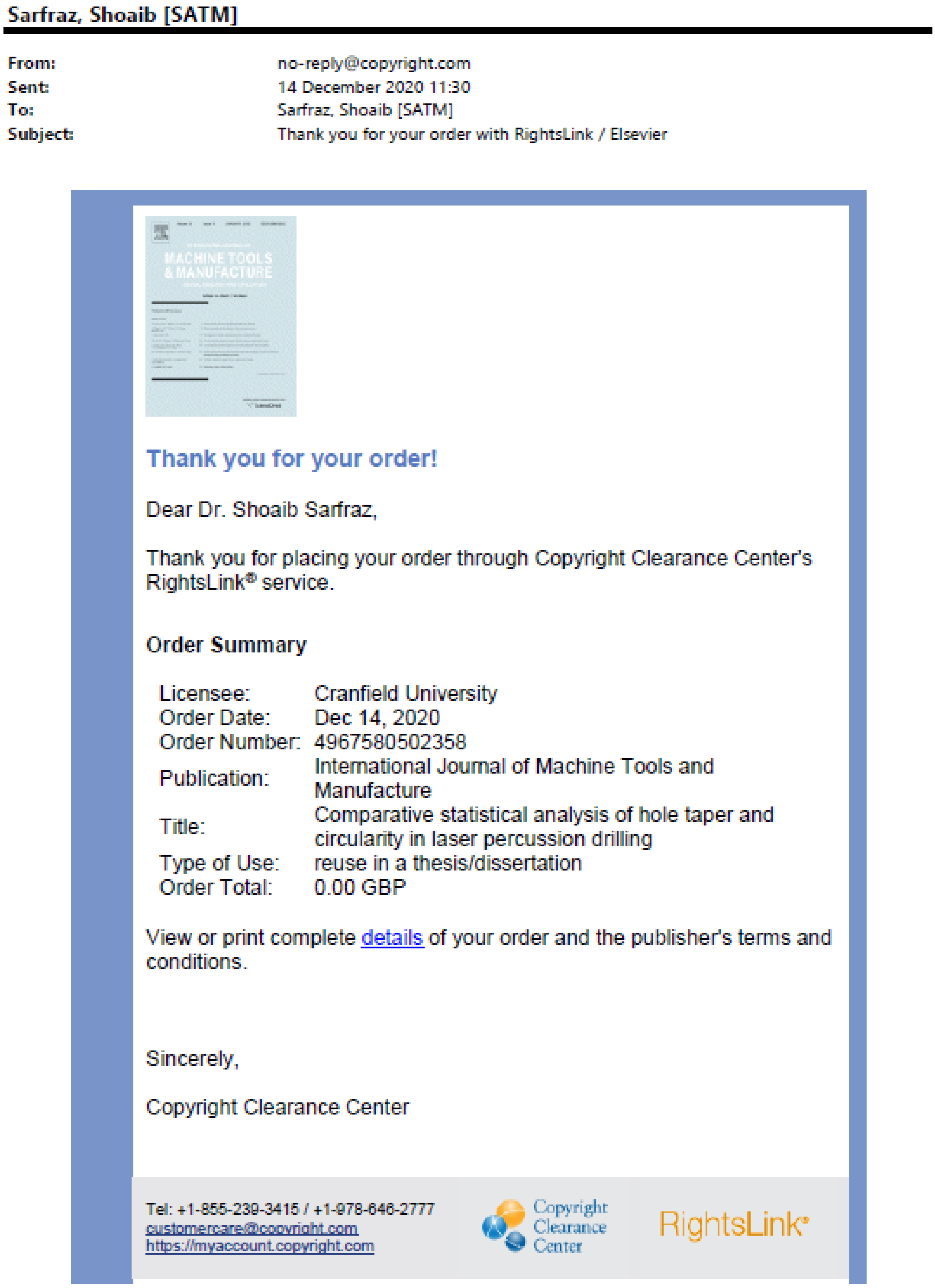
A.6 Figure 2-20 Schematic diagram showing the variation of focal position



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Appendix B Material Data Sheet

B.1 Technical information – Inconel® alloy 718

Mechanical properties	Values
Elongation at break (%)	<15
Hardness - Brinell	250-410
Modulus of elasticity (GPa)	200
Tensile strength (MPa)	800-1360
Physical properties	**Values**
Density (gcm^{-3})	8.19
Melting point (°C)	1260-1335
Thermal properties	**Values**
Coefficient of thermal expansion @20-100°C ($\times 10^{-6}$ K^{-1})	13
Maximum use temperature in air (°C)	700
Specifc heat @23°C (JK^{-1}kg^{-1})	435
Thermal conductivity @23°C (Wm^{-1}K^{-1})	11.2