FEASIBILITY STUDY OF LASER CUTTING PARAMETERS ON THE SURFACE FINISHED OF THE GALVANIZED PLATE

SARAH SHAHIRA BINTI SAIFUL BAHRI

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

FEASIBILITY STUDY OF LASER CUTTING PARAMETERS ON THE SURFACE FINISHED OF THE GALVANIZED PLATE

Submitted in accordance with the requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree in Manufacturing Engineering (Hons.)

By

SARAH SHAHIRA BINTI SAIFUL BAHRI

FACULTY OF MANUFACTURING ENGINEERING

2021

DECLARATION

I hereby declared this report entitled "Feasibility Study Of Laser Cutting Parameters On The Surface Finished of The Galvanized Plate"

is the results of my own research except as cited in the reference.

Signature : ……………………………………………………

Author's Name : SARAH SHAHIRA BINTI SAIFUL BAHRI

Date : 16 June 2021

APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Hons.). The member of the supervisory committee are as follow:

……………………………………………………………

(Supervisor) – Signature & Stamp

ASSOC. PROF. DR. MOHD AMRI BIN SULAIMAN
FACULTY OF MANUFACTURING ENGINEERING
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
HANG TUAH JAYA
76100 DURIAN TUNGGAL, MELAKA

ABSTRAK

Penyelidikan mengenai kajian kemungkinan parameter pemotongan laser pada permukaan plat galvanis ditulis dalam laporan khusus ini. Oleh kerana ciri anti karatnya, besi galvanis sering digunakan dalam projek pembinaan untuk membina struktur seperti balkoni, beranda, tangga, laluan pejalan kaki, dan juga peralatan permainan kanak-kanak seperti rak basikal dan set ayunan. Mengetahui kualiti permukaan bahan yang menggunakan kaedah memotong laser adalah penting kerana ia menyumbang kepada masalah keselamatan. Oleh kerana fakta ini, tujuan penyelidikan ini adalah untuk mengkaji pengaruh parameter pemotongan laser pada pemotongan permukaan untuk besi galvanis. Parameter pilihan adalah kelajuan pemotongan dan tekanan gas terbantu. Kedua-dua parameter ini dicapai dengan analisis saringan dengan melakukan jurang kajian dari penyelidik sebelumnya. Kelajuan pemotongan 1800mm/min, 2500mm/min, dan 3000mm/min dikategorikan kepada tahap rendah ke tahap tinggi. Julat dari ujian perintis untuk tekanan gas dibantu adalah 1 bar hingga 8 bar. Kekasaran permukaan adalah tindak balas proses yang akan diukur dengan menggunakan penguji kekasaran permukaan mudah alih pada akhir eksperimen. Untuk kedua-dua parameter, kedudukan fokus dan daya laser yang digunakan adalah sama. Mitsubishi Electrical Model ML2512HV2-R PLUS adalah mesin yang digunakan dalam penyelidikan ini. Teknik Reka Bentuk Eksperimen (DoE) telah diterapkan untuk merancang keseluruhan kajian. Eksperimen ini dirancang dengan dua tahap reka bentuk faktorial menggunakan perisian. Analisis ANOVA menunjukkan bahawa tekanan gas yang dibantu mempunyai kesan yang lebih besar pada kekasaran permukaan daripada kelajuan pemotongan. Model matematik dibina dari analisis ANOVA, dan bahagian kesalahan antara model dan nilai eksperimen disahkan menjadi 0.5%. Respons yang optimum diperoleh pada kelajuan pemotongan 1800 mm/min dan tekanan gas dibantu 8 bar pada akhir penyelidikan. Pengesahan parameter optimum ini dibuat antara model dan eksperimen. Hasilnya nilai ralat optimum tersebut sebanyak 7.08%.

ABSTRACT

The research on the feasibility study of laser cutting parameters on the surface finished of the galvanized plate is highlighted in this particular report. Due to its anti-rust feature, galvanized iron is frequently used in construction projects to build structures such as balconies, verandahs, staircases, ladders, walkways, and even children's playground equipment such as bicycle racks and swing sets. Knowing the surface quality of the material that used the laser cutting method as it contributes to the safety problem is important. Due to this fact, the purpose of this research is to investigate the effect of laser cutting parameters on surfaced cutting for galvanized iron. Cutting speed and assisted gas pressure are the preferred parameters. Both these parameters are accomplished by screening analysis by doing the research gap from previous researchers. The cutting speed of 1800mm/min, 2500mm/min, and 3000mm/min is categorized into three levels which are from low to high levels. The range from the pilot testing for assisted gas pressure is 1 bar up to 8 bar. Surface roughness is the process response that will be measured by using a portable surface roughness tester at the end of the experiment. For both parameters, the focus position and the consumed power of the laser are constant. Mitsubishi Electrical Model ML2512HV2-R PLUS is the machine used in this research. The Design of Experiment (DoE) technique has been applied to plan the entire study. The experiment is planned with two levels of factorial design using the software. ANOVA analysis indicates that assisted gas pressure has a greater effect on the surfaced roughness than cutting speed. Indeed, a mathematical model is constructed from the ANOVA analysis, and the proportion of error between the model and experimental values is validated to be approximately 0.5%. The optimal responses were obtained at a cutting speed of 1800 mm/min and an assisted gas pressure of 8 bar at the end of the research. Validation of these optimal parameters was made between the model and the experiment. As a result, the optimum error value is 7.08%

DEDICATION

I dedicate this final year project to:

My beloved parents;

Saiful Bahri & Rozidah

My dear friends;

For providing myself with endless moral encouragement, collaboration, support, and understanding.

Thank you so much and may Allah bless all of you.

ACKNOWLEDGEMENT

All praise be upon His Messenger to Allah, Lord of the World, and peace, in the name of Allah, the Most Gracious and Merciful. On top of all, I would like to thank him for rewarding me with patience and perseverance in completing this final year project successfully through ups and downs. I have learned so much not only in terms of academics, but also in terms of my personality during this process.

To my supervisor, Profesor Madya Dr. Mohd Amri Bin Sulaiman, I would like to express my deep and sincere and sincere gratitude for leading and supporting continuous morality and research in this whole research. His infinite technological advice and innovations helped me conquer challenges and kept me motivated and incredibly experienced in this study. Getting him as my supervisor was an outstanding pleasure and honor. I would also like to thank the three of my panels for their brilliant comments and suggestions. Particularly, my family members have my sincere appreciation. This thesis could not be written without their support. They have always embraced my academic efforts and have followed every step of the way regardless of my choices.

My heartfelt appreciation also goes to Mr. Mohd Ghazalan Bin Mohd Ghazi, and Mdm. Siti Aisah Binti Khadisah, who worked diligently and were cooperated to supply relevant information and technical knowledge to complete my research on laser cutting. Last but not least, I would like to thank all of my panels for providing me with a lot of motivation and cooperation in the completion of this study. During my study, they gave their critical suggestions and comments. Finally, I would like to thank all those who were relevant to this study, as well as express my apology for not being able to mention each one of you personally.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

LASER	-	Light Amplification through Stimulated Radiation
MASER	-	Microwave Amplification by Spontaneous Emission Radiation
ANOVA	-	Analysis Of Variance
FF	-	Full Factorial
FD	-	Two-Level Factorial Design
RPM	-	Robust Parameter Methodology
TM	-	Taguchi Methods
Fs	-	Focal Position
CO_2	-	Carbon Dioxide
DoE	-	Design Of Experiment
FD	-	Factorial Design
GI	-	Galvanized Iron
HAZ	-	Heat Affected Zone
MRR	-	Material Removal Rate
N_2	-	Nitrogen
Nd: YAG	-	Neodymium-Doped Yttrium Aluminium Garnet
HeNe	-	Helium-Neon
Ra	-	Edge Surface Roughness
Al-Cu	-	Aluminum Copper
Zn	-	Zinc
Wa	-	Arithmetic mean waviness
Rz	-	Arithmetic mean value

LIST OF SYMBOLS

mm/min	-	Millimetre per minute
m/min	-	Metre per minute
rpm	-	Revolution per minute
W	-	watt
m	-	Metre
Hz	-	Hertz
mm	-	Milimetre
sec	-	Second
bar	-	Pressure-bar
µm	-	Micrometre

CHAPTER 1

INTRODUCTION

The entire introduction to this work will be covered in this chapter. It began with a background of this study in the context. The problem statement that occurred is then followed by that. Then, the objectives in this report that need to be accomplished are described. The remainder of this chapter revealed the scope that narrows down the area of research, study significance, and also the summary of the chapter.

1.1 Background of Study

The laser beam cutting (LBC) method has a wide range of applications in various production processes within the industry because of its advantages of high cut quality and cost-effectiveness by large-scale production volume. Laser cutting is a typical production method used to economically cut different kinds of materials. Many current researchers like Eltawahni et al. (2012), said that the laser cut distance, cut edge quality, or finished surface quality are influenced by laser strength, cutting speed, gas pressure assistance, nozzle diameter, and focus point location, as well as workpiece material.

One of the most commonly used in construction projects to produce structures such as balconies, verandas, building frames, staircases, ladders, walkways, and more are galvanized iron materials. It is also particularly for playground equipment structures such as bicycle racks, jungle gyms, and swing sets because it's rust-resistant. According to Yeomans

(2004), galvanizing has been used in many types of elements exposed to a variety of environmental conditions for corrosion safety since the 1930s. Therefore, the consistency of the laser cut on the galvanized plate surface finish is very important to know.

One of the key measures of quality measurement of finished parts processed by laser cutting is surface roughness. Knowing the surface quality of the material that used the laser cutting method is important as it contributes to the safety problem. Laser cutting is commonly used in the cutting process, where the quality of the finished product depends primarily on the process parameters such as laser beam power, cutting speed, focal position, and assist gas pressure. Hence, this is an incredibly topic to be investigated in detail to increase the profound comprehension of laser cutting parameters that are significant to the finished output.

1.2 Problem Statement

Several variables can impact the efficiency of laser cutting, such as the unit, the operator, and the material can all affect the cut edge quality. However, the cutting speed, laser power, focal position, and supported gas pressure are the most important parameters for laser cut efficiency. To achieve high quality, optimization of process parameters is critical. The effect of the variance of input parameters on process output to achieve the goal of better product quality is often needed in any manufacturing process.

Noor et al. (2010) stated that there are different variables in laser cutting, including beam power, cutting speed, and distance of tips that affect the finished surface. The finished surface value decreases as the cutting speed and frequency increase and the laser power and gas pressure decrease. Based on the previous research and the analysis made by Löschner et al. (2016) on the cutting speed of stainless steel have a major effect on the surface finished, the heat-affected area, and the existence of macro defects, such as the presence of dross, molten and burned material. The heat-affected zone (HAZ) width also increases with the reduction in cutting speed, and the lower part of the cut surface is weakened below a certain threshold. In the manufacturing industry, if the input settings, such as the cutting speed and assisted gas pressure level, are incorrect, it results in problems for the entire batch of production. The cutting speed must be compatible with the work-piece form and thickness. A speed that is excessively fast or too slow prompts expanded roughness, the formation of burrs, and wide draglines.

Regarding the surface roughness, Madić et al. (2012) claimed that the most influential parameters were those related to the help gas, such as pressure, the diameter of the nozzle, and distance of stand-off. The roughness of the surface was found to be decreased by an increase in gas pressure support. It is important to adjust the thickness of the work-piece material to the gas pressure. Through torch cutting, the thin metal materials with high gas pressure are removed. The gas pressure must be very carefully set because even small adjustments in oxygen pressure affect the accuracy of the cutting. When defects happen, they influence the entire production line, reducing productivity. Apart from generating waste Work in Progress (WIP), the production schedule will be impacted due to the numerous rework processes required to cover the flaws caused by human error during the setting stage. Due to this inaccuracy, defects such as burrs will occur. When this issue develops as a result of the input parameters being set incorrectly, it affects the lead time in the manufacturing business. Worse yet, customers may lose trust in the organization.

The previous studies generally focused on the factors of laser cutting parameters that are significant to the surface finish for carbon steel, mild steel, or stainless steel, based on the above research. Thus, this thesis focuses on the galvanized iron laser cutting parameters.

1.3 Objectives

The objectives of this study are as follows:

a) To investigate the effect of laser cutting parameters on surfaced cutting for galvanized iron.

b) To optimize the surface quality of the finished output that used the laser cutting process.

1.4 Scope

The scopes of research are as follows:

(a) To study the effect of cutting speed, laser beam power, assisted gas pressure, and focal position on an interaction between the laser and galvanized iron material.

(b) This study will use the availability of raw material and laser cutting machines located in the Manufacturing Lab.

(c) Analyze the laser cutting quality parameters such as surface roughness.

(d) Optimization of the surface quality of the cutting part by using the design of the experiment (DOE) will be the ultimate finding of this study.

1.5 Significant of Study

The rationale of research is as follows:

(a) One of the essential quality features in a process of laser cutting is surface roughness. In microstructure, some defects such as burning, melting, and wavy surfaces have been identified. This analysis will recognize the impact of boundaries laser cutting on surface roughness. Thus, the optional cycle can be limited. Therefore, creation time and cost will be decreased.

(b) This thesis specifically explores optimization as a better approach to evaluating optimal system parameters and conditions for the laser cutting process than the "trial and error" approach.

1.6 Organization of the Thesis

To begin the investigations into laser cutting, the organization of this thesis is as follows. This thesis will be arranged according to the following chapters and is divided into three chapters. Chapter 1 includes the introduction of this project, problem statement, objective, project scopes, the significance of the study, thesis organization, and summary. The introduction involves laser data as a cutting device and galvanized iron as a workpiece. Chapter 2 highlights the project's literature analysis of articles, journals, and many more. The theories and components of research on the galvanized iron properties of the laser machine and laser-cut quality will be described. The result of a recent research paper focused on the laser. The methodology of this study is explained in Chapter 3. The proposed working process, the project procedures, and the collection of data will be defined. In this chapter, the flow chart also shows the progress of the project. Chapter 4 summarises the experiment's results and discussions, including the Design of Experiment (DOE), experimental setup, and experimental results and analysis. Each method used in this project is demonstrated and discussed in detail about the project's objectives. Each technique employed in this project is aimed at achieving the desired results. Chapter 5 is the concluding chapter of this thesis and will summarise the overall findings and results. Additionally, this chapter includes recommendations for future study and research.

1.7 Summary

Relatively, this chapter offers a summary of the project, problem statement, objectives, background, and also the scope and limitation. Overall, the chapter contains the key elements discussed in the entire review.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

More information about this research about the results and previous research regarding this project title will be discussed in this chapter. Most of the research papers are based on written articles or journals and books. The fundamentals of the laser system and the principles of laser beam cutting begin in this chapter. Then laser machining describes the method of drilling, marking, and cutting using a laser. In section 2.4, the types and parameters of the laser cutting machining were defined. Then, the variables that affect the cut quality will also be revealed in laser beam cutting. This chapter also examines the approaches of using galvanized iron also will be explained in section 2.6. Lastly, the surface roughness parameters will be addressed in connection with the laser machine and material. Moreover, this chapter helps to define and clarify the subject to be studied.

2.2 Fundamental Laser Cutting

2.2.1 Introduction

Laser cutting is a common method in most manufacturing industries. Laser progress is very rapid in the history of science, engineering, and technology. The versatility of pure energy in a highly focused form makes the laser an appealing tool and research instrument capable of being used in a wide range of fields. Inert-gas fusion cutting, reactive-gas fusion cutting, and vaporization cutting include proven variants of laser cutting technology. The materials are cut into metal and non-metal, welded, and surface treated by different sorts of lasers with various working forces (Zhou & Mahdavian, 2004). The laser is an electronic optical system that emits coherent radiation.

The acronym LASER stands for 'Light Amplification through Stimulated Radiation Emission,' which is a system that generates a focused, coherent light beam by inducing molecular or electronic transitions to lower energy levels, triggering photon emissions. The laser is an electromagnetic beam consistent, convergent, monochromatic with wavelengths of from 0.1 – 70 μm in regions of ultraviolet rays. Laser beam rays are perfectly parallel to a monochromatic design so that they can be focused on very small diameter and create a laser cutting power density function as it is a non-contact operation, it involves no instrument wear, vibration, and mechanical cutting forces (Sharma & Kumar, 2019).

2.2.2 History of Laser

Gbur (2020), acknowledges in his book that Theodore Maiman created a new kind of light for the first time on May 16, 1960, not found in nature, and changed the course of history. Until that day, to provide illumination, researchers researching the behavior and science of light had relied on stars, the sun, candles, and electric lamps. In a process called spontaneous emission, each of these sources involves a large number of atoms or molecules that release stored energy independently and at random.

In 1905, Albert Einstein openly theorized the existence of photons. Einstein spent the next several years working on his general relativity theory, an expansion of his particular relativity theory, which he had introduced in 1905. But in 1917, the problem of photons and how they are released from atoms came back to him. At the Electron Tube Research Conference in Ottawa in 1952, Dr. Joseph Weber, a newly-minted Ph.D. from the Catholic University of America, delivered a lecture on his concept of using stimulated emissions to amplify microwave signals. In essence, stimulated emissions can be used to generate an "avalanche" of synchronous photons, with the cascade caused by a small number of photons, just like a small number of rocks can launch a rockslide.

Through 1953, Charles Hard Townes and his graduates James P. Gordon and Herbert J. Zeiger created the first functioning MASER (Microwave Amplification by Spontaneous Radiation Emission), a device that could emit synchronous pulses, usually called 'coherent' microwave photons. Gbur (2020) also stated that brilliant ideas for science are formed not only by individual imagination, but by the work that others have already produced, and sometimes, once all the pieces are in place, many researchers may make the same discovery independently in a very short period. Therefore, in the Soviet Union, Nikolay Basov and Aleksandr Prokhorov successfully created their version that could send out a continuous microwave beam rather than a pulse series.

Working at Hughes Research Laboratories, Theodore Maiman managed to create the first working prototype ahead of the others. It used a synthetic ruby crystal as the stimulated emission medium and emitted red light pulses. The other research groups managed to develop similar equipment after this achievement, and the laser era was born.

2.2.3 Types of Laser

There are several different kinds of lasers available. A solid-state, fiber lasers, gas, liquid, chemical, free-electron, or semiconductor may be the laser medium. For each of the different laser methods, one might have to use different types of lasers, shown in Figure 2.1 below (Norman, 2008).

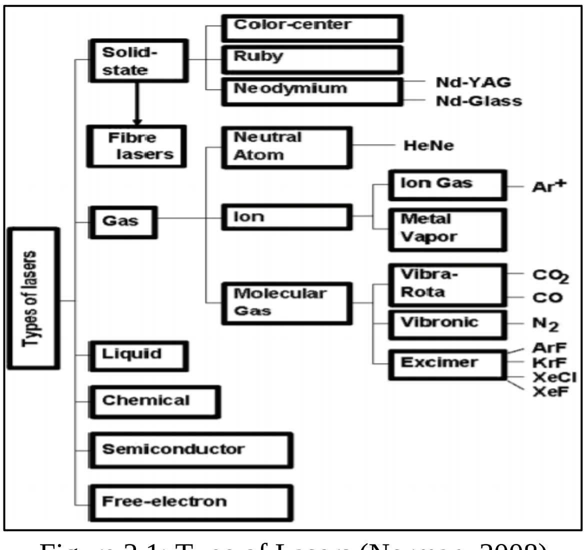


Figure 2.1: Type of Lasers (Norman, 2008)

The centered laser beam is essentially the method, these lasers vary in their wavelength, beam quality, and maximum power in addition to practical and economical aspects. Depending on the type of cut and what type of material is used, various laser types may also be used for laser cutting. In certain cases, this makes it possible to use less power to cut the same material with a different form of laser. Furthermore, a solid-state laser is one in which the light-emitting atoms are set inside a crystal or glass material. As indicated by Chau (2019), there are around 200 solids capable of being used as a laser-active medium. Some popular solid lasers are YAG-Neodymium: Yttrium Aluminum Garnet (YAG) plus 2-5% neodymium, with a wavelength in the near-infrared spectrum of 1060nm, is the active ingredient. Can continuously transmit up to 100W or pulses at frequencies of 1000-10000Hz.

Besides, Sandeep et al. (2019) also analyzed that are the most widely used lasers in the industry are CO_2 and Nd-YAG lasers as been provided by a power output of around 1 kW. He also mentioned that Nd: YAG lasers are strong lasers, have low beam strength, but high peak powers allow even thicker materials to be machined while working in pulsed mode. Shorter pulse period suits are also ideal for processing thinner materials. It is absorbable with high reflective materials that due to a shorter wavelength of 1 mm are difficult to process by CO_2 lasers. In the infrared field, CO_2 lasers, which are gas lasers, have a wavelength of 10 mm. It has a high beam power average, increased efficiency, and good beam quality. It can be used at high speeds for great sheet cutting. Carbon lasers are the highest power continuous-wave lasers widely accessible. It is also quite effective as well. Around 20% is the ratio of output power to input pump power.

For many purposes, gas lasers using many gases have been designed and used. As mentioned by Umredkar and Bhoyar (2019) in his study, gas lasers have a broad range of characteristics. For many purposes, gas lasers using many gases have been designed and used. They're one of the oldest laser forms available. For instance, due to its low price, (a) helium-neon (HeNe) laser is popular in education. (b) carbon dioxide lasers are also used for cutting and welding purposes in the industry. (c) gas lasers that produce deep ultraviolet wavelengths are metal ion lasers.

2.2.4 Laser Working Principle

A laser's fundamental component is very basic. It requires a lasing medium mounted within an optical cavity, an energy source pump, and a cooling system. To contain and intensify the photon chain reaction, it is important to position this reaction inside the optical cavity. The optical cavity consists of two parallel mirrors that are located on either side of the light-medium or laser medium. A fixed distance separates the mirrors, creating a Fabry-Perot interferometer. A bottle of gas (CO_2, argon), liquid, or solid crystal rod (garnet crystal usually made of Yttrium & aluminum to which the elements chromium, neodymium, holmium, or erbium are added) may be a lasing medium. Metals such as gallium, aluminum, and arsenide can also be solid-state semiconductors. Photons bounce off the mirrors in this configuration and re-enter the medium to induce the release of more photons. The mirrors collimate the light; that is, the photons re-enter the active medium exactly perpendicular to the mirrors, while those of the axis exit the lasing phase. A cooling system is provided, as the process is not 100% efficient and some energy is converted into heat. The other mirror is partly transmissive if one mirror is fully reflective (Ballal et al., 2013).

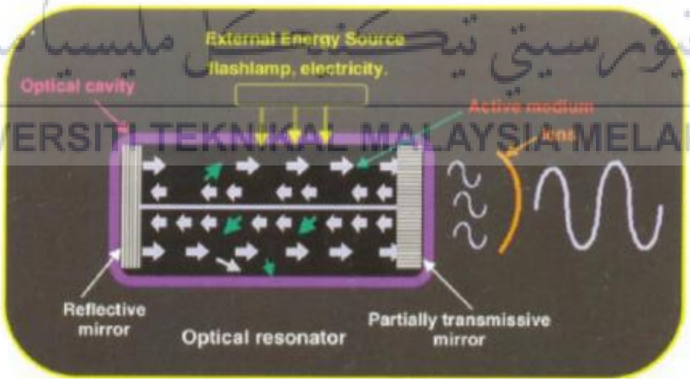


Figure 2.2: Components of Laser System (Ballal et al., 2013)

2.3 Laser Machining

2.3.1 Laser Drilling Process

As indicated by Sarfraz et al. (2017), the main production methods for making holes in the drilling process. Holes aid in various functions, including assembly fastening, weight reduction, and ventilation, accessing various components or tending to include components of aerospace engine cooling. One of the methods for drilling holes is laser drilling. In particular, when drilling of aerospace components is involved, this technique is much better than other production methods. Laser drilling has a wide variety of applications in industrial industries including automotive, aerospace, and electronics, due to the high degree of accuracy and no direct contact with the material surface. A multitude of parameters can be used to change the laser drilling operation. The material is immediately vaporized by the application of laser systems with a pulse length throughout the femtosecond region and a cold ablation can be made, which prevents an impact on borehole consistency, including thermal zones or recast layers. However, the achievable borehole quality for highly loaded components cannot be related to the mechanical drilling method as to diameter differences, roundness variations, surface quality, or conicity, particularly for boreholes with a greater length-to-diameter ratio (Michel and Biermann, 2018).

2.3.2 Laser Marking Process

Laser marking is a lasting method of creating indelible marks on the surface with a centered light beam. Laser markings cover a wide variety of applications typically done with fiber, pulsed, constant wave, green, or UV laser systems. Laser marking could be automated and handled at great speed but there are many other products left with permanent traceability marks including steel and titanium, aluminum, copper, ceramic, plastic, wood, paper, and glass. As indicated by Markov et al. (2015), precision laser marking varies from other methods of highly efficient, simple, miniature, and wear-firm imprint marking of symbols. A laser marking technology has many benefits such as high economic performance and low prime operating costs of marking, even by producing small batches of papers. Besides, by taking periodic checks, it has small prime cost control operations. The high-speed processing of inscriptions and photographs also means a greater ability to manage machinery. It uses an abnormally high coefficient in comparison with other marking methods. Also, laser marking is the optimum spare method for any materials and items, without any mechanical forces that can destroy the surface.

According to Lazov et al. (2015), there are plenty of ways in which laser marking can be done on the surface of products: Raster Marking, Vector Marking, and Mask Marking. Generally, for Raster Marking the idea is similar to a dot matrix printer, with the exception that the laser beam is the working method here. Raster marking is typically used in cases where high-speed textual information is required to be affixed. It is rarely used to illustrate photos in which high quality and detail are not required. Next, vector marking, the most popular laser marking technique. This is the highly flexible marking technique in which various applications can be realized almost everywhere in the sector involving the production of input data, serial numbers, two-dimensional codes, labels, and almost every other suitable marking. The beam is concentrated on the workpiece by an optical system (lenses and mirrors) with advanced computer program management. Using special software, a computer controls the galvanometer mirrors. Marking is achieved by pointing the beam to the work area in x and y directions. Finally, for mask labeling, a laser beam passes through a mask. A working area optical unit builds the beam. The system makes frequent use of the mask to avoid changing the processing parameter. The time to receive the image is very small, as it functions in pulsed laser mode.

2.3.3 Laser Cutting Process

Laser cutting is a non-contact thermal operation able to cut complex contours of high-precision materials. The material is heated, molten, and evaporated in a limited well-specified area that can cut almost all materials. As eloquently stated by Senthilkumar (2014), it is called a non-contact operating because the method would not need costly or replaceable equipment and does not create any force that can harm the workpiece so that it can be used as another choice to mechanical cutting processes. The affected zone by a coaxial jet of the aid gas shown in Figure 2.3 below is when concentrated in the spot melts, is removed by the high-density beam, and the substance is evaporated in a fraction of a second, and the molten material is evaporated.

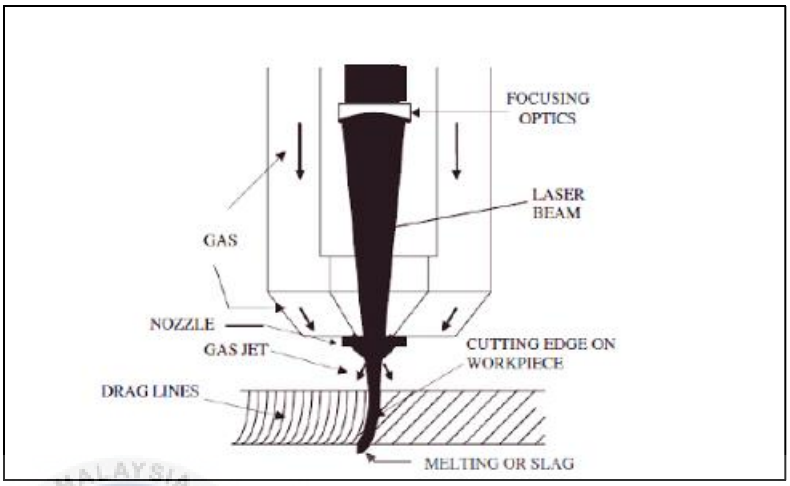


Figure 2.3: Schematic Diagram of Laser Beam Cutting (Senthilkumar, 2014)

As mentioned by Yilbas (2018) in his study revealed that the laser cutting process, the final product is highly dependent on the proper selection of the laser parameters and the characteristics of the workpiece material to ensure the high quality of the desired final product. Compared to conventional techniques, the method of laser cutting depends not on the mechanical properties but the thermal properties of the pieces, preventing surface defects to the material. Besides, the critical laser cutting procedures track the target location to achieve an accurate target and a small spot size, manipulating the parameters of the dust to make sure the right direction and flow of the aid gas. High pressure, greater nitrogen, or inert gasses were used for laser cutting to avoid oxidation reaction reactions and melted dross produced during the process (Zhang and Guan, 2014).

2.4 Parameters Involved in Laser Cutting

The process parameters include the laser cutting operation characteristics which could be adjusted to improve cutting quality and obtaining the optimal cutting outcomes. Any method parameters, however, are usually cannot be modified by the operator. Numerous studies conducted experiments with the parameters or processing parameters found the most relevant with no scientific experimental design process is used. The findings obtained are used to examine the effects on each factor's an observed performance measure and the mechanism of impact.

Anghel et al. (2020) concede that laser cutting is a dynamic process that is controlled by a multitude of variables with hard to estimate interactions. The laser-cut parameters are listed as system parameters, workpiece parameters, and processes, as shown in Figure 2.4. System parameters are inherent in the specific laser system used, although it is possible to adjust all other parameters to meet the desired outputs. The specifications for the workpiece apply to the type of material and the thickness to be cut. For processing with the laser, materials with smaller reflectivity and thermal conductivity are most acceptable. Both CO_2 and Nd: Yag laser machines can cut the frequent material used in manufacturing sectors throughout all variants such as mild steel, stainless steel, or alloy steel. The process efficiency is determined in terms of surface roughness and integrity, kerf geometry, and material removal rate by output parameters such as cut surface quality.

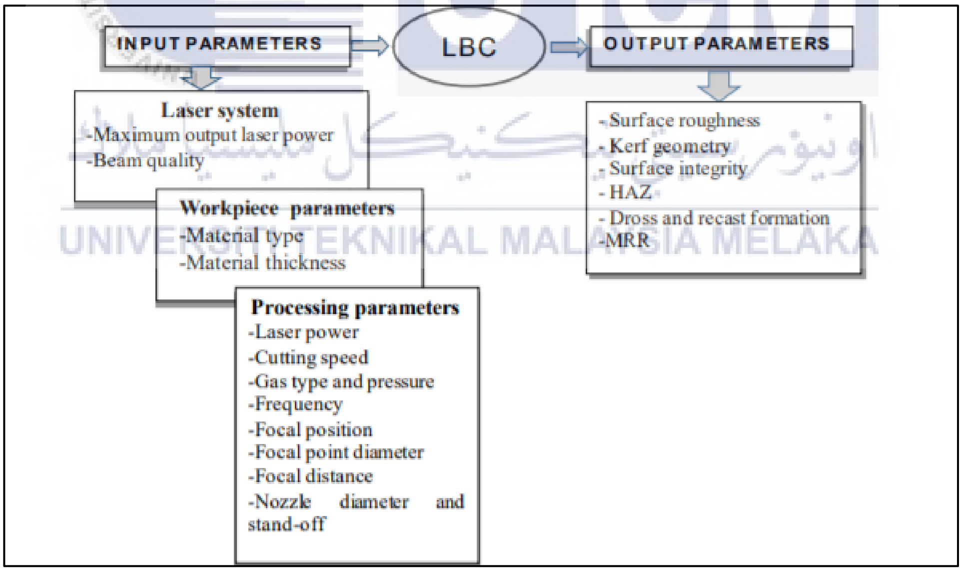


Figure 2.4: Laser beam cutting process parameters (Anghel et al., 2020)

The main parameters of operation correlated with laser machining are often laser strength, laser beam spot diameter, cutting speed, feed rate, and cutting depth. As output parameters, the cut quality features for instance Edge Surface Roughness (Ra) and Surface Hardness are considered. The cutting edge is cooled by the gas flow, reducing the distance from the heat-affected zone (HAZ). The aims of manufacturers with a limited theoretical and functional perspective to help with systematic selection are to maximize production and reduce quality, along with reducing costs. Laser process parameters are typically selected based on manual values, guidelines for other manufactures, and previous experience. High production costs, poor product quality, and high waste are caused by incorrect selection of cutting parameters. Laser cutting process efficiency mostly depends on laser parameters. By careful monitoring of the cutting parameters, high-quality cuts are achievable at elevated cutting speeds. It is, therefore, necessary to identify the impact of cutting parameters on cut efficiency (Suraj et al., 2020). Incorrect setting of parameters will decrease the consistency of the cut and the existence of burrs, heat, and affect the surface quality.

2.4.1 Laser Power

CO_2 and Nd: between multiple types of lasers, lasers of YAG have low power, improved efficiency, and good quality beams. Laser beam cutting seems to be preferable to any cutting process, whether traditional or not, due to flexibility in materials, no tool or wears change, large production efficiency material use, greater precision, and surface quality (Choudhury and Shirley, 2010).

The most essential criterion when selecting the laser power of the laser system is the application that must be used most often with the laser. Different laser power can lead to the optimal outcome, depending on the type of material. According to Kotadiya and Pandya (2016), the laser power was found to be the most significant compared to the cutting speed and pressure of a gas. The experiment was designed to investigate the effects of process parameters on the surface quality of processed surfaces and to create a specific relationship to display roughness changes according to those parameters. The contours of the reaction (surface roughness) against laser power and gas pressure are shown in Figure 2.5 at a speed of 2.1 m/min.

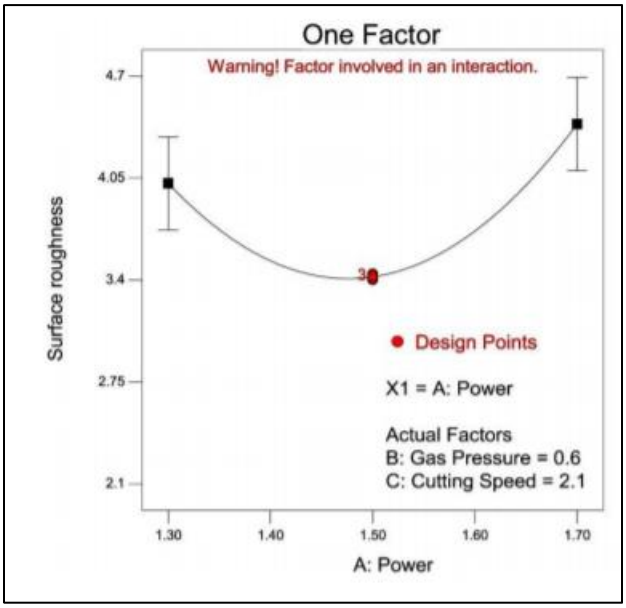


Figure 2.5: Power vs. Surface roughness (Kotadiya and Pandya, 2016)

2.4.2 Cutting Speed

The laser cutting energy balance means that the energy delivered to the cutting area is separated into two, which are the energy used to create the cutting area and the energy losses. The energy used for cutting is shown to be proportionate to the time taken, regardless of the time taken to perform the cut, whereas the release of energy from the cutting zone is commensurate with the time it takes. As the cutting process increases its effectiveness, the energy loss of the cutting zone will decrease. The shape and the thickness of the workpiece should correspond to the cutting speed. A speed that is too quick or too slow leads to greater roughness, the formation of burrs, and wide drafts. Reducing the cutting speed while thickening materials means that energy is lost more and that process is less efficient. With increased material thickness coupled with reduced cutting speed, leading loss levels that are the largest thermal losses for many of the metals in the cutting region are increasing. The cutting speed with the gas flow rate and strength is significant. Striations on the cutting edge become more apparent as cutting speed increases, dross remains at the bottom, and penetration drops. Too low a cutting rate contributes to a high cutting rate when oxygen is used to make mild steel cuts that reduce edge quality and increase the thermal area's width (HAZ). Cutting speed is normally inversely related to the thickness of the material as shown in Figure 2.6 below. While cutting sharp edges with reduced fire prevention ability, the speed must be lowered (Wadekar and Deokar, 2016).

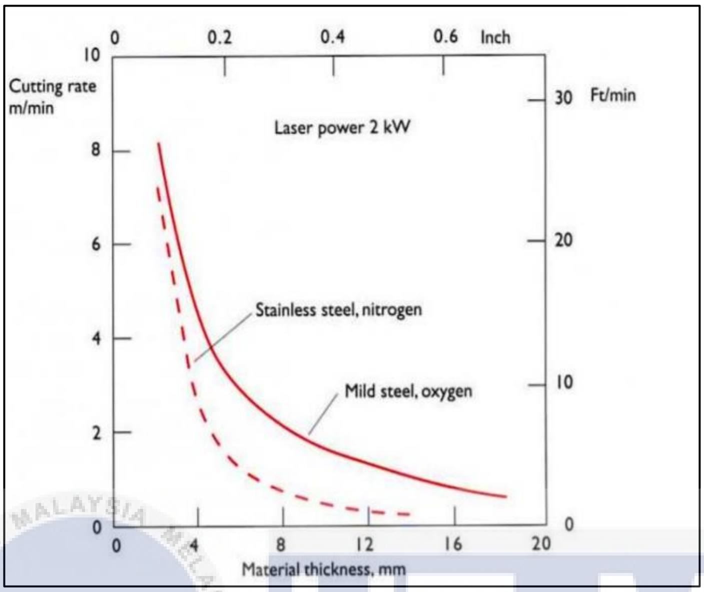


Figure 2.6: Cutting Rate Vs Material Thickness (Wadekar and Deokar, 2016)

2.4.3 Type and Pressure of Assist Gas

A common industrial method for sheet metal cutting is laser cutting. With the assistance of pressurized gas, the system depends on the removal of the melted material. The form of gas that supports the process is a significant factor among the main control variables. This gas is usually picked based on the material that has been extracted and the quality of the cut required. In this respect, the assistive gasses used to cut laser can usually be defined as inert or reactive gases. In regular laser cutting, an assist gas is used to remove the molten material through the bottom of the kerf.

The most well-known gases in laser cutting are nitrogen, argon, oxygen, and air. The reaction of the chemical between both the gas and the molten material provides added exothermic energy by using a reactive gas. This reaction provides extra energy that improves the process of cutting. In this sense, oxygen will give up to 60% of the energy needed to laser cut this material when cutting mild steel. Using oxygen as an aid gas, cutting speeds are thus normally, at least, twice. A study had been conducted on the effect of various gases (air, nitrogen, argon, and oxygen) throughout laser cutting of a standard Al-Cu alloy on the quality of the edge and its chemistry surface. A strong influence of the assist gas form can be observed concerning the cut edge efficiency, as seen clearly in Figure 2.7 below. Cut edge inspection shows the remarkably finer topography acquired when argon is being used as an assistance gas and greater high laser power is applied (Riveiro et al., 2011).

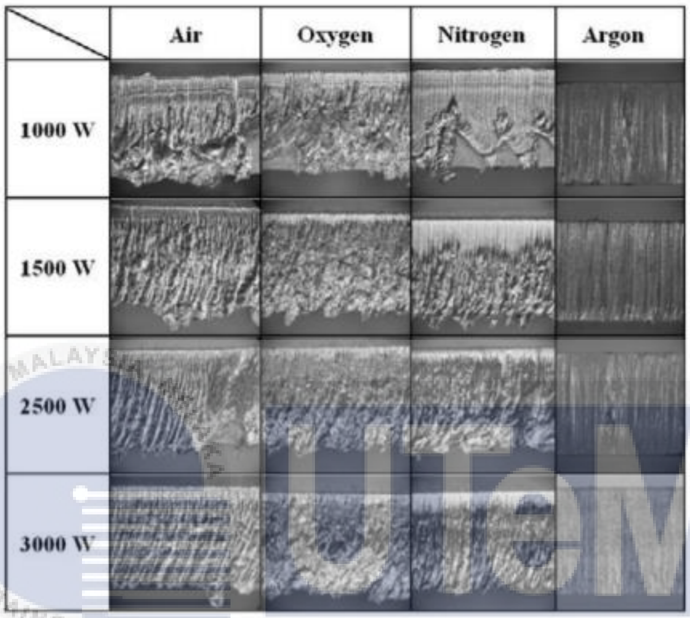


Figure 2.7: The Cut-Edge Sample Morphology Optical Micrographs Processed by selected Gas Assist as a Laser Power Feature (Riveiro et al., 2011)

Riveiro et al. (2011) also stated in Table 2.1, when oxygen or nitrogen is used, the overall average roughness is obtained, while the use of compressed air marginally decreases these variables. The required minimal roughness, averaging 3.7 μm for the conditions studied, was achieved by using argon as an assistive gas. Then, argon is the ideal choice in terms of quality and efficiency to produce Al-Cu alloys.

Table 2.1: Average roughness (evaluated at 1000, 1500, 2500, And 3000 W higher cutting requirements during processing) and HAZ extension calculated as a result of assistive gasses

Assist gas	**Average roughness (μm)**	**HAZ extension (μm^2)**
Compressed Air	8,2	131147
Oxygen	14, 2	182242
Nitrogen	13, 1	94591
Argon	3, 7	15469

Mathematical models for estimating surface quality characteristics such as average surface roughness have been built in another study Madić et al. (2012) for the CO_2 laser cutting of mild steel relying on laser cutting parameters. An increase in the pressure of the assist gas increases the roughness of the surface because the heat generated by exothermic reaction increases Figure 2.8 below. The functional relation between Ra and Rz and laser cutting parameters is nonlinear and follows the equivalent pattern, except that when using high gas-assist pressure, the change in Rz is more pronounced.

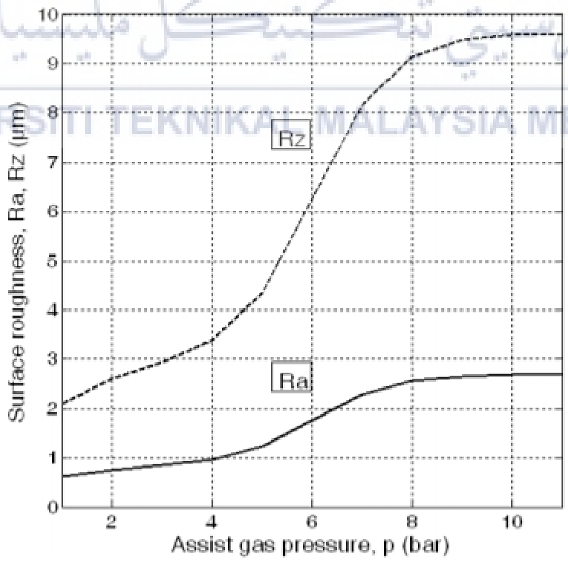


Figure 2.8: Effect of Assist Gas Pressure on Surface Roughness (M. Madić et al., 2012)

2.4.4 Pulse Frequency

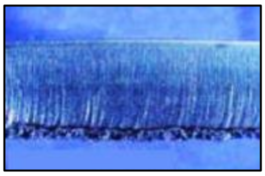
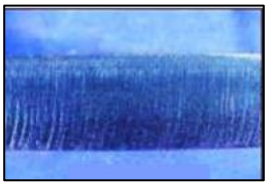
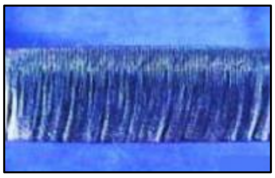
A lower frequency will produce spotted engraving, whereas line engraving will be possible with a higher frequency. HAZ decreases with the rise in pulse frequency. This is because the heat input length is limited and much of the heat is then used for material removal, and therefore less likely to form HAZ. But if the pulse frequency rises further, then the top surface is overheated compared to the heat conduction that appears to produce HAZ. The frequency of the laser pulse thus greatly influences the accuracy of the cut; but it does not linear with the kerf width and the height of the dross (Barge et al., 2019).

2.4.5 Focal Position

Andersson (2015) emphasizes that a focal spot position is the next observed parameter. The focal length is known as the distance to the point of focus from the center of the lens. It is said that the laser beam is focused within a range called the focus depth, in which the laser beam intensity is sufficiently high. A short focal length leads to the high strength of the beam but a limited focus depth and is thus more suited for cutting thinner materials. A longer focal length provides a greater focus depth but also reduces the strength of the beam. Thicker materials with a broad focal length are more fitting for cutting. In the cutting phase, the optimum focus location is crucial and has a substantial. In terms of surface roughness and the amount of dross at the lower of the cut surface, the consistency of the cut edge is affected. For cutting sheets up to 6 mm thick, a 65 mm lens is appropriate.

Burrs can be formed at the lower of the cut if the focus position is too close to a material. Alternatively, a wider position creates roughness on the surface and cut consistency to worsen. The location of the focal point is related to the height of its nozzle standoff, which is measured in terms of material thickness and cutting form (Zlámal et al., 2018). Table 3.1 below shows that the optimal focal spot position has the best surface finishing.

Table 2.2: Quality cutting with different Focal Spot settings (Zlámal et al., 2018)

Cut Quality	Low Value	Optimal	High Value
Focal spot position [mm]			

To ensure optimal cutting efficiency, the focal position has to be managed. Focus adjustments and variations in laser beam form can also include differences in material thickness. When the focusing plane is placed on the surface of the surface for thin sheets and about 1/3 of the plate thickness just under the surface for thick plates, the ideal cutting speed is achieved when oxygen is cut (Wadekar and Deokar, 2016). Variation of surface roughness with the location of the focal point in Figure 2.9 illustrates that there is an ideal focal point position that produces minimal cut surface roughness while there are focal point positions where it is difficult to achieve cutting through the material. The difference in surface roughness with focus location is shown in the figure below is the laser power of 4 kW, 190.5 mm focal length. The cutting speed of stainless steel is 1 m/min and the pressure of a gas is 19 bar, and the cutting speed of aluminum is 7 m/min and the gas pressure is 20 bar.

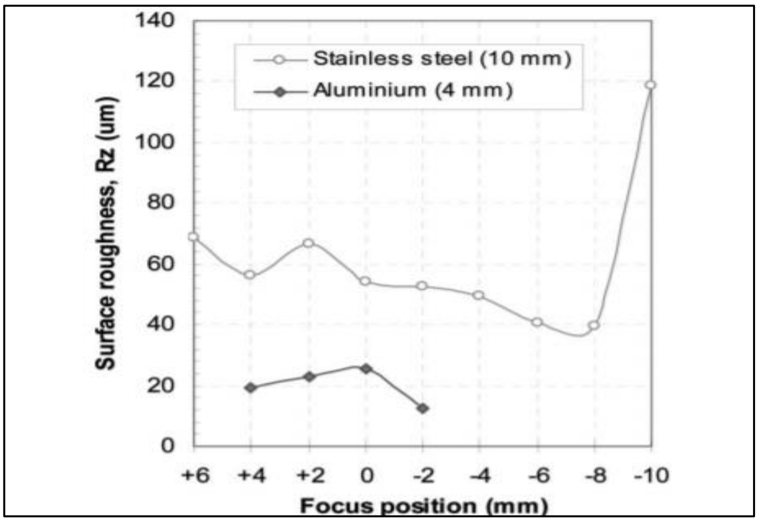


Figure 2.9: Surface Roughness vs. Focus Position (Wadekar and Deokar, 2016)

2.4.6 Nozzle Diameter and Standoff Distance

The standoff distance is a parameter that defines the gap between a nozzle as well as the workpiece surface during the cutting process. The gas flow is influenced by this gap, which further has a direct impact on cutting output and cutting efficiency. If the nozzle distance is greater than 1 mm, there will be major pressure variations. The distance between the pin and the piece should be less than the diameter of the pin since a greater distance will lead to turbulence and the major differential pressure between the pin and the workpiece. The nozzle distance of < 1 mm can generate increased nozzle wear and impurity, while the nozzle distance of > 1 mm can generate poor cut efficiency (Snežana et al., 2012).

The nozzle takes the cutting gas to the cutting front to ensure that the gas is reassured by the laser beam and, by stabilizing the pressure on the surface of the workpiece, reduces turbulence in the melting pool. The type of cutting gas jet and thus the cutting performance is defined by the structure of the dust, in particular the design of the aperture. As shown in Figure 2.10, the gap between the nozzle and the workpiece is the stand-off distance. The flow patterns of the gas affect the distance and have an important impact on cutting quality and efficiency. If the stand-off distance reaches around 1mm, high-pressure variations can occur. Given that the distance between the nozzle and the workpiece is greater and more turbulent, with a short stopping distance the kerf is no longer important in terms of structure and nozzle, it is proposed that its stand-off diameter is smaller (Wadekar and Deokar, 2016).

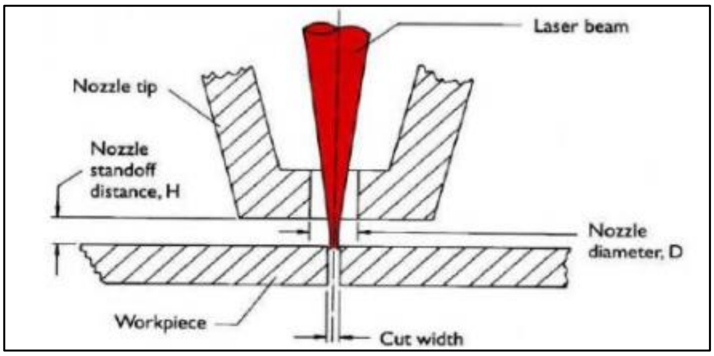


Figure 2.10: Nozzle Diameter and Standoff Distance (Wadekar and Deokar, 2016)

According to Anghel et al. (2018), the distance between the nozzle and its upper surface is a stand-off and is usually between 0.5 and 1.5 mm to reduce turbulence. In the industry, few common nozzle designs are used, such as parallel, conical, convergent, convergent-divergent nozzles, and many more. Supersonic laser cutting nozzle assembly developed by previous researchers can deliver oxygen at high velocity and mass flow rate. Evaluating the developed nozzle showed good characteristics of the gas flow inside and outside the nozzle, pressure uniformity, and no shock waves. The nozzle was used with a 1kW CO_2 laser to successfully cut 50 mm of carbon steel. That is an efficient way of using a low-power laser source to cut thick steel.

2.5 Material

The laser is used for the cutting of a wide variety of engineering products, along with metals including mild steel, stainless steel, and titanium also ceramic, glass, wood, paper, and plastic non-metallic materials. Badoniya (2018) believes that laser beam cutting is most widely used for cutting various material categories because due to material versatility, wear and tool adjustments are no longer needed, greater material uses and flexibility of output, precise cuts with a narrow kerf, faster-cutting operation, better accuracy, and cutting edge quality, the cutting of laser beams is better than any cutting process. In the laser cutting of various types of materials such as ceramics, composites, advanced engineering materials (super alloys), difficult-to-laser-cut materials, a lot of experimental and theoretical study has been carried out. For specific industrial usage, a range of different laser applications is designed.

2.5.1 Galvanised Iron

Galvanizing is a well-established, cost-effective, and reliable form of corrosion control for metals. Coating metal surfaces by soaking the metals into a molten Zn metal bath is essentially a surface treatment technique. For a long time, Zn coating was used as good metal protection against corrosive conditions. Galvanizing is commonly used to resist corrosion because of its ability. The essence of the security that zinc coatings provide is threefold. Second, the thick coating protects the entire surface as a shield and avoids interaction with any corrosive environment. If the coating is impaired, corrosion occurs only in zinc due to zinc's sacrificial conduct. Finally, the natural process of weathering helps to create a natural passive layer on the surface that can then resist corrosion (Ozturk et al., 2017). A preferred method for handling coated metals is laser cutting. When using CO_2 and fiber lasers, the desired function is to reduce the removal of the special layer on the base material.

2.5.2 Material Thickness

For metallic materials, the roughness of the cut edges increases with increasing material thickness, and the laser power needed for cutting is greater. With larger material thicknesses, with the same laser strength, noticeably lower cutting speeds are achieved. Workpiece thickness is found to have a substantial influence on the subsequent quality of the cut. Due to the research of Keles and Oner (2012), by improving the sideways burning, increasing workpiece thickness reduces the cutting efficiency. In the current study, the effect of workpiece thickness and laser pulse frequency on the kerf width are studied and the CO_2 laser cutting of 304 stainless steel sheets is examined. Using the optical microscope, the heat-affected zone (HAZ), kerf width, and dross height are evaluated. By holding other parameters constant, the heat-affected zone is analyzed for various workpiece thicknesses. It is reported that there is an increase in the width of the kerf with increasing workpiece thickness. Such findings are consistent with the results recorded in the past review. In this case, the energy needed to achieve efficient cutting is increased at large workpiece thicknesses. The greater input of energy to the workpiece, therefore, contributes to bigger widths of the kerf. Figure 2.11 also shows that the higher workpiece thickness contributes to greater the width of the kerf. Due to the high transfer of energy, the heat-affected zone size is observed.

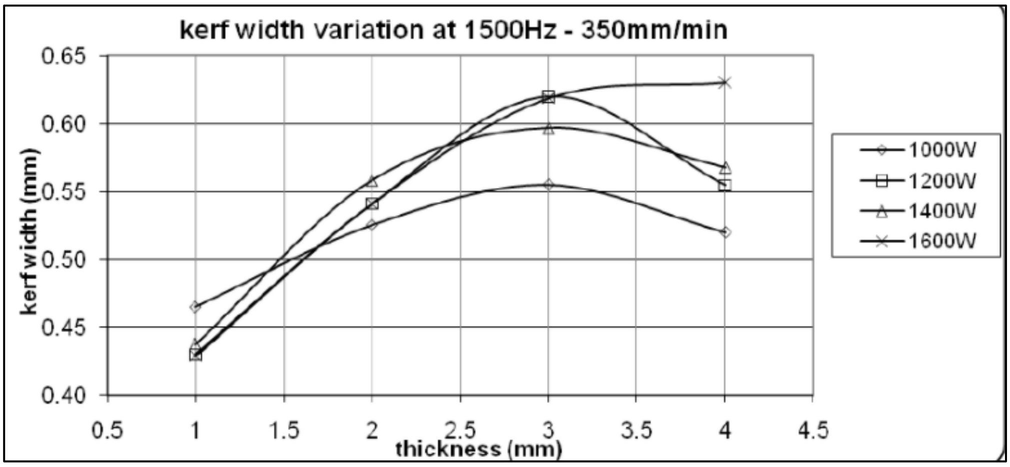


Figure 2.11: Difference of kerf width at 350mm/min-1500 Hz with power and workpiece thickness (Keles and Oner, 2012)

2.6 Characteristic Properties of The Laser Cut

Based on the experiments performed by the previous researcher, the laser cutting quality (kerf width, surface roughness, and HAZ) was determined primarily by the cutting speed, the assisted gas pressure, laser power, pulse frequency, and focus location. A significant number of researchers have drawn interest because of the great practical value of surface roughness and its dynamic existence. The quantity of the material removed and the material affected by the cutting operation obtain the cutting quality. The kerf width, perpendicularity of the cut edge, surface roughness, dross attachment, and heat-affected zone size is the characteristic characteristics of laser cutting used to characterize the cut quality (HAZ). The process parameters affect the performance of laser cutting and the accuracy of a cutting edge obtained (Toth et al., 2006).

2.6.1 Kerf Width

A part of the material is cut off by the laser, identified as a kerf that is a groove or a kerf. The width of the section once the cut is done is referred to as the kerf width. The width of the kerf relates to the width of the gap formed during the cutting of cross-thickness and is normally wider at the base of the workpiece than at the top. During the cutting process, the kerf width represents the amount of material that has been extracted, which is a waste material; hence, a smaller kerf width is often preferable, particularly when small details are to be cut. The width of the cut kerf corresponds to the size of the circular beam, which is determined primarily by the quality of the laser beam and the optical focus. The power at the point of emphasis, the cutting speed, and the assisted gas jet also affect the size of the cutting kerf (Wadekar and Deokar, 2016). Figure 2.12 shows a basic schematic diagram of the kerf width at the end of the cutting process.

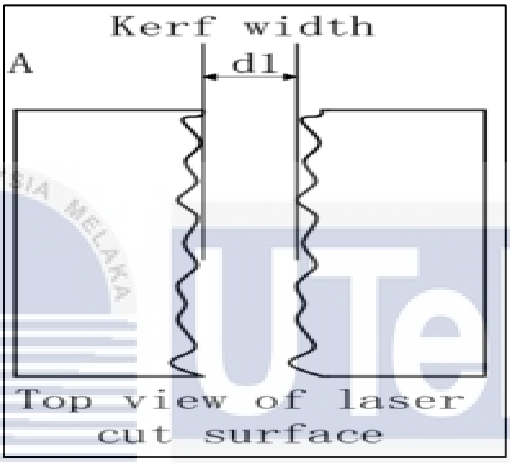


Figure 2.12: Schematic of Kerf Width (Wadekar & Deokar, 2016)

The cut kerf being transformed and shown in the center of the picture, according to Ozaki et al. (2012) the cross-sectional types of the kerf were determined by the kerf profiles for all the cut specimens. Figure 2.3 below displays the cross-sectional shapes of the kerf at various laser power and cutting speeds. In this diagram, the top part is equal to each graph's laser surface. Cut kerfs are shaped perpendicular to the surface of the plate under all cutting conditions. Besides, the shapes of the kerf are almost the same, even if the strength of the laser or the cutting speed is varied.

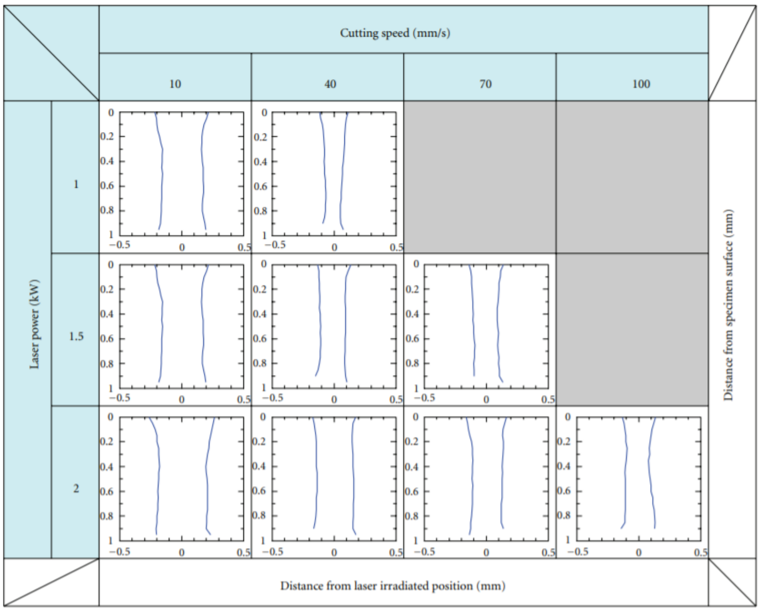


Figure 2.13: Cross-Sectional Kerf Shapes at Different Laser Power and Cutting Speeds (Ozaki et al., 2012)

2.6.2 Surface Roughness

Fatigue, corrosion, thermal conductivity, friction, and wear and tear of parts are caused by surface roughness. In laser cutting, the variables leading to surface roughness formation are complex. It is necessary to analyze surface roughness as this allowed the quality of the cut to be calculated alongside the values obtained from previous work and the values reported for (Placeholder1) other manufacturing processes (Black et al., 1998).

The mechanism behind the development of surface roughness has been challenged by the interaction effects between the laser beam, process parameters, and workpiece properties. The estimate of a given surface roughness parameter often depends on the values and interactions of other parameters. There are many ways to define surface roughness, including the average surface roughness, which is sometimes described by the Ra symbol, and the ten-point mean roughness, Rz, which is one of the most commonly used. Ra is defined as the arithmetic value of the departure of the profile from the centerline to the duration of the sampling. Rz is the arithmetic mean of the individual roughness of the five adjacent, representative measuring paths. It is well known that surface roughness influenced the life of fatigue, corrosion, thermal conductivity, friction, and wear and tear of parts (M. Madić et al., 2015).

The average exact value is the height of the arithmetic during the experiment. When it comes to the surface roughness profile, the mean arithmetic roughness is called Ra in Figure 2.14 below, while Wa is referred to as the arithmetic mean waviness of the waviness profile.

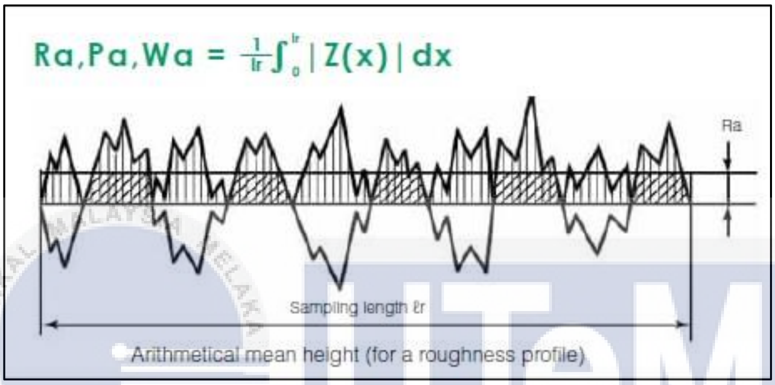


Figure 2.14: Graph for Arithmetical Mean Roughness (Ra) (M. Madić et al., 2015)

The highest possible profile height reflects the actual vertical distance between the maximum profile height and the maximum valley profile depth over the sample length. Where the roughness profile is concerned, Rz is considered the highest roughness, while Wz is called the greatest roughness when it comes to the wavelength profile.

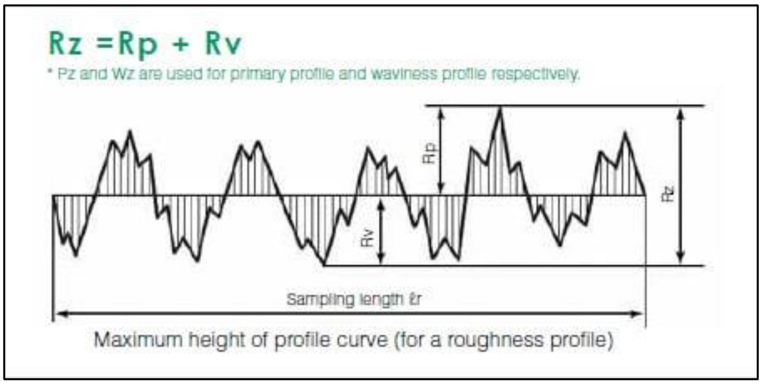


Figure 2.15: Graph of Ten-Point Mean Roughness (Rz) (M. Madić, 2015)

2.6.3 Heat Affected Zone (HAZ)

When there is a combination of different factors, the heat-affected zone (HAZ) of the laser cutting process may be produced. The laser goes through an intense thermal cycle while the laser cutting material is at the cutting edge. Fast cooling and heating can cause changes in microstructure. The area known as HAZ consists of a substance that has not melted but underwent thermal microstructural changes in a solid state. The HAZ can observe martensitic transformations, carbide dissolution, and grain growth. The adjusted microstructure of the HAZ affects the consistency and performance of the material involving hardness and corrosion. Martensitic transformations lead to an improved hardness of the HAZ when laser cutting from steel. The existence of a brittle martensitic surface layer addresses issues about the initiation and distribution of cracks. The measurements of the HAZ are therefore of concern (Al-Mashikhi et al., 2011).

Based on Miraoui et al. (2016), the heat-affected zone can cause adverse reactions such as fatigue resistance, surface cracking, and distortion. It is, therefore, crucial to identify the correct laser cutting parameters so that the affected heat zone is minimized. A variety of studies have been conducted to study the implications of the input laser cutting parameters for the consistency of the cut surface and heat region.

2-D plots were generated to analyze the principal and interaction effect of laser cutting parameters in the heat field. The analysis revealed that the cutting speed had the greatest effect on the heat. Laser control, concentrate location, and gas pressure support zone followed. The optimum laser cutting parameter values were found through the Monte Carlo method to reduce the thermal field. As appeared in Figure 2.16 the width of HAZ decreases non-linear as the cutting speed increases. The contact duration between Laser Beam and Material is decreased as the cutting speed is increased, which decreases the width of HAZ (M. J. Madić and Radovanović, 2013).

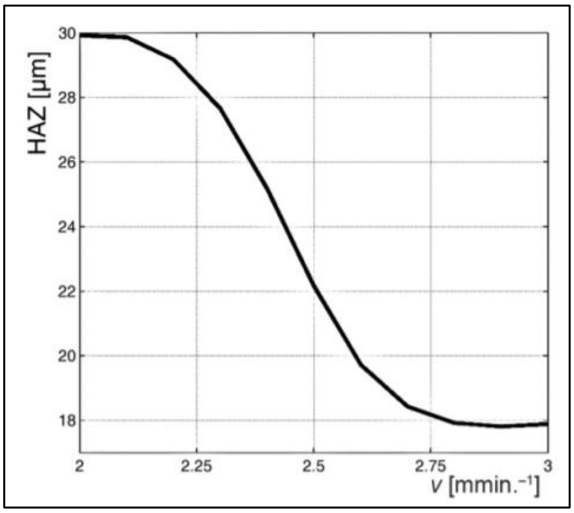


Figure 2.16: Effect Cutting Speed Parameters on The Width of HAZ
(M. J. Madić & Radovanović, 2013)

2.6.4 Burr

Burrs are characterized as undesired material protrusion beyond the edge of a workpiece. Burrs create a slew of issues during the inspection, assembly, and automated manufacture of precision components. Burr (or dross) accumulation around the lower edges of laser fusion cut flanks is a relatively common occurrence. Indeed, it is considerably more likely to generate a burr-filled cut than a burr-free cut, a finding validated by this study. A burr is not only unsightly but also has significant practical difficulties, such as when blanks are piled (Stoyanov et al., 2020).

2.7 Material Removal Rate (MRR)

When the characteristics of cuts of quality (roughness of area, the width of the kerf, angle of tapping of the kerf, the width of the HAZ, and height of dross) are lesser it is considered to be better. However, in terms of material removal rate (MRR) is classified into the higher is a way better.

As states in previous research by Farasati et al. (2019), a disruption plot showing the impact on the rate of material removal of the laser micro-cutting parameters is shown in Figure 2.17. Laser power and pulse frequency (curves A and B, in both) are not found to be significant in MRR variation, according to the figure. It is apparent, however, that an increase in gas pressure rises the MRR. The high-flow air stream facilitates the removal of molten material from the workpiece as the assisted gas pressure rises. The workpiece may get better energy from the heating source, resulting in higher MRR.

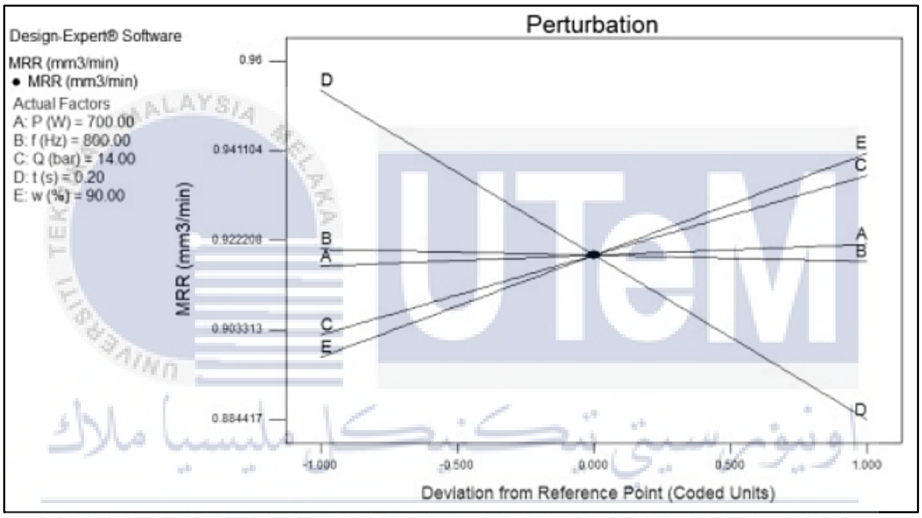


Figure 2.17: A Graph Showing Material Removal Rate By Process Factors (Farasati et al., 2019)

As a feature of cutting speed, kerf width, and material thickness, cutting the same steel with compressed air like that with nitrogen as an assisting gas result in higher material removal rates. Even after some additional removal of material, it may not always indicate that the material removal is the most effective. All cutting characteristics must be considered as objectives for the method to be reliable and flexible. This is critical because it must be clearly defined for the final product (Yusoff et al., 2008).

2.8 Investigations with Design of Experiment (DoE)

The design of the experiments is a way of operating where statistical techniques are used to detect the linear effects of the factors used and the interaction of the factors. The benefit of using this approach compared to the use of a classical factor-by-factor experiment set where one factor is changed while the other is constant is the probability of both identifying rivalry effects and the potential to minimize the number of tests (Andersson, 2015).

According to Patil et al. (2017), the design of experiments is a critical tool used systematically to analyze processes and structures to assess the effects of variables. To draw inferences about the method or device, it is used to obtain a sufficient collection of experimental data to be used for statistical analysis. Several techniques used DoE but the most significant techniques are including ANOVA, Full Factorial (FF), Response Surface Methodology (RSM), Robust Parameter Methodology (RPM), or Taguchi Methods (TM). A modern DoE software can be used, for example, Statistica, Design-Ease® and DesignExpert®, and Minitab. The main objectives of DoE are to discover the connection between. Responses of the given factors All aspects of the experiment have interacted simultaneously. When you run an experiment, you can eliminate the influence of other variables by properly randomizing the experiment (Astakhov, 2012).

2.9 Summary

In a nutshell, the summaries of the previous studies of previous researchers related to the perception of the laser cutting parameters which such as cutting speed, laser power, assisted gas pressure, standoff distance, and focal location which has a significant impact on the ruggedness of the surface and the width and the heat affected area. A further explanation of the research methods will be discussed in the next chapter.

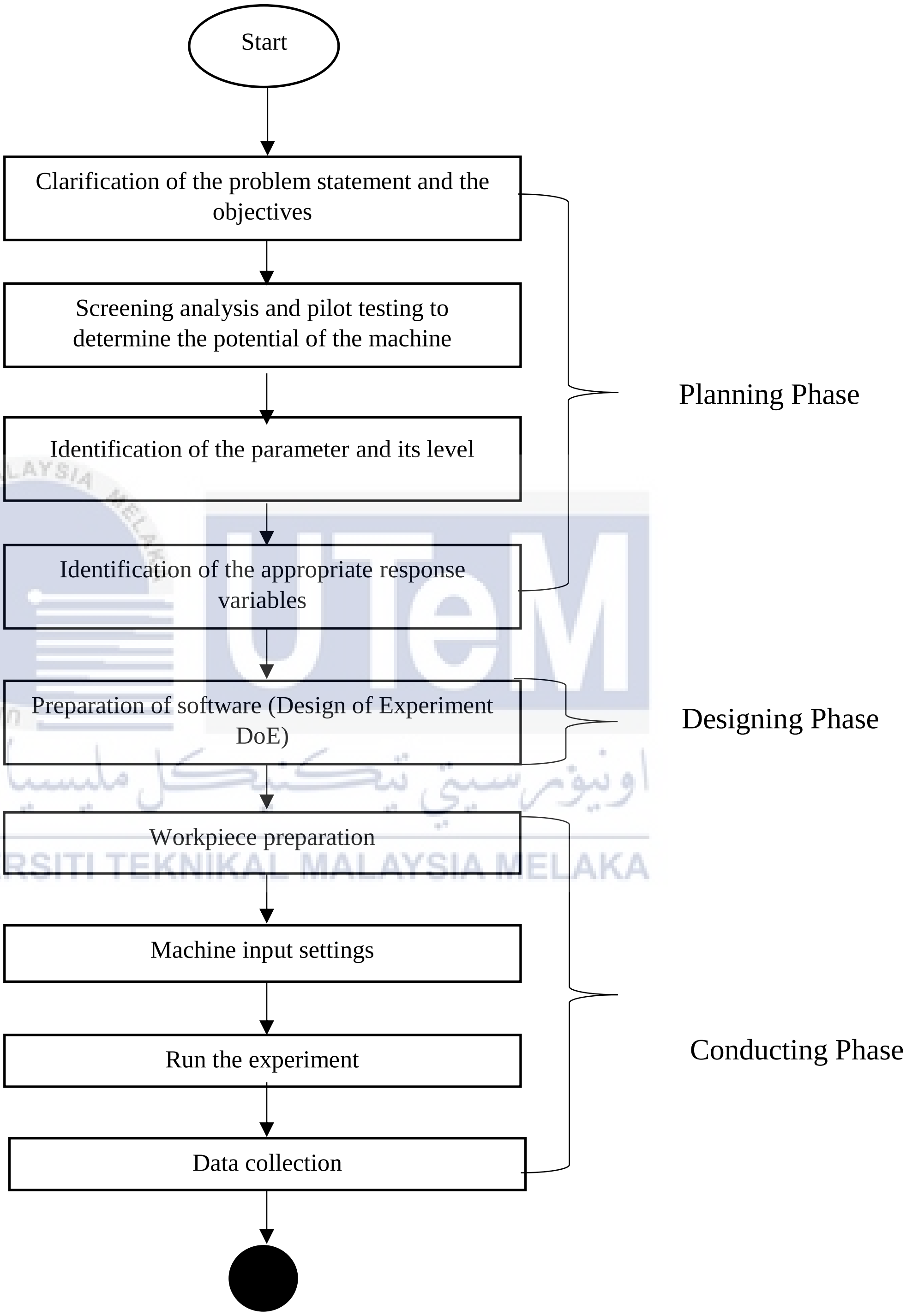
CHAPTER 3

METHODOLOGY

This chapter aims to describe the basic experimental work processes for the entire study in detail. From the beginning until the end of this experiment, this chapter will be the guide for performing the research. To ensure that the research runs in an orderly order, all procedures and steps have been listed to provide a clear understanding. In this research, the main technique to be used is Two-Level Factorial Design (FD), which is a well-known experiment design method in the Design of Experiment (DoE).

3.1 Introduction

The methodology flow is represented as a flow chart in detail as illustrated in Figure 3.1. The elements discussed in this chapter included the planning of the experimental phase, the phase design, the phase conduct, and the analyzing phase. Starting with the planning phase where the problem statement and the objectives were clarified. The parameters were identified by previous research including the level and the necessary reaction variables. In order to minimize machining time, every process has been evaluated. Next, the experiment design (DoE) approach used in the design phase by Design Expert® software will be reviewed. A detailed explanation, which emphasized the tools and equipment used, is discussed during the conduct phase. Besides, both the experiment and the preparation of the workpiece are outlined in a flowchart. The last element in this chapter consists of the analysis phase, which discussed and verified all the data collected through the use of surface roughness tests and equipment.



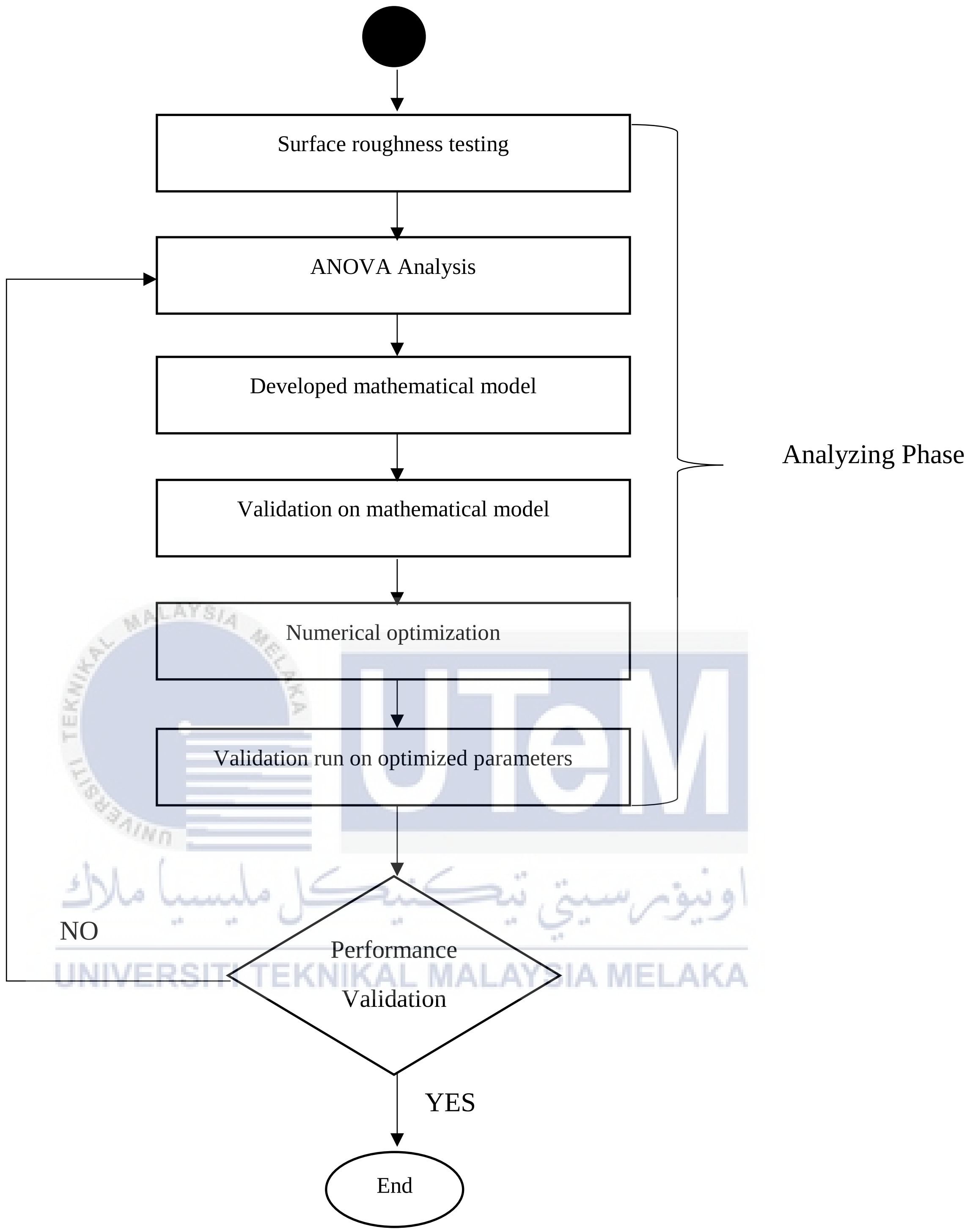


Figure 3.1: Flowchart of the whole study and experiment

3.2 Planning Phase

3.2.1 Clarification of The Problem Statement and Objectives

Many research studies in laser cutting focus on the feasibility analysis of laser cutting parameters on the finished surface. Many studies showed the interest in varying the process input parameters for quality features, including the kerf width and their variance along with the cut. All cutting parameters may have a huge effect on the resulting work quality. The cutting parameters are usually balanced and adjusted to ensure the desired cutting efficiency. However, it requires a great deal of time and effort. The effect of cutting parameters on cutting quality is relevant to research. Therefore, the purpose of this survey is to study the effect of laser cutting parameters on galvanized iron surface roughness (Ra). Eventually, the input parameters need to be set and all the settings will be set by using DoE.

3.2.2 Research Gap

The research gap knowledge on previous studies from 2008 to 2020 was presented in Table 3.1. The most important laser cutting parameters are identified in this research gap. During the screening stage, two and more marked parameters are selected as parameters. The list of researchers is filtered by the most important studies. In total, there are six (6) parameters were selected which are laser power, cutting speed, assisted gas pressure, pulse frequency, focal positioning, and standoff distance. In total, there are six (6) parameters were selected which are laser power, cutting speed, assisted gas pressure, pulse frequency, focal positioning, and standoff distance.

Table 3.1: Research gap of parameters

Authors & Year	Responses	Parameters					
		A	**B**	**C**	**D**	**E**	**F**
Patel et al. (2020)	Kerf width and the surface roughness	/	/	/		/	
Pandya et al. (2016)	Surface roughness	/	/	/			
Deokar et al. (2016)	Surface roughness and kerf width	/	/				/
Riveiro et al. (2011)	Edge quality and surface roughness			/			
Madica et al. (2012)	Average surface roughness and ten-point mean roughness	/	/	/			
Barge et al. (2019)	Surface roughness, kerf with and HAZ	/	/	/		/	/
Radonjić et al. (2012)	Adequate accuracy of the quality and shape of the cut	/	/	/		/	/
Jen et al. (2018)	Surface roughness, HAZ, kerf width, and tapper	/	/	/		/	
Ozaki et al. (2012)	Kerf width, and material removal rate	/	/				
Madić et al. (2015)	Burr height, dragline separation, depth of separation line, surface roughness, and perpendicularity of the cut	/	/	/	/		
Miraoui et al. (2016)	Melted zone, HAZ, and microhardness beneath the cut surface	/	/				
Radovanović, and Milos Madic	Heat affected zone (HAZ)	/	/	/		/	
Farasati et al. (2019)	Material removal rate (MRR) and taper	/		/	/		
Yusoff et al. (2008)	Cut quality, kerf width, and material removal rate	/	/	/		/	/
Oner and Omer Keles (2012)	Cutting quality	/			/		
V. Senthilkumar (2014)	Surface roughness, kerf width, and heat-affected zone (HAZ)	/	/	/		/	
Kumar et al. (2017)	Kerf width, kerf deviation, and material removal rate	/	/	/	/		
	Total	**16**	**16**	**13**	**4**	**7**	**4**

Note: (A: Laser Power; B: Cutting Speed; C: Assisted gas pressure; D: Pulse frequency; E: Focal positioning; F: Standoff Distance)

3.2.3 Parameters Identification and Pilot Testing

The parameters taken into account in this laser cutting analysis were the cutting speed and the assisted gas pressure with a constant laser power of 2000 Watt and focus point, where fs=0 (mm) respectively was to be focused on top of the material. A pilot test has been carried out to identify the machine's capability in respect of the respective parameters. The design parameter for pilot testing is shown in Table 3.2 below.

Table 3.2: Design parameter for pilot testing

Power, P (Watt)	**Focal Positioning, fs (mm)**	**Cutting Speed, v (mm/min)**	**Assisted Gas Pressure, p (Bar)**	**Condition**
2000 Watt	0	1200	0.5	
		1800	1	
		2600	5	
		3000	8	

The range of parameters involved was classified in Table 3.3, according to the pilot test. The cutting speed represents the speed at which the work moves concerning the tool and adjustment of the focal spot while the assisted gas pressure represents the pressure level of the supplied assisted gas. This experiment employed three levels of parameters that for both parameters, were low, center, and high. The power and focal location of 2000 Watts and Fs=0 (mm) were set at a constant rate.

Table 3.3: The range of the parameter and the level of this experiment

Parameter	**Level**		
	Low	**Center Point**	**High**
Cutting Speed, v (mm/min)	1800	2500	3000
Assisted Gas Pressure, p (Bar)	1	4.5	8
Power, P (Watt)	2000 Watt		
Focal Positioning, Fs (mm)	Fs=0		

3.2.4 Responding Variables Identification

At the end of the experiment, this research examined the surface roughness (Ra) of the galvanized iron plate.

3.3 Designing Phase

3.3.1 Software Design of Experiment (DoE)

The Design Expert® software version 6.0.8 had been used in this study to extract data as a result of various parameters from input data. The design used in the study is two levels Factorial, where the cutting speed and the assisted gas pressure are the two (2) parameters, while the focal position has been set to constant. The characteristics of the design of the experiment by using two-level factorial are:

i. Two-level factorial which is a part of the Factorial method is used as there are only two factors with various values which are cutting speed and assisted gas pressure. Another focal point parameter has been set to be constant. The model with k=2 was built
ii. The run (z) number is shown in Equation 3.1. In this particular study, three points are selected. The purpose of the center point was reviewed in Chapter 2.

$Z = 2^k + C_0$ .... Equation 3.1

Table 3.4 shows the generated numbers of experiments. There are eleven experiments designed by Two-Level Factorial for this study, where the number of center points was set to be three with two replicates. Experiments are carried out to find the most applicable cutting conditions where the process parameters are optimized. The selection of the optimum cutting parameter is crucial to determine the surface roughness with the minimum surface roughness for this study.

Table 3.4: Generated design of experiment by using two-level factorial

Run	Factor A: Cutting Speed, v (mm/min)	Factor B: Assisted Gas Pressure, p (Bar)	Factor C: Focal Positioning, Fs (mm)	Average Surface Roughness, Ra (µm)
1	1800	1.0		
2	2400	4.5		
3	3000	8.0		
4	3000	1.0		
5	3000	1.0		
6	3000	8.0	Fs = 0	
7	1800	8.0		
8	1800	8.0		
9	1800	1.0		
10	2400	4.5		
11	2400	4.5		

3.4 Conducting Phase

3.4.1 Laser Cutting Machine

The experiment was conducted based on a Laser Cutting Machine in the Faculty of Manufacturing Engineering as shown in Figure 3.2 which is Mitsubishi ML 2512HV2-R PLUS. Table 3.5 summarizes the settings used in this analysis. Nitrogen gas is used to cut the galvanized iron plate as the assisted gas pressure in this study. In the meantime, this analysis probably demonstrates constants of power (W), pulse frequency (Hz), duty cycle (%), offset (mm), pierce (sec), focus position (mm), and nozzle distance (mm).

Figure 3.2: Mitsubishi Electric model ML2512HV2-R PLUS (Source: FKP Lab)

Table 3.5: Constant input setting of the laser cutting machine to cut galvanized iron plate (Source: Mitsubishi Electric model ML2512HV2-R PLUS)

Parameter	**Settings**
Power, W	2000
Frequency, Hz	2000
Duty cycle, %	70.0
Offset, mm	0.140
Focal Positioning, mm	0
Pierce, sec	0.0
Nozzle Gap, mm	2.000

3.4.2 Preparation of The Experiment

The method for planning this experiment was conducted in stages such as workpiece preparation, testing, and analyzing stage. The flowchart of the procedure is shown in Figure 3.3. This procedure is repeated eleven times according to the data that was designed by the Design of Experiment (DoE).

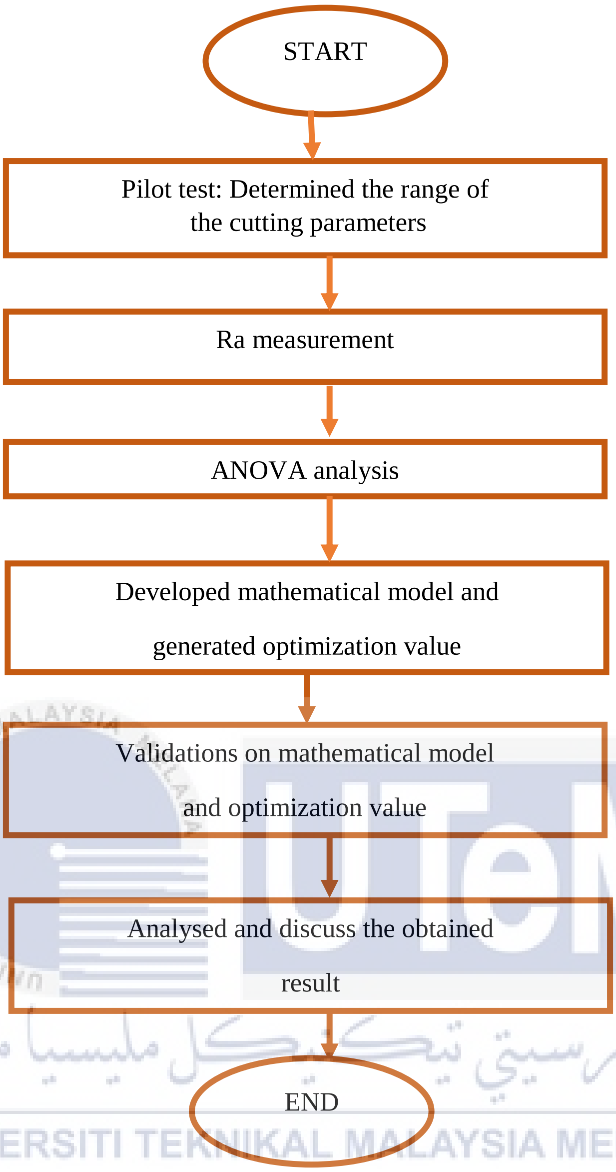


Figure 3.3: Flowchart of the overall procedure in this study

3.4.3 Workpiece Preparation

The workpiece used is the galvanized iron plate in this experiment. The 150 mm x 25 mm size of this galvanized iron plate is prepared by the laser cutting machine itself, as shown in Figure 3.4. The thickness has been set to be constant which is 2.0 mm as shown in Figure 3.5. Galvanized iron is chosen in the first place as it is a non-corrosion material.

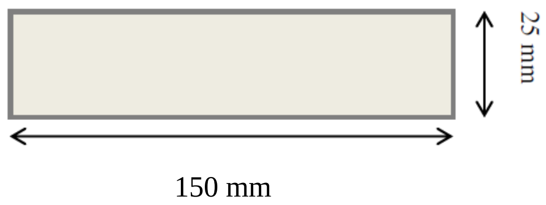


Figure 3.4: Workpiece (top view)

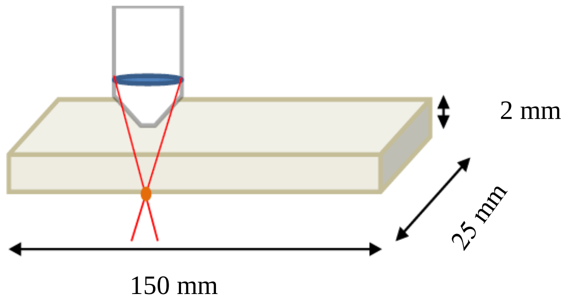


Figure 3.5: Workpiece (isometric view)

3.4.4 Method of Cutting The Specimen

The drawing of the workpiece is firstly created according to specific dimensions. Upload the drawing into software that is compatible with the laser cutter. Place the material in the centre of the laser cutting mat, ensuring that it fits within the laser cutter's work area and cutting it to size if necessary. This is the optimal position for obtaining a high-quality result. Metal should be selected in the material settings. This will dictate the laser's settings. Following that, the critical parameters of a laser cutting are set, including power, speed, assist gas pressure, frequency, duty cycle, offset, nozzle gap, and focus position. Finally, it should be prepared to begin cutting. 11 plates must be cut in this experiment according to the data that was designed by the Design of Experiment (DoE). Additionally, this process of cutting utilizes high-pressure gas to expel molten material from the cutting area, significantly reducing the required power. After heating the material to the melting point, a gas jet blows the molten material out of the kerf, obviating the need to increase the material's temperature further. On a laser cutting machine, the head is moved over the metal plate in the desired shape, effectively cutting the part out of the plate. A capacitive height control system ensures an extremely precise distance between the nozzle's tip and the plate being cut.

3.5 Analysing Phase

3.5.1 Measuring and Testing

The analysis process, consisting of measurement and testing, was carried out for surface roughness testing in this study at the meteorology laboratory at the Faculty of Manufacturing Engineering (FKP). The surface roughness is the output responses that were taken into consideration in this particular experiment.

3.5.2 Surface Roughness Test and Equipment

The equipment to check the surface roughness on the cut surface is shown in Figure 3.6 below (cross-section of the cut). The device is classified as portable equipment for surface roughness. The model used for this device is the Mitutoyo SJ-301. Able to conduct measurements, like vertical and upside-down, in every orientation. Available accessories, including an adapter for height measuring, allow measuring in various conditions and configurations to be done easily. In the quality control department of any manufacturing industry, machining intent and processing statistics, this equipment is generally and usually used. The combination of the detector, drive unit, and display unit allows for a wide range of machine configurations. Whereby, as shown in Figure 3.7 the detector contains a probe that traces the workpiece surface (measure surface). The material and radius of the diamond stylus tip can provide an accurate reading and it is very convenient to use. To be calibrated, the detector has been positioned on the surface of the specimen and after pressing the start button it will traverse.

Figure 3.6: Portable Surface Roughness Tester (Source: FKP Lab)

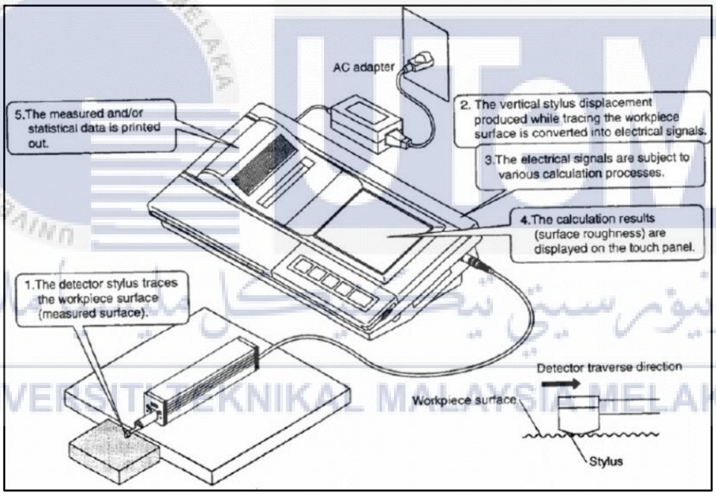


Figure 3.7: Schematic description of the Mitutoyo Surftest SJ-301 (Korkut et al., 2009)

Profile measurements were taken with a stylus device standard. The tool measured at a speed of 10 mm/min, a pin diameter of 4 m, and a pin top angle of 90º, respectively. On the surface of the samples, roughness measurement points were randomly designated. Measurements were carried out in the direction perpendicular to the five sides of the workpiece. The mean arithmetic deviation of the profile (Ra) indicates the average distance between the profile and the mean line across the evaluation period. At room temperature, measurements were taken, and the pin was calibrated before the tests. Calibration may be accomplished easily by simply inputting and measuring the Ra value inscribed on the roughness reference specimen, which is 2.95 μm in this experiment. The results consisting of the parameter values and the curved ones will be shown on the LCD panel and the results can be printed out around the same time. For further study and discussion, the results of the five sides measurement value of surface roughness obtained were collected and calculated to get the average surface roughness. Lastly, the average value of surface roughness is then transferred into design expert software.

3.6 Expected Outcomes

The expected outcomes are as follows while this study is prepared:

i. The machine's capabilities are obtained through pilot testing.

ii. Utilized the Design of Experiment software on finding the correlation of cutting parameters like cutting speed and another significant parameter due to its effect on surface roughness.

iii. Due to the cutting parameters, a mathematical prediction model of surface roughness was established.

iv. Optimum parameters that are significant to the output result which is the surface roughness, Ra of Galvanized Plate

CHAPTER 4
RESULTS AND DISCUSSION

The results of the study are presented and analyzed in this chapter concerning the study's objective; the flow of the results is determined by the stated objectives in Chapter 1. To begin, the pilot testing results and a discussion of the effect of each outcome are offered in this chapter as assistance for the Design of Experiment (DoE) in Design-Expert, which utilized a two-level factorial design. The proposed DoE will reveal the state of the galvanized iron after it has been laser cut. Additionally, the relationship between the various elements will be described to aid in the study. The findings were discussed concurrently with the findings; what was discovered in this investigation was compared to what was discovered in the literature. All of the associated results from the laser cutting process will be discussed using figures and tables.

4.1 Result of The Pilot Testing

A small-scale pilot test was conducted in this study to determine the laser cutting machine's performance. The purpose of this pilot test is to determine the machine's maximum and minimum parameters for cutting galvanized iron. This test is conducted on a sufficient number of trials to demonstrate the machine's capacity and to establish the range of parameters to be included in the Design of Experiment (DoE). Each cutting speed of 1800mm/min, 2500mm/min, and 3000mm/min was evaluated using three different gas-assisted pressures: 1 bar, 4.5 bar, and 8 bar. Table 4.1 summarises the results of the pilot testing under constant power and focal position conditions, which are P=2000 Watt and Fs=0mm, respectively.

Table 4.1: Result of the Pilot testing and its condition

Power, P (Watt)	Focal Positioning, Fs (mm)	Cutting Speed, v (mm/min)	Assisted Gas Pressure, p (Bar)	Condition
2000	0	1800	1.0	Burr and HAZ both occurred in a very bad way
		2400	4.5	Cutting completed
		3000	8.0	Cutting completed but HAZ occurred
		3000	1.0	Burr and HAZ both occurred
		3000	1.0	Burr and HAZ both occurred
		3000	8.0	Cutting completed
		1800	8.0	Cutting completed
		1800	8.0	Cutting completed
		1800	1.0	Burr and HAZ both occurred
		2400	4.5	Cutting completed
		2400	4.5	Burr occurred

In the first instance, the power has been set up constant as 2000watt and the intersection is positioned at Fs=0 mm which is on the surface of the material. Therefore, when the first run experiment was where cutting speed is 1800mm/min, it is seen that at 1.00 bar pressure, the material was difficult to remove by hand due to the severe burr that formed. Burr is the surface of metal materials with an excessive number of residual particles. In reality, it was discovered that HAZ had developed on the cutting surface when the gas pressure was applied. It was necessary to use another tool to force the material to be removed. Previously published investigations by M. J. Madić and Radovanović (2013) reached similar outcomes. As can be observed, the width of the HAZ increases linearly as assist gas pressure reduces. This beneficial effect on the width of the HAZ can be attributed to the assist gas's excellent cooling actions.

However, for the other parameters, the material can be simply removed after the cutting has been completed and the laser has penetrated the sample sheet in all directions. On the other hand, even with the assisted gas pressure set at 1.0 bar and the cutting speeds set at 3000mm/min and 1800mm/min, burr and HAZ continue to occur. During this time, the HAZ is visible at 8.00 bar gas pressure and 3000 mm/min, but there has been no formation of burr. However, when the gas pressure is 4.50 bar and the cutting speed is 2400 mm/min, the development of HAZ is observed. By contrast, all of the other aspects of the cutting have been accomplished without the creation of burrs or HAZ.

It is clear from this finding that the response surface roughness is strongly influenced by the amount of assisted gas pressure required. Because of the data that were obtained about the state of the sample sheet, it was determined that the ideal range of assisted gas pressure for the subsequent experiment would be between 1 bar and 8 bar.

4.1.1 Result of the experiment by using two-level factorial

Table 4.2: Experimental Result by using 2 Level Factorial

Run	Factor A: Cutting Speed, v (mm/min)	Factor B: Assisted Gas Pressure, p (Bar)	Average Surface Roughness, Ra (µm)
1	1800	1.0	5.85
2	2400	4.5	3.92
3	3000	8.0	3.85
4	3000	1.0	3.98
5	3000	1.0	3.93
6	3000	8.0	2.78
7	1800	8.0	2.36
8	1800	8.0	2.72
9	1800	1.0	5.04
10	2400	4.5	3.07
11	2400	4.5	5.07

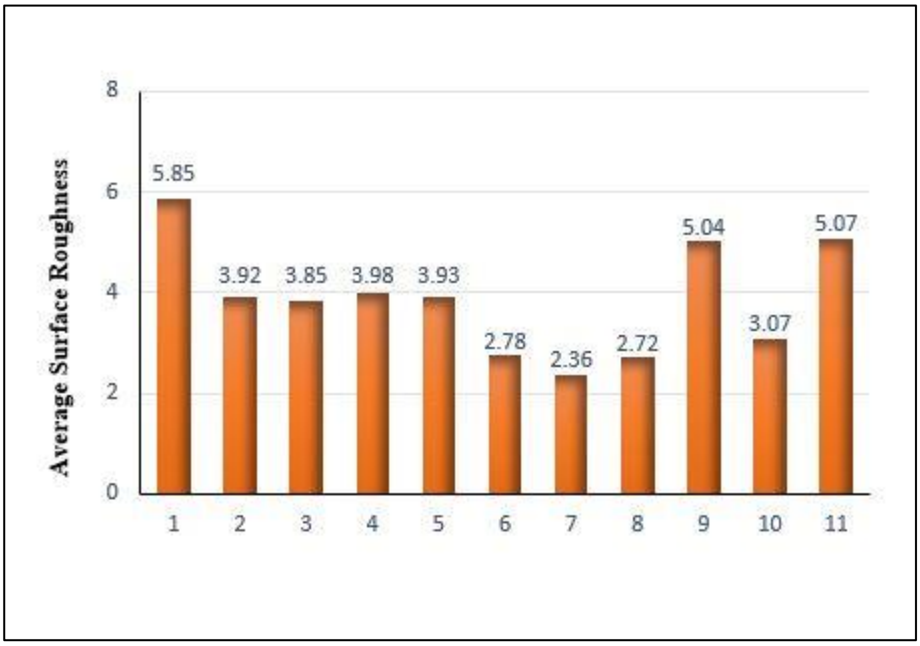


Figure 4.1: Values of cutting surface

Response: Average Surface Roughness, Ra

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source		Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model		9.10	3	3.03	6.11	0.0296	significant
	A	*0.26*	*1*	*0.26*	*0.51*	*0.5002*	
	B	*6.28*	*1*	*6.28*	*12.64*	*0.0120*	
	AB	*2.57*	*1*	*2.57*	*5.16*	*0.0635*	
Curvature		0.093	1	0.093	0.19	0.6807	not significant
Pure Error		2.98	6	0.50			
Cor Total		12.18	10				

Figure 4.2: ANOVA table generated from the software

As shown in Figure 4.1 and Figure 4.2, the Design-Expert design layout included eleven samples, as well as the results obtained from the input parameters and the average surface roughness graph, which were both gained through the design process. According to the results of the experiment, the surface roughness was significantly influenced by the range of assisted gas pressures that were selected for the minimum and maximum values. It can be observed from the replication of the input parameters that the responses followed a consistent pattern.

In the case of factor A, which is cutting speed, it was discovered that the three different cutting speeds, ranging from 1800 mm/min to 3000 mm/min, did not make a significant difference in the surface roughness. This insignificant difference could be referring to the ANOVA table shown in Figure 4.2, where the F-value for factor A is 0.51, which indicates that there is no significant difference.

As for factor B (assisted gas pressure), it was demonstrated that the higher the level of assisted gas pressure, the lower the value of surface roughness, which served as a response. According to the ANOVA table, factor B has the highest F value which is 12.64, indicating it is the most significant factor. This conclusion can be supported by a study conducted by Genna et al. (2020), who discovered that when the assisting gas pressure was increased, the surface roughness and kerf width decreased, owing to the increase in drag force, which facilitates the effective removal of melt from the groove. This article also mentions that, when the molten metal is dragged from the kerf by the assisting gas jet, it forms a boundary layer over it, which allows heat transfer to take place and prevents overheating of the surface.

4.1.2 Effects of the galvanized iron in laser cutting

Table 4.3: Average surface roughness for the highest and lowest value of pressure bar

Factor A: Cutting Speed (mm/min)	Factor B: Assisted Gas Pressure (Bar)	Average Surface Roughness, Ra (µm)
1800	8.00	2.36
1800	8.00	2.72
3000	8.00	3.85
3000	8.00	2.78
1800	1.00	5.85
1800	1.00	5.04
3000	1.00	3.98
3000	1.00	3.93

Table 4.3 shows the average surface roughness for the highest and lowest pressure bar values that are varied with cutting speeds of 1800 mm/min and 3000 mm/min, respectively, for the highest and lowest pressure bar values. The obtained values provide unequivocal evidence that the higher the assisted gas pressure, the lower the average surface roughness is on the surface of the object. It was determined by Miloš Madić and Radovanović (2012), that the drop in assist gas pressure resulted in dross attachment as a result of the decreased kinetic energy of the gas, which prevented the molten material from being forced out of the kerf surface. Concerning magnitude, the effects of cutting speed and assist gas pressure on the surface finish are more pronounced than the effects of laser power on surface finish when the order of magnitude is taken into account.

It is created by molten metal that solidifies before it can be evacuated, resulting in the presence of burrs at low levels of assist gas pressure. As a result of this reaction, the solid material at the bottom of the kerf grows stronger, resulting in the formation of a burr.

4.2 Parameter Interaction Study by Using Two-Level Factorial DESIGN-EXPERT®

This study makes use of the Design Expert® software to analyze the data that has been collected. In addition to comparative tests, screening, characterization, optimization, and robust parameter design, Design–Expert also provides mixture and combined models. According to the software, the sequence of this analysis is divided into four parts: transformation, selection of the data model, ANOVA, mathematical model validation, model diagnostics plot, and model graphs. Transformation, selection of the data model, ANOVA, mathematical model validation, model diagnostics plot, and model graphs in the section on the sensitivity of the variables factor, it was discussed in greater detail how the analysis was conducted.

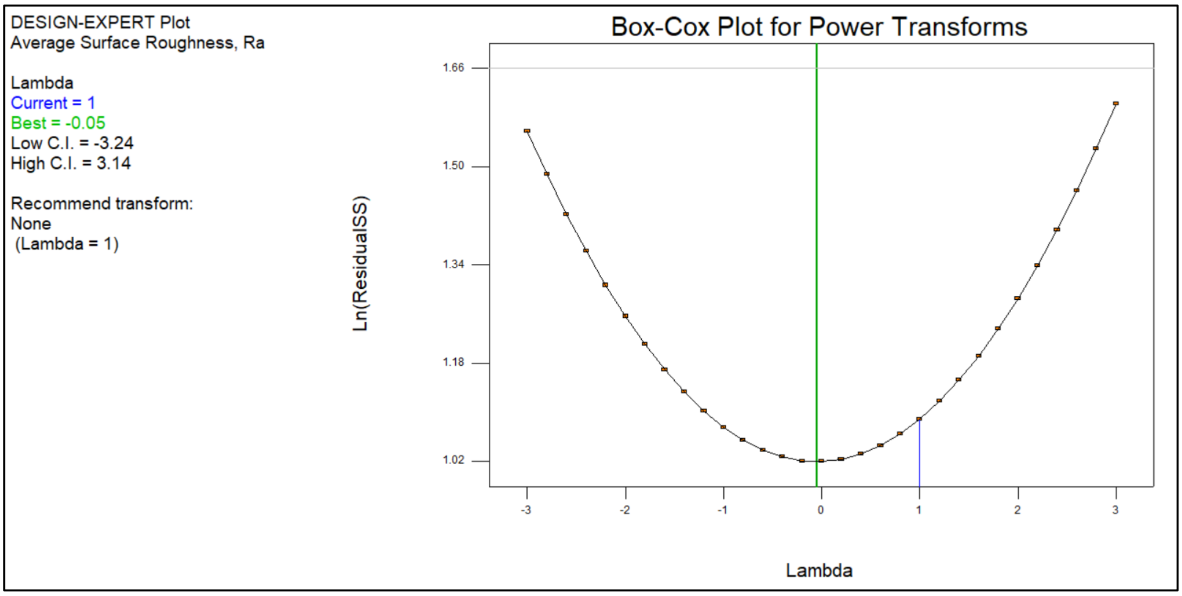


Figure 4.3: Box-Cox plot for power transformation

The fundamentals of mathematical function are applied to all response data, such as surface roughness, in transformation analysis. It is used to produce and analyze ANOVA. Additionally, response transformation is a critical component of any data study. If the error (residuals) is a function of the amplitude of the response, transformation is required (predicted values). Design-Expert includes a comprehensive diagnostic tool for determining whether the statistical assumptions behind the data analysis are met. The residuals' normal plot is used to determine their normality. If a trend occurs in the residuals vs expected response values plot, this indicates a problem. Unless the ratio of the maximum to smallest answer is great, changing the response makes little influence. On the Diagnostics button, a Box-Cox plot will display a proposed transformation from the power family. The two non-power law transformations, logit for bounded data and arcsin-sqrt for proportions, must be used according to the answer type. When proportional data is provided, the Box-Cox plot frequently recommends a square-root transformation, while bounded data requires a log transformation.

In this study, a helpful plot called Box-Cox under the diagnostics tab in Design-Expert® identifies the transformation that will be used in the ANOVA. The Box-Cox recommendation states that the appropriate transformation to use is power with lambda -0.05, as illustrated in Figure 4.3.

4.2.1 Selection of The Data Model

The experimental data were analyzed using the Design Expert® software (version 6.0.8) program, which has the feature of full factorial analysis, to obtain the mathematical modeling analysis. This experimental data set contains the response, which is surface roughness. The sequential model sum of the square table is used to analyze all of the different model types, including Model A (cutting speed) and Model B (assisted gas pressure). The confidence level for the study was set at 95%, with any model type with a p-value (Prob > F) less than 0.05 being considered significant.

On a half-normal probability plot, the absolute values of all effects in this experiment were plotted in a square pattern, indicating that they were statistically significant. As shown in Figure 4.4, the model's chosen factors were Factor A, which represented cutting speed, and Factor B, which represented assisted gas pressure.

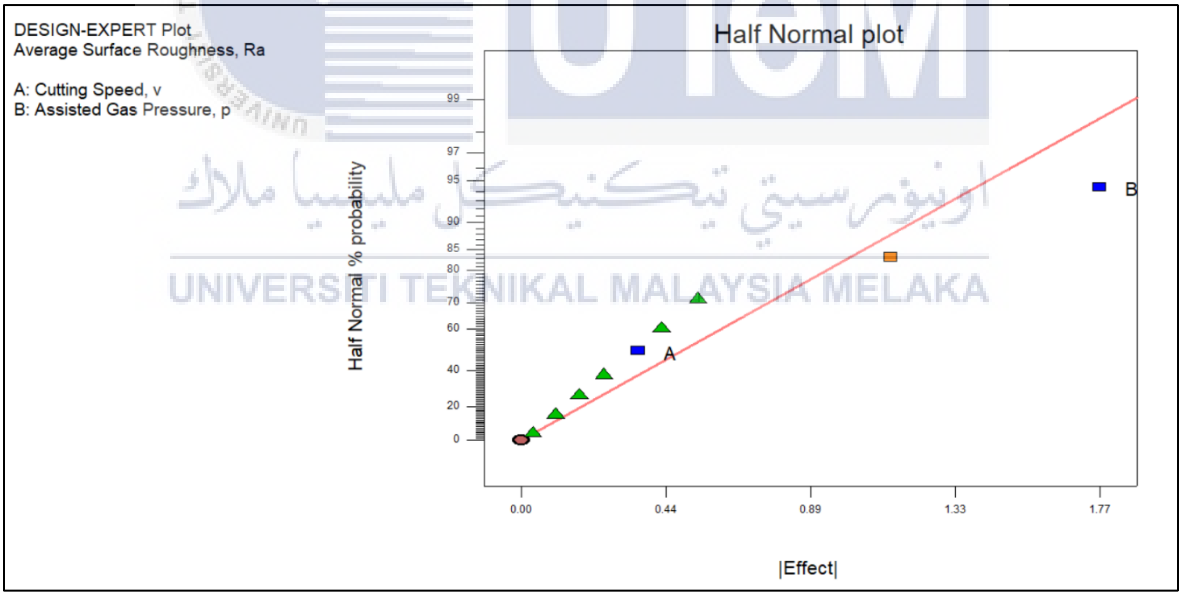


Figure 4.4: Half-normal probability plot

It will rank the absolute values of the effects, starting with the lowest and progressing up to the highest values in the Design-Expert software. The half-normal probability plot graph is used to represent the construction of these effects. The greater the magnitude of the model effects, the greater the likelihood that the model will be able to become more significant. Model B has the highest effects and has moved to the right on this plot, but

Model A has a smaller value of effects and has moved to the left on this plot, indicating that the assist gas pressure is more significant than the cutting speed in laser cutting. In this instance, it demonstrates that Model A is superior to Model B.

4.2.2 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) is generated as shown in Table 4.4 once the model has been selected from the sequential model sum of squares. The ANOVA includes information such as the source, sum of squares (difference of freedom), mean square (F value), Prob > F, and their condition of significance. In this case, there are two (2) variables: A is the cutting speed, and B is the assisted gas pressure.

Table 4.4: ANOVA table for surface roughness model

Sources	**Sum of Squares**	**Degree of Freedom (DF)**	**Mean Square**	**F Value**	**Prob > F**	**Condition**
Model	9.10	3	3.03	6.11	0.0296	significant
A	0.26	1	0.26	0.51	0.5002	
B	6.28	1	6.28	12.64	0.0120	
AB	2.57	1	2.57	5.16	0.0635	
Curvature	0.093	1	0.093	0.19	0.6807	not significant
Pure Error	2.98	6	0.50			
Total	12.18	10				

The Model F-value of 6.11 indicates that the model is statistically significant, according to the ANOVA. Because of noise, there is only a 2.96% probability that a "Model F-value" this large will occur. Model terms that have a probability less than 0.0500 are considered significant. The presence of values greater than 0.0500 indicates that the model terms are not statistically significant. If your model has a large number of unimportant model terms (excluding those required to support hierarchy), model reduction may be beneficial to you.

The "Curvature F-value" of 0.19 indicates that the curvature (defined as the difference between the average of the center points and the difference between the average of the factorial points) in the design space is not statistically significant when compared to the noise. There is a 68.07% chance that a "Curvature F-value" of this magnitude will occur as a result of random fluctuations.

Table 4.5: Regression statistics

Std. Dev.	0.70	R-Squared	0.7533
Mean	3.87	Adj R-Squared	0.6300
C.V	18.22	Pred R-Squared	0.3103
PRESS	8.40	Adeq Precision	6.112

Table 4.5 shows the regression statistics for the model experiment in which the "Pred R-Squared" of 0.3103 is not as near to the "Adj R-Squared" of 0.6300 as one might assume based on the normal distribution. This could be indicative of a significant block effect or a potential fault with the model and/or data set. Model reduction, response transformation, outliers, and a variety of other considerations are all important. The term "Adeq Precision" refers to the signal-to-noise ratio. It is preferable to have a ratio bigger than 4. where the signal-to-noise ratio of 6.112 suggests a sufficient signal. This model can be used to help navigate the design area more effectively.

This particular ANOVA yielded the following equations, which we have included below for reference. It is necessary to construct two (2) equations, one of which is the final equation in terms of coded factors and the other which is the final equation in terms of actual factors, as shown in Equations 4.1 and 4.2, respectively. It is the ultimate equation when it comes to actual factors, which is the equation that is employed in the regression model. When comparing the actual outcome with the expected result, a specific equation is employed to do so. This equation is utilized to calculate the percentage of inaccuracy that exists between the two variables. Cutting speed is denoted by the letter A, while assist gas pressure is denoted by the letter B.

Final Equation in Terms of Coded Factors:

$Average\ Surface\ Roughness, Ra = +3.81 - 0.18 * A - 0.89 * B + 0.57 * A * B$...Equation 4.1

Final Equation in Terms of Actual Factors:

$Average\ Surface\ Roughness, Ra = +8.5804 - 1.5113x10^{-3} * Cutting\ Speed - 0.9004 * Assist\ Gas\ Pressure + 2.6964x10^{-4} * Cutting\ Speed * Assist\ Gas\ Pressure$....Equation 4.2

4.2.3 Mathematical validation

The surface roughness value for the mathematical model was manually calculated using the selected parameters in the previous run of experiments that are still within the parameter range of 3000 mm/min cutting speed and 1 bar assisted gas pressure. The focal length was set to fs=0 mm, and the laser cutting power was set to 2000 Watt, as shown in Table 4.6 below. The calculation below illustrates the mathematical model when the factor A=3000 mm/min and factor B=1 bar.

Table 4.6: Selected cutting speed and assisted gas pressure

Factors	Parameter	
	In range	Selected
Cutting Speed, v (mm/min)	1800 - 3000	3000
Assisted Gas Pressure, p (Bar)	1 - 8	1
Focal Positioning, fs (mm)	0	
Power, P (Watt)	2000	

$$Average\ Surface\ Roughness, Ra = +8.5804 - 1.5113x10^{-3} * Cutting\ Speed - 0.9004 * Assist\ Gas\ Pressure + 2.6964x10^{-4} * Cutting\ Speed * Assist\ Gas\ Pressure$$

$$Average\ Surface\ Roughness, Ra = +8.5804 - 1.5113x10^{-3} * 3000 - 0.9004 * 1 + 2.6964x10^{-4} * 3000 * 1 = 3.96\ \mu m$$

According to the results of the mathematical model calculation, the value of surface roughness is 3.96 µm. Previously, the percentage error of the mathematical model and the mathematical validation experiment had been shown in Table 4.7 below.

Table 4.7: Surface roughness value for mathematical model and validation experiment with error

	Surface Roughness, µm	Error %
Mathematical model	3.96	0.5
Validation experiment	3.98	

$$Percentage\ Error = \left|\frac{(Predicted\ Value - Actual\ Value)}{Predicted\ Value}\right| x100\% \text{.................Equation 4.3}$$

$$Perecentage\ Erros = \left|\frac{3.96 - 3.98}{3.98}\right| x100\%$$

$$Percentage\ Error = 0.5\%$$

The validation experiment yielded a value of 3.98 µm for surface roughness. In the mathematical validation experiment, there was only a 0.5% error. Typically, an acceptable percentage of error is determined by the type of parameter. In structural experiments, an error of less than 10% is considered acceptable.

4.2.4 Model diagnostics plot

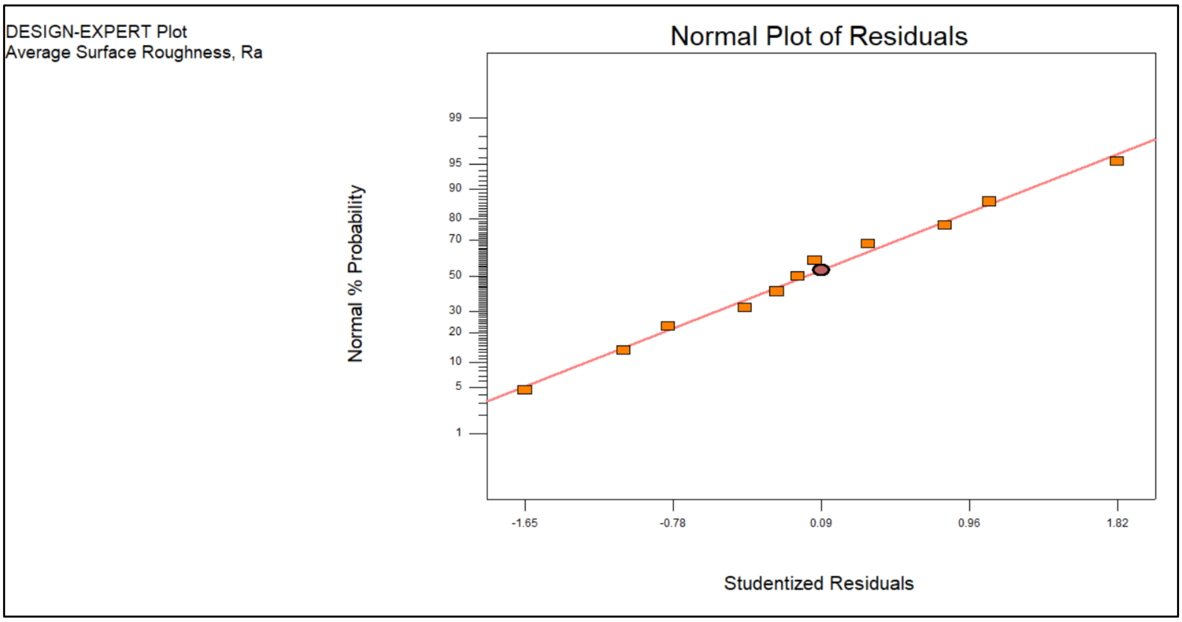


Figure 4.5: Normal plot of the residual for surface roughness

The normal probability plot of the residuals for surface roughness is shown in Figure 4.5. Each point on the plot corresponds to a straight line pattern, and this pattern shows that no violations occurred during the study. Graph showing residuals vs increasing projected response values of surface roughness, where the plot is used to investigate whether or not the assumption of constant variance holds in this case. The normal probability plot also shows that the residual fall is either close or straight line in the normal probability plot. There is no evident pattern or distinctive structure when comparing the residuals to the anticipated response plot, which indicates that the errors are regularly distributed. This implies that the model that has been proposed is adequate. The expanding variable that occurred in this plot necessitates the use of a transform. Using the projected values of surface roughness as a starting point, the residuals plots were normalized, and they did not reveal any noticeable patterns. This has also been demonstrated by Trivedi et al. (2014), who stated that the model given is adequate when errors are regularly distributed and the residuals versus projected response plot reveal that there is no obvious pattern or distinctive structure.

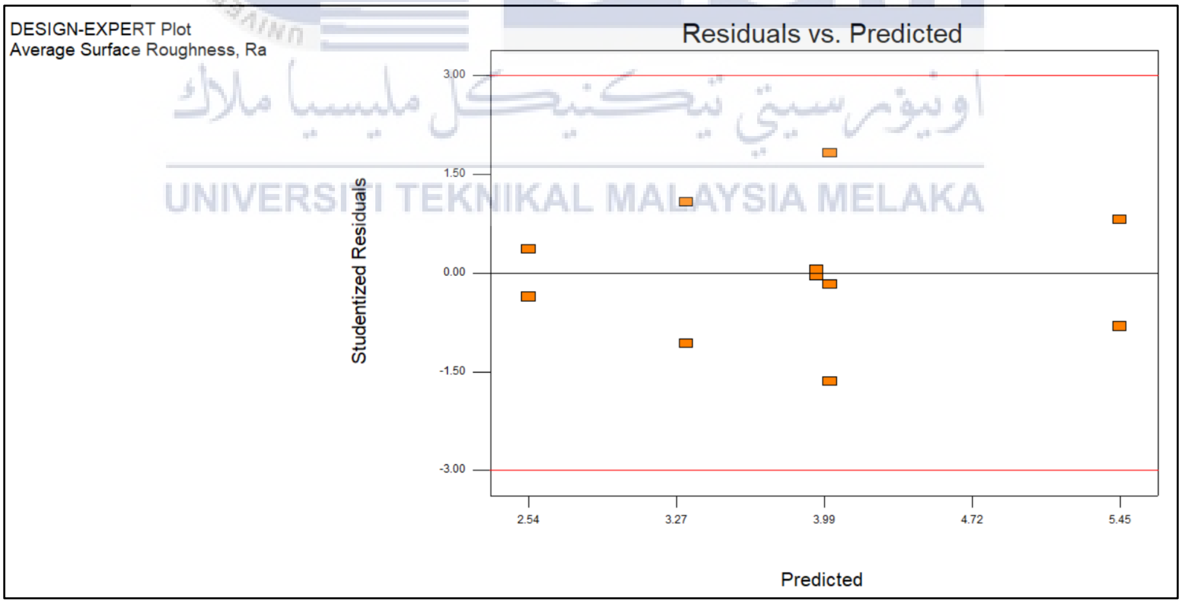


Figure 4.6: Plot of residuals vs. predicted response for surface roughness

Figure 4.6 above illustrates the residuals vs predicted responses for various surface roughness values. The residuals versus expected plots reveal that the data lack any discernible pattern had an odd structure. It is desirable for the residual plot to be devoid of discernible patterns. As the residual is widely distributed in both positive and negative directions, it can be assumed that it is standardized well along with the projected value of surface roughness. Within a three-sigma range, the respective spots are nicely plotted. As a result, it implies that the proposed model is adequate. This indicates that the suggested model is adequate and that there is no reason to think that the independence or constant variance assumptions have been violated.

4.2.5 Model graph

The one-factor plot graph of surface roughness vs cutting speed is shown in Figure 4.7 below. Design-Expert software developed a constant value for factor B automatically, where B is the assisted gas pressure's midpoint, which is set to 4.5 bar. According to the graph, when the cutting speed is 1800 mm/min, the surface roughness is 3.9925 µm., and when it is 3000 mm/min, the surface roughness is 3.635 µm. According to the perturbation plot for Factor A, when the cutting speed moves from a limit range whereby lower to higher, the surface roughness decreases marginally. This rather flat decreasing line demonstrates the insensitivity of this study's cutting speed to change.

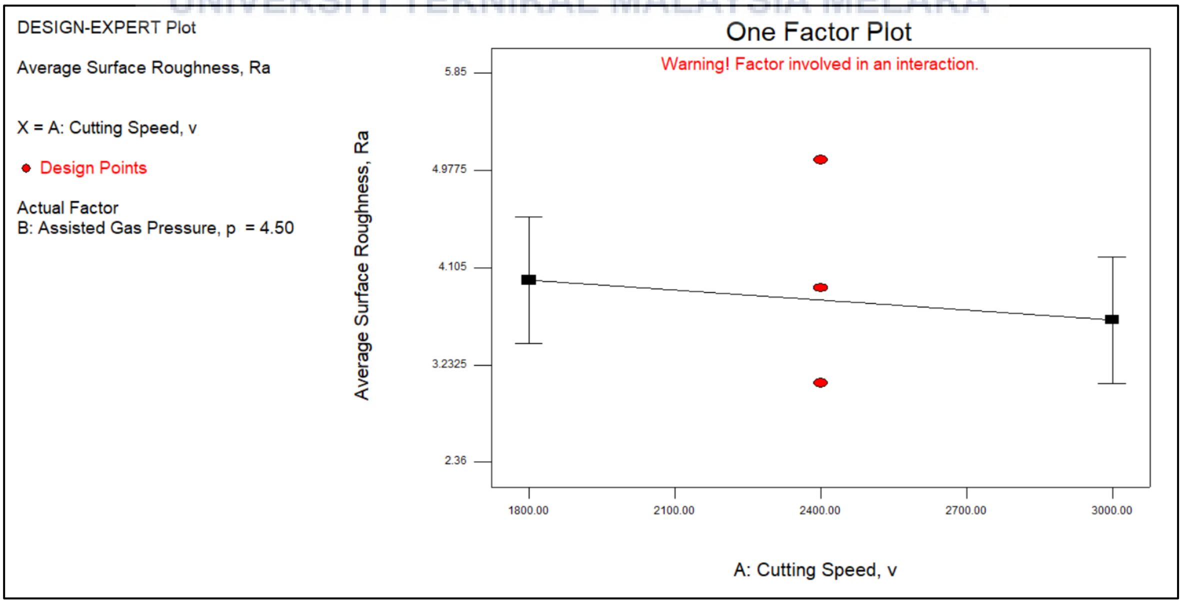


Figure 4.7: One-factor plot of cutting speed versus surface roughness

The one-factor plot of surface roughness vs assist gas pressure is shown in Figure 4.8 below. Design-Expert software developed a constant value for factor A, where A is the cutting speed's midpoint, which has a value of 2400 mm/min. According to the graph, when the assisted gas pressure is at its lowest setting of 1 bar, the surface roughness is 4.7 µm, and when it is at its greatest setting of 8 bar, the surface roughness is 2.9275 µm. According to the perturbation plot for factor B, the surface roughness decreases dramatically as the assist gas pressure bar level increases. As the parameter value and reaction descend steeply in the graph, it becomes clear that the change in assisted gas pressure is extremely sensitive to the responses. In short, the literature of M. Madić et al. (2012) strongly stated that the combination of high cutting speed and high assist gas successfully and quickly cleared the molten material, resulting in a smoother surface. In terms of surface roughness, the parameters that had the most influence were those linked to the assist gas, such as pressure, nozzle diameter, and stand-off distance. Increased assist gas pressure was observed to reduce surface roughness.

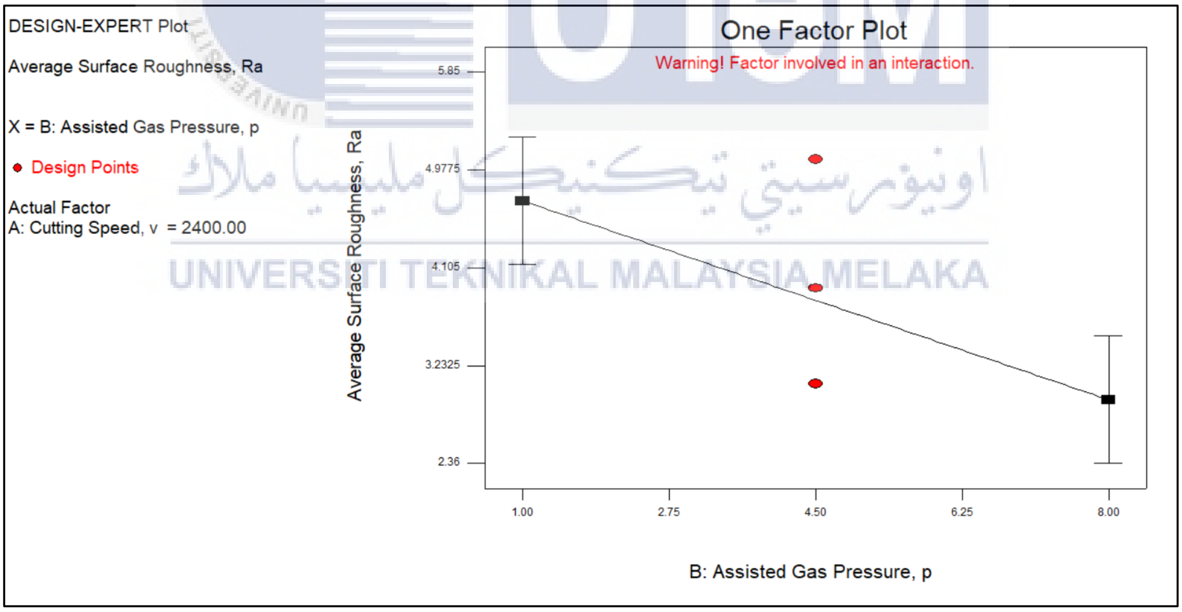


Figure 4.8: One-factor plot of assisted gas pressure versus surface roughness

4.3 Optimization by using Two-Level Factorial in Design Expert®

4.3.1 Criteria of parameters and responses in numerical optimization

Table 4.8 details the numerical optimization criteria for each factor. This numerical optimization is used to determine the ideal parameter combination that produces the best surface roughness result. Each parameter, including responses, has its numerical optimization objective. To ensure that the parameters remain within the scope of this study, the goal values for factors A and B, which are cutting speed and assisted gas pressure, must be between 1800 mm/min to 3000 mm/min and 1 bar to 8 bar, respectively. Concerning the response, which is surface roughness, it was set to be as low as possible (minimum) to increase the quality of machining goods.

Table 4.8: Criteria for each factor in the numerical optimization

Factors	Target	Lower Limit	Upper
A: Cutting speed, mm/min	In range	1800	3000
B: Assisted gas pressure, Bar	In range	1	8
Surface roughness, µm	Minimum	2.36	5.85

4.3.2 Solutions provided by Design-Expert software

The Design-Expert software enables the user to develop a set of recommended solutions comprised of the ideal parameter and response values. As shown in Table 4.9, these recommended solutions frequently serve as a guide for the verification process. This software recommends 2 solutions. The recommended solutions were automatically ranked from least to the greatest value of surface roughness, which corresponds to the numerical optimization aim. The attractiveness of the confirmation experiment was ranked from highest to lowest to assess the solutions' effectiveness. The first solution, which is 2.54 µm, was chosen as the optimal combination due to its minimal surface roughness and high attractiveness.

Table 4.9: Solutions generated by Design-Expert software

Number	Cutting Speed	Assisted Gas Pressure	Surface Roughness	Desirability	
1	1800.00	8.00	2.54	0.948	Selected
2	2910.31	8.00	3.25708	0.743	

4.3.3 Result of the attained responses from the confirmation trial

To verify the Design-Expert recommendations, the formula indicated in Equation 4.4 had to be used in conjunction with the solutions that were advised. To demonstrate that the method is effective, the percentage error must be less than 10%.

Table 4.10: Optimum data selected for experimental validation with the error

Description	Cutting Speed (mm/min)	Assisted Gas Pressure (bar)	Surface roughness, µm	Error, %
Selected Value	1800	8	2.54	7.08
Experiment Validation	1800	8	2.72	

$$Percentage\ Error = \left|\frac{(Predicted\ Value - Actual\ Value)}{Predicted\ Value}\right| x100\% \text{..........................Equation 4.4}$$

$$Percentage\ Error = \left|\frac{2.54 - 2.72}{2.54}\right| x100\%$$

$$Percentage\ Error = 7.08\%$$

According to Table 4.10 and the percentage error result, there was only a 7.08% error in the confirmation trial for the optimization. The error was computed to account for uncontrollable elements in the experiment, such as noise. In structural experiments, an error of less than 10% is deemed acceptable.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This chapter summarises the major findings by projecting them onto the study's initial aims. Meanwhile, ideas for further study are included to ensure a good laser cutting workflow in the future. Several recommendations are offered to improve the performance of the organization in terms of sustainability and even environmental impacts.

5.1 Conclusion of Research

The effect of cutting parameters such as cutting speed, assist gas pressure, focus spot location, and laser power is analyzed on galvanized iron during the laser cutting process was investigated using a two-level factorial. The current work analyses the surface quality (roughness) following laser cutting operations under a variety of test settings and also forecasts the roughness values using a simple mathematical model as a practical tool. The experimental results can be utilized in industry to determine the best parameter combination for achieving the desired surface roughness levels on products. One may argue that the cutting settings utilized in this case had a significant effect on the surface roughness values, Ra. Confirmation runs were conducted to ensure the developed model was adequate. By comparing the fluctuation in the percentage error between anticipated and measured values from confirmation runs, we were able to compare the predicted and measured values. The variation in percentage errors was estimated to be roughly 7.08% of the roughness values.

The models are valid and can be used to forecast machining reactions within the experimental zone. The following conclusions can be drawn from the obtained data and analysis:

i. Based on the results of an ANOVA analysis, it is discovered that the most important component affecting surface roughness during laser cutting is the assist gas pressure and has a substantial impact on the surface quality of the cut generated when using a linear model. Meanwhile, cutting speed and laser power have a negligible effect

ii. The result of the laboratory experiment indicates that run no.7 produces the lowest Ra which is 2.36 um at a cutting speed of 1800 mm/min and an assist gas pressure of 8 bar

iii. ANOVA analysis of the surface roughness model indicates that small parameter variations in cutting speed have no significant effect on surface roughness

iv. The following are the results of the ANOVA analysis that produced the mathematical model for surface roughness:

$$Average\ Surface\ Roughness, Ra = +8.5804 - 1.5113x10^{-3} * Cutting\ Speed - 0.9004 * Assist\ Gas\ Pressure + 2.6964x10^{-4} * Cutting\ Speed * Assist\ Gas\ Pressure$$

v. The percentage of error resulting from the mathematical validation test is 0.5% in cases where it is deemed necessary

vi. Surface roughness, Ra, should be reduced by using a high assisted gas pressure combined with a low cutting speed value to get a smaller Ra value

vii. In the cutting of galvanized iron, an optimized value of Ra = 2.72 µm was reached with a percentage error of 7.08% by employing N_2 pressure = 8.0 bar, cutting speed 1800 mm/min, laser power, P = 2000 Watt, and focus position, fs = 0 mm

5.2 Recommendations

Laser cutting is widely employed in the industry because of its unique benefits over conventional thermal techniques. It is advised that future studies take advantage of this technology to increase productivity while maintaining the requisite quality. There are various recommendations for future research that include the following:

1. Future research should focus on the usage of other materials such as mild steel with a greater range of thicknesses greater than 2mm, as it is widely used in the manufacturing industry.
2. Based on the previously reported data on the material's surface, it is advised that additional testing, such as the width of the heat-affected zone (HAZ) and kerf width, be performed in the future to ensure the highest possible quality of the result.
3. Proper selection of additional processing parameters should be considered when comparing the significance of each parameter in the laser cutting process such as material thickness and standoff distance.

5.3 Sustainable Development

Several components of sustainable development were discovered in this study through the use of laser cutting, including the following:

i. Nitrogen (N_2) is a non-toxic gas that poses no threat to aquatic environments or human health. It is required for all forms of life and is a critical component of boosting food production to sustain the world's ever-growing human and animal populations.

ii. Apart from energy usage, assist gas and waste material to contribute significantly to the environmental impact of CO_2 laser cutting procedures. However, sustainable development can be facilitated during this process by selecting the optimal machining parameters that minimize energy consumption while maintaining cost productivity.

Utilizing a greater assisted gas pressure with the appropriate cutting speed has been shown to reduce surface roughness, hence increasing the product's quality and resulting in fewer faults. Fewer flaws imply the usage of less material. As a result, material consumption will be lowered as well.

REFERENCES

Al-Mashikhi, S. O., Powell, J., Kaplan, A., & Voisey, K. T. (2011). Heat affected zones and oxidation marks in fiber laser–oxygen cutting of mild steel. *Journal of Laser Applications*, *23*(4), 042003. https://doi.org/10.2351/1.3614404

Andersson. (2015). Laser cutting in Ti-6Al-4V sheet: DOE and evaluation of process parameters Informative. *The Lancet*, *323*(8381), 848.

Anghel, C., Gupta, K., & Jen, T. C. (2020). A review on laser beam cutting. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, *August*, 3168–3178.

Anghel, C., Gupta, K., Mashamba, A., & Jen, T. C. (2018). Recent developments in laser cutting of metallic materials. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, *2018*(NOV), 1881–1891.

Astakhov, V. P. (2012). Design of experiment methods in manufacturing: Basics and practical applications. *Statistical and Computational Techniques in Manufacturing*, *9783642258*, 1–54. https://doi.org/10.1007/978-3-642-25859-6_1

Badoniya, P. (2018). CO 2 Laser Cutting of Different Materials – A Review. *International Research Journal of Engineering and Technology (IRJET)*, *05*(06), 1–12.

Ballal, N. V., Kundabala, M., & Bhat, K. S. (2013). Lasers general principles: A review. *Clinical Dentistry Research Compendium*, *January 2013*, 133–148.

Barge, RS and Kadam, RR and Ugade, RV and Sagade, SB and Chandgude, AK and Karad, M. (2019). Effect and Optimization of Laser Beam Machining Parameters using Taguchi and GRA Method: A Review. *International Research Journal of Engineering and Technology, Alandi*, *06*(03), 1907–1917. https://d1wqtxts1xzle7.cloudfront.net/60395814/IRJET-V6I336520190825-71257-a75y4m.pdf?1566800590=&response-content-disposition=inline%3B+filename%3DIRJET_Effect_and_Optimization_of_Laser_B.p

df&Expires=1602351633&Signature=ETunb4CFiAgx7oZcIwls-ZS--YS6bhS-A

Black, I., Livingstone, S. A. J., & Chua, K. L. (1998). A laser beam machining (LBM) database for the cutting of ceramic tile. *Journal of Materials Processing Technology*, *84*(1–3), 47–55. https://doi.org/10.1016/S0924-0136(98)00078-8

Chau, M. Q. (2019). An overview study on the laser technology and applications in the mechanical and machine manufacturing industry. *Journal of Mechanical Engineering Research and Developments*, *42*(5), 16–20. https://doi.org/10.26480/jmerd.05.2019.16.20

Choudhury, I. A., & Shirley, S. (2010). Laser cutting of polymeric materials: An experimental investigation. *Optics and Laser Technology*, *42*(3), 503–508. https://doi.org/10.1016/j.optlastec.2009.09.006

Eltawahni, H. A., Hagino, M., Benyounis, K. Y., Inoue, T., & Olabi, A. G. (2012). Effect of CO 2 laser cutting process parameters on edge quality and operating cost of AISI316L. *Optics and Laser Technology*, *44*(4), 1068–1082. https://doi.org/10.1016/j.optlastec.2011.10.008

Farasati, R., Ebrahimzadeh, P., Fathi, J., & Teimouri, R. (2019). Optimization of laser micromachining of Ti–6Al–4V. *International Journal of Lightweight Materials and Manufacture*, *2*(4), 305–317. https://doi.org/10.1016/j.ijlmm.2019.08.002

Gbur, G. J. (2020). *A Brief History of Lasers: 60th anniversary of the laser*. Charlotte: Cambridge University Press. Retrieved from http://www.cambridgeblog.org/2020/04/a-brief-history-of-lasers-60th-anniversary-of-the-laser/

Genna, S., Menna, E., Rubino, G., & Tagliaferri, V. (2020). Experimental investigation of industrial laser cutting: The effect of the material selection and the process parameters on the kerf quality. *Applied Sciences (Switzerland)*, *10*(14). https://doi.org/10.3390/app10144956

Keles, O., & Oner, U. (2012). Laser Cutting Process: Influence of Workpiece Thickness and Laser Pulse Frequency on the Cut Quality. *Arabian Journal for Science and Engineering*, *37*(8), 2277–2286. https://doi.org/10.1007/s13369-012-0306-2

Korkut, S., Alma, M. H., & Elyildirim, Y. K. (2009). The effects of heat treatment on physical and technological properties and surface roughness of European Hophornbeam (Ostrya carpinifolia Scop.) wood. *African Journal of Biotechnology*, *8*(20), 5316–5327. https://doi.org/10.4314/ajb.v8i20.65966

Kotadiya, D. J., & Pandya, D. H. (2016). Parametric Analysis of Laser Machining with Response Surface Method on SS-304. *Procedia Technology*, *23*, 376–382. https://doi.org/10.1016/j.protcy.2016.03.040

Lazov, L., Deneva, H., & Narica, P. (2015). Laser marking methods. *Vide. Tehnologija. Resursi - Environment, Technology, Resources*, *1*(June), 108–115. https://doi.org/10.17770/etr2015vol1.221

Löschner, P., Jarosz, K., & Niesłony, P. (2016). Investigation of the effect of cutting speed on surface quality in abrasive water jet cutting of 316L stainless steel. *Procedia Engineering*, *149*(June), 276–282. https://doi.org/10.1016/j.proeng.2016.06.667

Madić, M. J., & Radovanović, M. R. (2013). Analysis of the heat affected zone in CO2 laser cutting of stainless steel. *Thermal Science*, *16*(SUPPL.2), 363–374. https://doi.org/10.2298/TSCI120424175M

Madić, M., Radovanović, M., & Nedić, B. (2012). Correlation between surface roughness characteristics in CO2 laser cutting of mild steel. *Tribology in Industry*, *34*(4), 232–238.

Madić, M., Radovanovića, M., Petkovića, D., & Nedićb, B. (2015). Multi-criteria analysis of laser cut surface characteristics in co2 laser cutting of stainless steel. *Tribology in Industry*, *37*(2), 236–243.

Madić, Miloš, & Radovanović, M. (2012). An artificial intelligence approach for the prediction of surface roughness in Co2 laser cutting. *Journal of Engineering Science and Technology*, *7*(6), 679–689.

Markov, V. V., Lebedeva, L. I., & Kanatnikov, N. V. (2015). Results of research on causes of the defects of laser marking articles. *IOP Conference Series: Materials Science and Engineering*, *91*(1). https://doi.org/10.1088/1757-899X/91/1/012027

Michel, S., & Biermann, D. (2018). Analysis of the laser drilling process for pilot holes in complex shaped components. *Procedia CIRP*, *74*, 398–402. https://doi.org/10.1016/j.procir.2018.08.156

Miraoui, I., Boujelbene, M., & Zaied, M. (2016). High-power laser cutting of steel plates: Heat affected zone analysis. *Advances in Materials Science and Engineering*, *2016*. https://doi.org/10.1155/2016/1242565

Nisarg M. Trivedi, P. J. (2014). Improvement of Surface Finish by Vibration Control in Machine. *Journal of Engineering Research and Applications*, 17-23. Retrieved from https://core.ac.uk/download/pdf/25732488.pdf

Noor, M. M., Kadirgama, K., Rahman, M. M., Zuki, N. M., Rejab, M. R. M., Muhamad, K. F., & Mohamed, J. J. (2010). Prediction modelling of surface roughness for laser beam cutting on acrylic sheets. *Advanced Materials Research*, *83–86*, 793–800. https://doi.org/10.4028/www.scientific.net/AMR.83-86.793

Norman, P. (2008). Process monitoring and analysis of laser welding and of milling. *Phd Thesis*.

Ozaki, H., Koike, Y., Kawakami, H., & Suzuki, J. (2012). Cutting properties of austenitic stainless steel by using laser cutting process without assist gas. *Advances in Optical Technologies*, *2012*. https://doi.org/10.1155/2012/234321

Ozturk, F., Evis, Z., & Kilic, S. (2017). Hot-Dip Galvanizing Process. *Comprehensive Materials Finishing*, *3–3*, 178–190. https://doi.org/10.1016/B978-0-12-803581-8.09175-X

Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., Del Val, J., & Pou, J. (2011). The role of the assist gas nature in laser cutting of aluminum alloys. *Physics Procedia*, *12*(PART 1), 548–554. https://doi.org/10.1016/j.phpro.2011.03.069

Sandeep, R., Pon Selvan, M. C., Sudhakara, D., & Senthil Kumar, M. S. (2019). Optimization of Control Variables in Laser Welding of Dissimilar Materials Using GA Approach. *2019 Advances in Science and Engineering Technology International Conferences, ASET 2019*, 1–4. https://doi.org/10.1109/ICASET.2019.8714233

Sarfraz, S., Shehab, E., & Salonitis, K. (2017). A review of technical challenges of laser drilling manufacturing process. *Advances in Transdisciplinary Engineering*, *6*(November), 51–56. https://doi.org/10.3233/978-1-61499-792-4-51

Senthilkumar, V. (2014). Laser cutting process – A Review. *International Journal of Darshan Institute on Engineering Research & Emerging Technologies*, *3*(1), 1–6.

Sharma, V. K., & Kumar, V. (2019). Study on material transfer and surface properties during fiber laser cutting of A653 galvanized steel sheet. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *41*(8), 1–17. https://doi.org/10.1007/s40430-019-1842-4

Smita Patil, Hemant Adhale, Pankaj Bagav, Shweta Shinde, A. J. (2017). Effect of Fiber Laser Machining for Surface Roughness of Thick Stainless Steel. *International Conference on Ideas, Impact and Innovation in Mechanical Engineering (ICIIIME 2017)*, *5*(6), 764–770.

Snežana Radonjić, A. M. and P. K. (2012). DEFINING NEW PROCESSING PARAMETERS IN LASER CUTTING Ph . D . Snežana Radonji ć , f ull professor. *16th International Research/Expert Conference ”Trends in the Development of Machinery and Associated Technology, September*, 1510–1516.

Stoyanov, S., Petring, D., Arntz-Schroeder, D., Günder, M., Gillner, A., & Poprawe, R. (2020). Investigation on the melt ejection and burr formation during laser fusion cutting of stainless steel. *Journal of Laser Applications*, *32*(2), 022068. https://doi.org/10.2351/7.0000074

Suraj S Patel Ketul M Patel , Bhaumik A Patel, Aseem A Patel, Saumil C Patel, V. H. P. (2020). To Determine Process Parameter of Laser Cutting Machine: A Review. *International Journal of Engineering Research & Technology (Ijert)* , *9*(11), 65–69.

Toth, P. I., Deliver, C. D., Toth, D. P., & Regards, B. (2006). *Laser cutting of austenitic stainless steel with a high quality laser beam*. *May*, 3–7.

Umredkar, S., & Bhoyar, V. (2019). *Advance Manufacturing Processes Review Part II*. 2578–2586.

Wadekar, S., & Deokar, S. U. (2016). Effect of Process Parameters on Laser Cutting Process: A Review. *Imperial Journal of Interdisciplinary Research (IJIR)*, *2*(7).

Yilbas, B. S. (2018). Some applications of laser cutting. In *The Laser Cutting Process*. https://doi.org/10.1016/b978-0-12-812982-1.00005-9

Yusoff, N., Ismail, S. R., Mamat, A., & Ahmad-Yazid, A. (2008). Selected Malaysian wood CO2-laser cutting parameters and cut quality. *American Journal of Applied Sciences*, *5*(8), 990–996. https://doi.org/10.3844/ajassp.2008.990.996

Zhang, D., & Guan, L. (2014). Laser Ablation. In *Comprehensive Materials Processing* (Vol. 4). Elsevier. https://doi.org/10.1016/B978-0-08-096532-1.00406-4

Zhou, B. H., & Mahdavian, S. M. (2004). Experimental and theoretical analyses of cutting nonmetallic materials by low power CO2-laser. *Journal of Materials Processing Technology*, *146*(2), 188–192. https://doi.org/10.1016/j.jmatprotec.2003.10.017

Zlámal, T., Malotová, Š., Petrů, J., Brytan, Z., & Musil, V. (2018). The evaluation of the surface quality after laser cutting. *MATEC Web of Conferences*, *244*, 1–7. https://doi.org/10.1051/matecconf/201824402009

APPENDICES

(Refer to the next page)

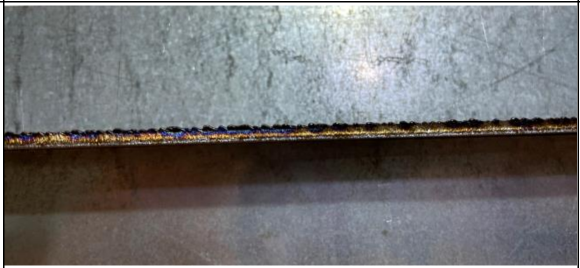
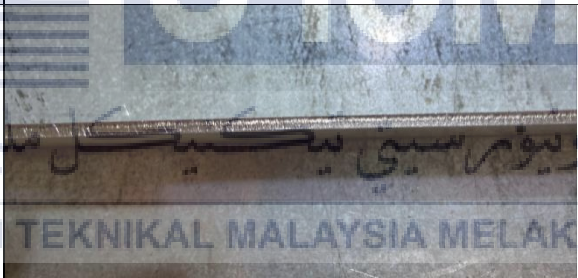
A - Gantt Chart for FYP I

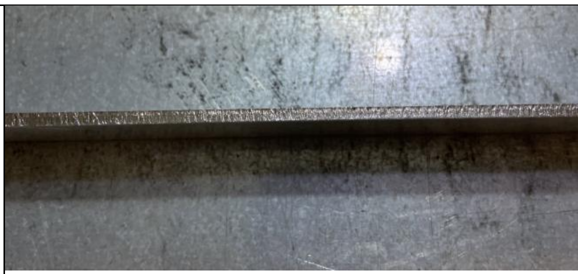
GANTT CHART FOR PSM I																
NO.	**TASK**	**WEEK**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Selection of PSM title															
2	Registration FYP Title to the Committee															
3	Findings on relevant information, journals and reference books															
4	Discussion with supervisor on objectives and scopes															
5	Literature Review															
6	Review introduction and literature review by supervisor															
7	Methodology															
8	Submission of Logbook															
9	Preparation for Presentation and QnA															
10	Presentation and QnA															
11	Preparation for Final Report															
12	Complete report and submit to supervisor and panel															

B - Gantt Chart for FYP II

GANTT CHART FOR PSM II																			
NO.	**TASK**	**WEEK**																	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1.	Project Discussion																		
2.	Data Collection																		
3.	Result Analysis																		
4.	Report Writing																		
5.	Logbook Submission																		
6.	Apply Final Correction with Supervisor																		
7.	PSM 2: Presentation																		
8.	Preparation of Draft Report																		
`9.	Final Submission Report/Thesis																		
10.	Hardbound of Final Year Project																		

C- Observation of Workpiece for Each Experiment

Run	Factor A: Cutting Speed (mm/min)	Factor B: Assisted Gas Pressure (bar)	Surface Roughness Picture	Roughness Reading (µm)
1	1800	1.0		5.85
2	2400	4.5		3.92
3	3000	8.0		3.85
4	3000	1.0		3.98
5	3000	1.0		3.93

6	3000	8.0		2.78
7	1800	8.0		2.36
8	1800	8.0		2.72
9	1800	1.0		5.04
10	2400	4.5		3.07
11	2400	4.5		5.07

D – Summary from the Previous Study

Author/Title of Journal	Materials Used	Parameters	Responses	Findings
Smita Patil, Hemant Adhale, Pankaj Bagav, Shweta Shinde,Aniket Jadhav / Effect of Fiber Laser Machining for Surface Roughness of Thick Stainless Steel	Stainless Steel	Laser power, assist gas pressure and cutting speed.	Top surface (microns)	In comparison to cutting speed and gas pressure, it was discovered that laser power is the most relevant factor. Surface roughness decreases with an increase in laser power whereas it increases with an increase in gas pressure. With an F value of 0.64, the most significant interacting parameter was determined to be laser power and gas pressure.
S.O. Al-Mashikhi, J. Powell, A. Kaplan and K.T.Voisey / Heat affected zones and oxidation marks in fiber laser-oxygen cutting of mild steel	Mild Steel	Cutting speed, focal spot, laser power	Heat affected zone (HAZ)	When thicker materials are cut, more melt will flow out of the cut zone, increasing the amount of heat transferred into the surrounding material by the melt, thereby expanding the HAZ. With faster cutting speeds, the melt departs the cut more quickly and so has less time to conduct heat into the surrounding material, reducing the HAZ.
Imed Miraoui, Mohamed Boujelbene, and Mouna Zaied / High-Power Laser Cutting of Steel Plates: Heat Affected Zone Analysis	Low Carbon Steel	Laser power, cutting speed, laser beam diameter	Heat affected zone (HAZ) and melted zone (MZ)	The laser power and cutting speed are the most important cutting parameters impacting the HAZ, whereas the laser beam diameter is the least important. The HAZ dimension grows with increasing laser power and decreases with increasing cutting speed. However, the laser power and the diameter of the laser beam are the most important cutting parameters impacting

				the MZ, while the cutting speed is the least important. MZ depth reduces as cutting speed increases and grows as laser power increases.
Hitoshi Ozaki, Yosuke Koike, Hiroshi Kawakami, and Jippei Suzuki / Cutting Properties of Austenitic Stainless Steel by Using Laser Cutting Process without Assist Gas	Austenitic Stainless Steel	Assist gas pressure, laser power, cutting speed, piercing time	Kerf width	When the heat input was raised, the kerf width and eliminated kerf area were increased as well. The dross-free cutting was accomplished by increasing the cutting speed. By reducing the laser power or increasing the cutting speed, the rate of pressure rise in the chamber during the cutting process was reduced.
V. Senthilkumar / Laser cutting process – A Review	Titanium Alloy Sheet	Power, cutting speed, gas pressure, focus position, pulse frequency	Surface roughness, kerf width, and heat-affected zone (HAZ)	Surface roughness reduces as cutting speed and assist gas pressure are increased.
B.S. Yilbas / Laser cutting quality assessment and thermal efficiency analysis	Mild Steel	Laser power, assist gas pressure, workpiece thickness, laser beam scanning velocity	Kerf width and surface roughness	Kerf width increases with increasing laser output power, which is especially noticeable at low scanning rates. All of the factors' primary effects have a substantial effect on the ensuing waviness and out of flatness. Significant effects are shown for first-order interactions between laser output power and laser beam scanning speed, laser output power and assisting gas pressure, and laser output power and thickness.
Shubham Wadekar & Swapnil U. Deokar / Imperial Journal of Interdisciplinary Research (IJIR) Page	Steel	Assist gas pressure, focal position, nozzle alignment, cutting speed,	Surface roughness, kerf width	A high degree of precision and accuracy can be achieved with the laser cutting process when cutting complex profiles in a variety of materials. The performance of the laser cutting process is dependent on the input process parameters such as laser power, cutting speed, assist gas

434 Effect of Process Parameters on Laser Cutting Process: A Review		nozzle diameter, and standoff distance		pressure, and stand-off distance as well as important performance characteristics such as surface roughness and kerf width.
K.Huehnlein, K. Tschirpke, R. Hellmann / Optimization of laser cutting processes using design of experiments	Al_2O_3 Ceramic Layers	Laser power, velocity, a distance of the nozzle, gas pressure, focal position	Surface roughness	It is discovered that the difficulty in determining the optimal parameter set for the cutting process is because various parameters are highly connected. The higher pressure of the gas is required to achieve a speedier process. When a disappearing burr is used to define a cutting process, DOE gives the optimum parameter sets for the cutting process.
B S Wardhana, K Anam, R M Ogana and A Kurniawan / Laser Cutting Parameters Effect on 316L Stainless Steel Surface	316L Stainless Steel	Gas pressure, cutting speed	Surface roughness, hardness, and microstructure	To examine the effect on the surface character, cutting parameters in the form of cutting speed and gas pressure were adjusted between 60 mm/minute and 100 mm/minute and 17 bar and 21 bar respectively. The changing hardness qualities of the material are significantly influenced by the pressure at which it is compressed. The cutting speed has a greater impact on the surface quality produced.