اونيۏرسيتي تيكنيكل مليسيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SURFACE FORMATION AND KERF IMPROVEMENTS DURING SINGLE-PASS ABRASIVE WATERJET CUTTING ON ALUMINIUM BLOCK.

SITI FATIHAH BINTI JUSOH

B092010033

BACHELOR OF MANUFACTURING ENGINEERING TECHNOLOGY (PROCESS & TECHNOLOGY) WITH HONOURS

2024

Faculty of Industrial and Manufacturing Technology and Engineering

SURFACE FORMATION AND KERF IMPROVEMENTS DURING SINGLE-PASS ABRASIVE WATERJET CUTTING ON ALUMINIUM BLOCK

SITI FATIHAH BINTI JUSOH

Bachelor of Manufacturing Engineering Technology (Process & Technology) with Honours

2024

SURFACE FORMATION AND KERF IMPROVEMENTS DURING SINGLE-PASS ABRASIVE WATERJET CUTTING ON ALUMINIUM BLOCK

SITI FATIHAH BINTI JUSOH

A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Manufacturing Engineering Technology (Process & Technology) with Honours

Faculty of Industrial and Manufacturing Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA

TAJUK: **SURFACE FORMATION AND KERF IMPROVEMENTS DURING SINGLE-PASS ABRASIVE WATERJET CUTTING ON ALUMINIUM BLOCK**

SESI PENGAJIAN: **2023-2024 Semester 1**

Saya **SITI FATIHAH BINTI JUSOH**

mengaku membenarkan tesis ini disimpan di Perpustakaan Universiti Teknikal Malaysia Melaka (UTeM) dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hak milik Universiti Teknikal Malaysia Melaka dan penulis.
2. Perpustakaan Universiti Teknikal Malaysia Melaka dibenarkan membuat salinan untuk tujuan pengajian sahaja dengan izin penulis.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (✓)

☐ TERHAD (Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia sebagaimana yang termaktub dalam AKTA RAHSIA RASMI 1972)

☐ SULIT (Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

☑ TIDAK TERHAD

Disahkan oleh:

Alamat Tetap:

Lot 2511, Kg Alor Jambu ,
16020, Tawang,
Bachok, Kelantan.

Cop Rasmi:

TS. DR. HANIZAM BIN HASHIM
Pengurus Operasi, Kilang Pengajaran
Pejabat Timbalan Naib Canselor (Akademik & Antarabangsa)
Universiti Teknikal Malaysia Melaka

Tarikh: 24/ 01/2024

Tarikh: 24/01/2024

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh laporan PSM ini perlu dikelaskan sebagai SULIT atau TERHAD.

DECLARATION

I declare that this Choose an item. entitled “SURFACE FORMATION AND KERF IMPROVEMENTS DURING SINGLE-PASS ABRASIVE WATERJET CUTTING ON ALUMINIUM BLOCK” is the result of my own research except as cited in the references. The Choose an item. has not been accepted for any degree and is not concurrently submitted in candidature of any other degree

Signature :

Name : (SITI FATIHAH BINTI JUSOH)

Date : 10 January 2024

APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Manufacturing Engineering Technology (BMMP) with Honours.

Signature	:	
Supervisor Name	:	TS. DR. HANIZAM BIN HASHIM
Date	:	10 January 2024

DEDICATION

To my beloved family especially to my parents :

En.Hassan bin idris and Pn. Hasnah binti Jusoh

To my respected supervisor :

Dr. Hanizam bin Hashim

To my supportive friends in UTeM :

Especially for my coursemates from BMMP and housemates

ABSTRACT

Abrasive Waterjet (AWJ) cutting to cut a wide range of materials from soft to hard. Abrasive waterjet (AWJ) cutting has many different benefits over other cutting technologies, including no thermal distortion, high machining versatility, high flexibility, and low cutting forces. It also appears to be an effective technology to processing multiple engineering materials, especially "difficult-to-cut" materials such as aluminium.Surface quality and kerf taper angle are crucial to the accuracy and functionality of machined products. This study focuses on the single-pass abrasive waterjet cutting procedure applied to an aluminum block in order to investigate surface quality and taper angle enhancements. This study investigates the influence of water pressure, traverse speed, and standoff distance on these parameters. Increasing water pressure during abrasive waterjet cutting tends to improve surface quality by reducing surface roughness and irregularities. However, care must be taken to prevent excessive erosion and turbulence when water pressures are excessively high. Slower traverse speed enable more time for abrasive particles to consistently erode the material, resulting in surfaces with a higher degree of smoothness. In contrast, excessively traverse speed can increase surface irregularity and material deformation. The taper angle is affected by the standoff distance, which is the vertical distance between the nozzle and the workpiece surface. Due to the dispersion of the cutting discharge, increasing standoff distance tends to enlarge the taper angle. Therefore, determining the optimal standoff distance is essential for preserving the intended taper angles.besides , the specific values and relationships between cutting parameters and surface quality and kerf angle can vary depending on the cutting system, aluminum block properties, and application requirements. Using Taguchi's principle, Design of Experimentations are used to determine the best parameter can use to improve surface roughness and kerf taper angle. Experimentation and analysis were conducted to determine the relationships between the cutting parameters, resulting surface quality and taper angle in a form of a predictive model.

ABSTRAK

Pemotongan Abrasive Waterjet (AWJ) digunakan untuk memotong pelbagai jenis bahan, daripada yang paling lembut kepada yang paling keras. Pemotongan pancutan air kasar (AWJ) mempunyai banyak kelebihan berbanding teknologi pemotongan lain. Ini termasuk daya pemotongan yang rendah, fleksibiliti yang tinggi, kepelbagaian pemesinan yang tinggi dan tiada herotan haba. Nampaknya ia adalah teknologi yang baik untuk memproses pelbagai bahan kejuruteraan, terutamanya bahan seperti aluminium yang "sukar dipotong." Permukaan yang baik dan sudut tirus adalah penting untuk ketepatan dan keberkesanan produk mesin. Kaedah pemotongan pancutan air melalui satu laluan yang digunakan pada blok aluminium digunakan dalam kajian ini untuk mengkaji kualiti permukaan dan peningkatan sudut tirus. Kajian ini mengkaji bagaimana tekanan air, kelajuan lintasan, dan jarak kebuntuan memberi kesan kepada tiga faktor ini. Semasa pemotongan pancutan air yang kasar, meningkatkan tekanan air cenderung untuk meningkatkan kualiti permukaan dengan mengurangkan ketidakteraturan dan kekasaran permukaan. Walau bagaimanapun, apabila tekanan air terlalu tinggi, perhatian perlu diambil untuk mengelakkan hakisan dan gelora. Dengan kelajuan lintasan yang lebih perlahan, zarah kasar mempunyai lebih banyak masa untuk menghakis bahan secara serentak. Ini menghasilkan permukaan yang lebih kelicinan. Sebaliknya, terlalu banyak kelajuan lintasan boleh menyebabkan permukaan tidak rata dan ubah bentuk bahan. Sudut tirus dipengaruhi oleh jarak kebuntuan, yang merupakan jarak menegak antara muncung dan permukaan bahan kerja. Dengan peningkatan jarak kebuntuan, sudut tirus cenderung meningkat disebabkan oleh penyebaran pelepasan pemotongan. Oleh itu, untuk mengekalkan sudut tirus yang dimaksudkan, adalah penting untuk menentukan jarak kebuntuan yang ideal. Tambahan pula, nilai khusus dan hubungan antara parameter pemotongan dan kualiti permukaan atau sudut tirus mungkin berbeza-beza bergantung pada sistem pemotongan, jenis blok aluminium dan tujuan. Reka Bentuk Eksperimen menggunakan prinsip Taguchi untuk menentukan parameter terbaik untuk meningkatkan kekasaran permukaan dan sudut tirus kerf. Eksperimen dan analisis telah dijalankan untuk menentukan hubungan antara parameter pemotongan mengunakan model ramalan untuk kualiti permukaan dan sudut tirus.

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

I would like to express my sincerest gratitude and appreciation to everyone who has contributed to this thesis' completion. This endeavor would not have been possible without their assistance, advice, and encouragement.First and foremost, I am indebted to my thesis supervisor, TS. DR. HANIZAM BIN HASHIM. Throughout the course of this research voyage, their knowledge, compassion, and constant guidance have been invaluable. Their unwavering support and incisive feedback have influenced my development as a researcher and this thesis.I would like to thank the faculty and personnel at UNIVERSITI TEKNIKAL MALAYSIA MELAKA for their assistance and support. Their commitment to providing a conducive environment and resources for research was essential to the completion of this thesis.I am grateful to my family for their unwavering support and encouragement throughout this endeavor. Their affection, comprehension, and faith in me have been a constant source of inspiration.Lastly, I would like to acknowledge the assistance of everyone who has contributed in some manner, whether large or minor, to the completion of this dissertation. Each interaction, conversation, and encouragement has contributed to the formation and refinement of my ideas and this work.To everyone who contributed to this thesis, I extend my deepest gratitude. Your contributions have left an indelible impression on my academic and personal development, and I am extremely appreciative of the opportunities and assistance that have been provided to me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AWJM	-	Abrasive waterjet machining
Ra	-	Roughness average
µm	-	Micrometer
mm	-	Milimeter
Rz	-	Average maximum height
Rq	-	Root mean square roughness
DOE	-	Design of experiment

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

High velocity water entrained with abrasive particles is used in Abrasive Waterjet (AWJ) cutting to cut a wide range of materials from soft to hard(Jegaraj and Babu, 2005). Abrasive waterjet (AWJ) cutting has many different benefits over other cutting technologies, including no thermal distortion, high machining versatility, high flexibility, and low cutting forces. It also appears to be an effective technology to processing multiple engineering materials, especially "difficult-to-cut" materials such as aluminium(Shanmugam, Wang and Liu, 2008) .

A particular high-pressure pump or intensifier, a water collecting unit, a nozzle positioning system, an abrasive delivery system, and a mixing unit comprised of an orifice, a mixing chamber, and a focus nozzle are typical components of an abrasive waterjet system. Entrainment machines are the most generally utilised or conventional AWJ machines. Abrasive waterjet systems that use intensifier technique to pump water to extremely high pressures. Water is often pressurised typically between 30,000 and 90,000 pounds per square inch (psi). This high-pressure water after that passes through an aperture to generate a high-velocity water jet. Due to the vacuum formed by the water jet as it passes through the mixing chamber, abrasive particles are pulled into the mixing chamber through a separate entrance. The turbulent process in the mixing chamber mixes the water and particles, resulting in an extremely strong abrasive waterjet. High velocity streams of abrasives with excellent cutting capabilities are created by transferring momentum between water and particles of abrasive in a narrow nozzle(Liu *et al.*, 2004).

The term "kerf" refers to the width of the cut formed by the waterjet stream as it passes through the material being cut in the context of abrasive waterjet cutting while variation in kerf width between the top and bottom of the cut is referred to as taper. The diameter of the waterjet nozzle, the pressure and velocity of the waterjet, the kind and size of the abrasive particles, and the material being cut all influence the kerf. Furthermore, cutting parameter research was carried out to investigate the influence on cutting surface quality, and the kerf taper angle technique and also find a way to improve abrasive waterjet cutting quality.

1.2 Problem Statement

Surface quality and taper angle are crucial factors in the precise machining of materials, especially in single-pass abrasive waterjet cutting on aluminum blocks(Chithirai Pon Selvan, Mohana Sundara Raju and Sachidananda, 2012a). Despite the numerous benefits of abrasive waterjet cutting, such as its adaptability and ability to cut complex shapes, there are still obstacles to obtaining the desired surface quality and taper angle with this technique.Currently, the surface quality of aluminum blocks cut with abrasive waterjet in a single pass falls short of desired standards. Frequent surface irregularities, such as roughness, compromise the final product's dimensional accuracy and aesthetic appeal. These flaws not only hinder the functional performance of the machined components, but also increase costs by necessitating additional surface improving operations.In addition, the taper angle, which refers to the gradually change in cutting width from the start to the exit of the cut, is an important consideration in single-pass abrasive waterjet cutting of aluminum blocks. Excessive taper angles can result in dimensional inaccuracies, risking the functionality and fit of machined parts, especially in applications requiring high precision. Achieving a low and consistent taper angle is essential for maintaining the dimensional accuracy and geometric precision of the cut surfaces.

Therefore, it is important to investigate and resolve the root cause factors that contribute to the a poor surface quality and taper angle in single-pass abrasive waterjet cutting of aluminum blocks(Deaconescu and Deaconescu, 2021a). By identifying the underlying causes of these problems, it is possible to develop effective strategies and interventions that can improve the surface quality and taper angle, thereby enhancing the overall performance and usability of the machined aluminum components.This investigation aims to investigate comprehensively the factors affecting surface quality and taper angle during single-pass abrasive waterjet cutting of aluminum blocks. Through an in-depth analysis of process parameters, material properties, and cutting conditions, this study seeks to gain a greater comprehension of the complex interactions between these variables. Subsequently, the research will concentrate on proposing new methods, such as optimization techniques and adjustments to process parameters, to mitigate surface quality issues and achieve reduced and consistent taper angles.

1.3 Research Objective

1. To determine the parameters that have significant impact surface quality and the kerf angle on aluminium block.
2. To optimize the significant parameters using an orthogonal matrix of Taguchi method.
3. To identify the best achievable surface roughness and taper angle on cutting surface using scope.

1.4 Scope of Research

The aim of this project is to studied the effects of machining strategies, and parameters on aluminium block to improve surface quality and reduce the taper angle, Brand and model of the machine, abrasive type and size. This project is to find the best parameter should be used to get the good result of the surface quality and angle of taper. The thickness of aluminium block use is 8mm. The cutting parameters used in this project including the parameter is water pressure, traverse speed and the last parameter is standoff distance which was varied between 2 until 6mm that considered in this research. This project will use MINITAB software applications where this software helps to save the time to define the best solution. In this MINITAB software, Taguchi method are used to define the best solution and record the sample data for process of improving the surface quality and the taper angle based on data of parameter record.

1.5 Summary

In the conclusion , this chapter offers not only project details, but also basic knowledge for readers to grasp the essence of what this project is all about. This chapter includes prior research papers' project objectives, scope, and problem statements. The issue problem statement is then applied to existing parameters in order to create a better and more effective parameter that may be utilised to improve surface quality and taper angle.the parameter use for this project were chosen which is based on the parameter first is the thickness of aluminium block water pressure and also standoff distance Finally, the project scope is highly distinctive, necessitating productivity

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this review of the literature, we will examine the main findings and advancements reported in recent research pertaining to surface quality and taper angle enhancements during single-pass AWJM on aluminium blocks. By critically analyse the existing corpus of knowledge, this review seeks to identify the current state of the art, identify research voids, and propose potential avenues for future research in this field. Overall, the enhancement of surface quality and taper angle in AWJ on aluminium blocks has significant implications for industries where precise machining is essential. Manufacturers can enhance the functionality, performance, and aesthetics of their products by attaining a superior surface finish and precise taper angles. Understanding the fundamental mechanisms and optimizing the process parameters in AWJ can also contribute to reducing manufacturing costs, increasing productivity, and mitigating material waste(Siores *et al.*, no date).

2.2 Abrasive waterjet machining (AWJM)

Abrasive waterjet (AWJ) is a versatile and extensively employed manufacturing technique for cutting a broad range of materials, including metals(Chen, Siorest and Wong, 1996). Its non-thermal nature and ability to cut complex shapes make it ideal for use in industries such as aerospace, automotive, and manufacturing(Chen, Siorest and Wong, 1996). Nevertheless, achieving a high-quality surface finish and precise taper angles during single-pass AWJ on aluminium blocks remains difficult(Singh, Srinivasu and Ramesh Babu, 2021). Surface quality and taper angle are crucial factors influencing the performance, functionality, and visual appeal of machined components(Jegaraj and Babu, 2005). The surface quality in AWJ refers to the uniformity, irregularity, and integrity of the cut surface, whereas the taper angle is the deviation from the vertical axis of the cut. Several process parameters, such as the abrasive flow rate, standoff distance, traverse speed, and orifice diameter, influence the quality of these characteristics.

Over the years, researchers have exhaustively investigated methods for improving the surface quality and taper angle of AWJ aluminium blocks. These studies have investigated a variety of approaches, such as optimizing process parameters, modifying nozzle designs, and employing sophisticated control strategies(Siores *et al.*, no date). The objective is to identify minimum surface irregularities like striations, delamination, and burrs while attaining minimal taper angle deviation. Extant literature on surface quality and taper angle enhancements in AWJ on aluminium blocks is extensive and diverse. Numerous experimental and numerical studies have been conducted to comprehend the intricate interactions between process parameters and their impacts on machining outcomes. The results of these investigations have provided valuable insight into the fundamental mechanisms that govern surface quality and taper angle formation during AWJM.

2.3 Abrasive waterjet machining (AWJM) process

Abrasive Waterjet Machining (AWJM) is a machining process procedure that applies a high-pressure jet of water containing abrasive particulates to cut a variety of materials, including aluminium blocks. Several principles, components, and parameters are summarized in this section;

2.3.1 principles of AWJM

A high-pressure water jet is used to cut a variety of materials(Jegaraj and Babu, 2005). The water can attain velocities of up to 4,000 feet per second and pressures of up to 90,000 psi. A compact nozzle focuses the high-pressure water discharge, concentrating the energy and enabling precise cutting. The high-pressure water jet is capable of penetrating a variety of materials, including metals, plastics, composites, and even stone(Jegaraj and Babu, 2005). It is a non-thermal cutting technique, which produces neither heat nor flames(Chen, Siorest and Wong, 1996). This makes the trimming process safe and environmentally friendly.

AWJM is a versatile method of cutting that can be utilized for a variety of purposes. In the manufacturing industry, it is frequently used to cut parts for a variety of products, including automobiles, aerospace components, and medical devices(Mohankumar, Kanthababu and Velayudham, 2021). In the construction industry, it is used to carve concrete and other building materials. AWJM is a comparatively new method of cutting, but it has rapidly gained popularity for a wide range of applications. It is a versatile, safe, and environmentally beneficial method of cutting a variety of materials.

Injecting abrasive particulates into the water jet stream improves its cutting efficiency. In an abrasive mixing chamber, typically made of garnet or aluminium oxide, abrasive particulates are mixed with water and then accelerated through a nozzle. The workpiece is eroded by the high-velocity water discharge and abrasive particulates, resulting in a clear, precise cut(Jegaraj and Babu, 2005).

The type of abrasive used in AWJM varies according to the material being cut. For instance, garnet is frequently used to cut materials such as wood, plastics, and composites, whereas aluminium oxide is frequently used to cut metals. The size of the abrasive particulates has an effect on the efficacy of the incision. Smaller particulates result in a finer incision, but they can obstruct the nozzle. AWJM is a versatile method for cutting a variety of materials. Such industries as aerospace, automotive, and manufacturing utilize it frequently. AWJC is a cost-effective and eco-friendly method that can reduce waste and increase productivity(Singh, Srinivasu and Ramesh Babu, 2021; Dadgar *et al.*, 2023).

2.3.2 Components of AWJM

AWJM consists of pump or intensifier, mixing chamber and a nozzle. Figure 2.1 below show the schematic of Abrasive Waterjet Machining (AWJM).

i. Pump or Intensifier:

The pump or intensifier is the core of the system, as it generates and maintains the high-pressure water flow required for cutting. Typically, pumps are employed for low-pressure applications, whereas intensifiers are utilized for higher-pressure needs. The water discharge is accelerated through a nozzle, where abrasive particles are mixed with it. The abrasive particles are subsequently accelerated alongside the water jet, whereupon they impact the material being cut and abrade it. The water jet can cut through metal, plastic, and glass, among other substances.

ii. Mixing Chamber:

An important component of an abrasive water jet cutting system is the mixture chamber. It is responsible for combining the abrasive particles and high-pressure water stream. (Llanto *et al.*, 2021a)This ensures that the abrasive particulates are distributed similarly throughout the water jet, leading to a more consistent cutting performance. To withstand the high pressures and temperatures involved in abrasive water jet cutting, the mixture chamber is typically made of a durable material, such as stainless steel. Additionally, it is designed to minimize turbulence, which can cause abrasive particulates to cluster.

The mixture chamber is a comparatively basic component of an abrasive water jet cutting system, but it plays a crucial role in its performance(Llanto *et al.*, 2021b). Mixing the abrasive particulates uniformly with the high-pressure water stream ensures that the abrasive water jet can accurately and precisely cut through a variety of materials.

iii. Nozzle:

The final component of an abrasive water jet cutting system is the nozzle. It is responsible for regulating the shape and size of the water flow and creating a vacuum that draws abrasive particles from the mixture chamber. Typically, nozzles are constructed from materials that can withstand the erosive forces of abrasive particulates. A critical component of an abrasive water jet cutting system is the nozzle. It ensures that the water discharge is focused and possesses the intended cutting properties. The nozzle is also responsible for preventing abrasive particulates from clogging the water discharge.

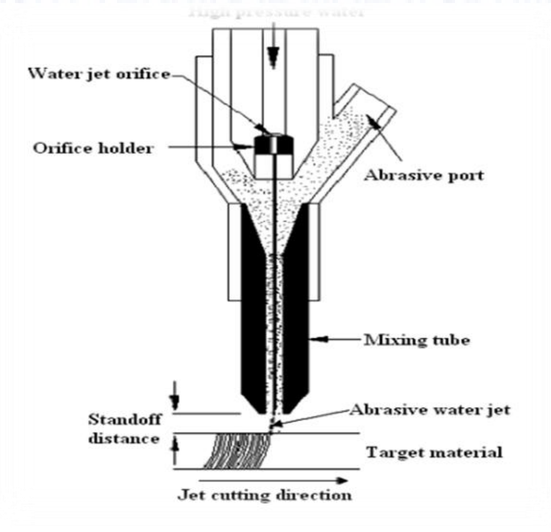


Figure 2. 1 Schematic of AWJM

2.3.3 Parameters of AWJM

The success of AWJM is heavily dependent on properly managing and optimising numerous critical process parameters. These characteristics are critical in defining the precision, quality, and efficiency of the machining process. Every parameter, from water pressure and material thickness to standoff distance and traversal speed, adds to the AWJM system's overall performance. Figure 2.2 show the diagram of process parameters that influence AWJM.

i. Standoff Distance:

In abrasive water jet cutting, the standoff distance is the distance between the nozzle point and the workpiece surface. It is a crucial parameter that influences the cutting quality, as it effects jet stability, kerf width, and surface roughness. The standoff distance influences the water jet's stability. The water discharge can become unstable and vibrate if the separation distance is too small. This can result in an inconsistent trim and a poor surface finish. If the distance is too great, the water flow can disperse and lose its concentration. This may also result in an inconsistent cut and a poor surface finish. For the kerf width, if the standoff distance is too little, the width of the kerf will be narrow. If the standoff distance is excessively huge, the kerf width will be excessively wide and, when the standoff distance is too little, the surface quality will be too high and the surface roughness will be low if the standoff distance is too great. For thin materials, typically a short distancing distance will be used. This will guarantee the water discharge is concentrated and the kerf width is narrow while for the thick material, typically a greater distancing distance is will be used. This will prevent the water discharge from becoming unstable and ensure that the kerf width is wide.

ii. Material thickness:

The thickness of the material being cut is a crucial material characteristic that affects the cutting process and its results. The AWJM process's cutting capacity is influenced by the thickness of the material being cut. From tiny sheets to thicker blocks, AWJM has the ability to cut a wide variety of material thicknesses. The thickness, however, may have an impact on the cutting efficiency and speed. To cut through thicker materials with the specified depth, it may be necessary to use slower cutting speeds or multiple passes to get the desired cut(Gupta *et al.*, no date).

The greatest possible thickness for efficient cutting in AWJM is dependent on a number of variables, including the strength of the cutting system, the nozzle design, the rate of abrasive flow, and the characteristics of the material. The suggested maximum thickness for various materials is frequently specified or laid forth in guidelines by manufacturers of AWJM equipment. To get the cutting results you want and keep up the high standard of work, it's crucial to optimise the process parameters and methods based on the material thickness.

iii. Water pressure:

A crucial factor that directly impacts cutting performance and efficiency is the water pressure utilised in abrasive waterjet cutting (AWJM). When referring to AWJM, the term "water pressure" refers to the pressure at which water is pressurised before it is combined with abrasive particles and released via the cutting nozzle. To cut through thicker materials with the specified depth, it may be necessary to use higher water pressure to get the desired cut(Ramalingam et al., 2015a, 2015b).

iv. Traverse speed/cutting speed(Siores *et al.*, no date):

In abrasive waterjet cutting (AWJM), traverse speed is a crucial factor. It describes the speed at which the cutting nozzle traverses the surface of the workpiece when cutting. The cutting effectiveness, quality, and overall productivity of AWJM are all directly impacted by traverse speed.

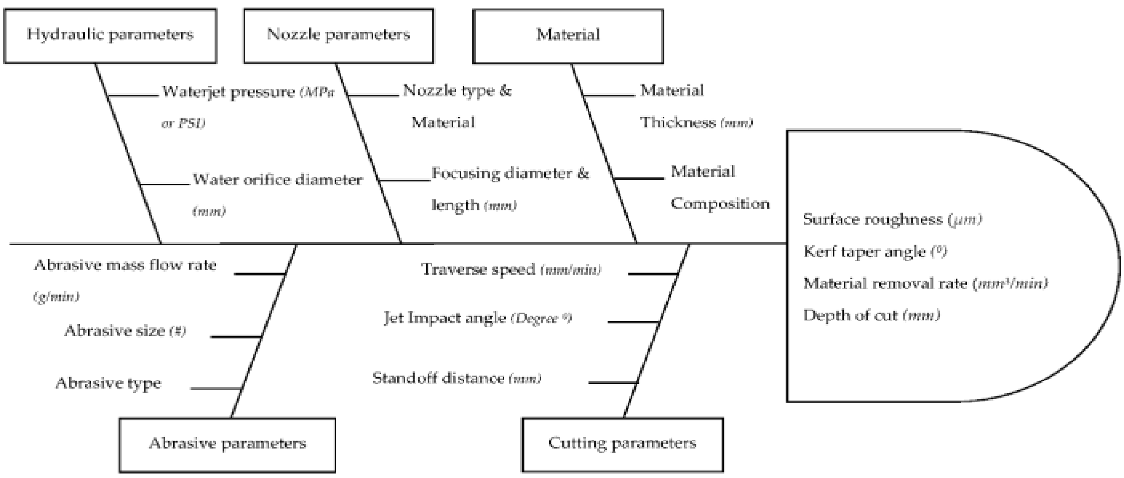


Figure 2. 2 Process parameter that influencing the awjm diagram

2.3.4 Cutting system.

This consists of the traverse speed, standoff distance, and projectile impact angle. The traverse speed, measured in millimeters per minute, corresponds to the rotation of a tank during machining. The standoff distance is the height between the tip of the nozzle and the upper surface of the target material, which is measured in millimeters. The jet impact angle is the jet's orientation relative to a cutting-level surface(Saravanan *et al.*, 2020). Utilizing AWJM with multiple cutting heads has recently resulted in an appreciable increase in productivity. Two traverse systems can be used simultaneously and independently to machine larger and multiple elements (Liu, 2017).

Impacts of traverse speed: Variation in travel speed has a significant effect on AWJM output parameters. Sasikumar et al.(Sasikumar *et al.*, 2018) reported that minimizing the kerf angle and surface irregularity in AWJ cutting of hybrid aluminum 7075 metal matrix composites can be achieved by using a low traverse speed and high pressure. Their findings align with those of Gnanavelbabu et al,(Llanto *et al.*, 2021c) who investigated minimizing the kerf taper angle when cutting AA6061 at a low traversal speed. Traverse speed was the most significant and influential parameter for the rate of material removal during AWJ cutting of stainless-clad steel workpieces. Moreover, the feed rate was found to be the most influential parameter in regulating the surface roughness and kerf-angle responses in abrasive waterjet cutting of 5 mm thick AISI 1018 (Llanto *et al.*, 2021c). Moreover, Karmiris-Obrata 'nski et al(Karmiris-Obratański *et al.*, 2021)investigated AWJM multiple passes and achieved a greater depth of cut by utilizing a greater number of passes and a higher-level traverse speed; thus, the application of multiple passes can provide superior results compared to single pass machining under certain conditions. The traverse speed is directly proportional to the material removal rate but inversely proportional to the depth of cut, surface irregularity, and kerf taper, according to these studies.

Impacts of stand-off distance: A greater distance between the nozzle exit and the upper surface of the workpiece results in a decrease in particle velocity, which denotes a decrease in material removal rate, irregularity, and kerf taper angle(Llanto *et al.*, 2021c). When cutting steel sheets with an abrasive waterjet machine (TRIP 800 HR-FH and TRIP 700 CR-FH), Kechagias et al.2012 (Kechagias, Petropoulos and Vaxevanidis, 2012) found that the kerf width and surface roughness of the cut parts can be decreased by using a close standoff distance, a slower traverse speed, and a smaller nozzle diameter at a greater material thickness. In conclusion, it was discovered that a combination of a high-level separation distance and a high-rate traversal speed reduces the contact duration of abrasive particles during the cutting process.

Impacts of jet impact angle: Changing the jet impingement angle affects the AWJM output parameters differently based on the workpiece's hardness scale. Specifically, emphasized the significance of controlling the jet impact angle in order to enhance AWJM cutting output responses. When cutting AA5083-H32, the kerf width, taper ratio, and surface texture can be affected by altering the impingement angle of the jet and the mesh size of the abrasive. An oblique jet angle of 70 degrees has been shown to reduce kerf taper ratio, surface irregularity, and striations. In addition, Kumar et al.(Llanto *et al.*, 2021c) conducted an experiment with a different metal, D2 Steel, and determined that a jet impact angle of 70° maintained a more intact cut surface. A greater degree of jet impingement angle results in a greater rate of material removal, particularly in difficult-to-cut materials; consequently, an acute jet impact angle provides precise cutting performance primarily with flexible materials (Melentiev and Fang, 2018)In this paper, Figure 2.3 depicts the statistical distribution of the identified influential AWJM input process parameters from 2017 to 2020(Llanto *et al.*, 2021c). Figure 2.3 depicts the weighted distribution of the AWJM cutting input process parameters determined to have a significant impact on AWJM cutting performance.

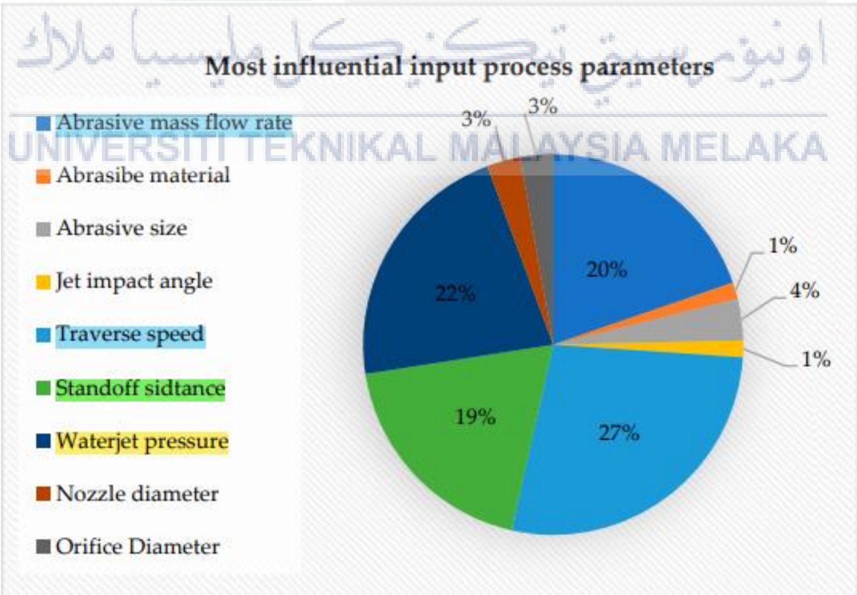


Figure 2. 3 Survey of identified most influential AWJM cutting input process parameters reviewed publications from 2017 to 2020(Llanto *et al.*, 2021c)

Refer to figure 2.3,27% of these research findings demonstrated that traverse speed is the most influential input parameter in the AWJ cutting process, followed by waterjet pressure, abrasive mass flow rate, and standoff distance, with 22%, 20%, and 19% contributions, respectively. There are few studies that have considered the abrasive size, nozzle and orifice diameter, abrasive material, and jet impact angle; consequently, the effects of these input parameters cannot be justified because they have received less attention from researchers and have been utilized infrequently in experimental studies. This can be viewed as a prospective area for future research and development.

2.3.5 Advantages of AWJM on pure aluminium block

Abrasive Waterjet Cutting (AWJC) is different from other cutting techniques in a number of ways and provides special benefits for machining aluminium blocks(Siores *et al.*, no date). Here are a few distinguishing features and advantages of AWJC:

i. Non-Thermal Cutting(Chen, Siorest and Wong, 1996): The fact that AWJ is a non-thermal cutting process is one significant feature. In different methods like laser or plasma cutting, AWJ does not use heat to melt or vaporise the material(Siores *et al.*, no date). Instead, it uses a high-pressure water jet containing abrasive particles to erode and remove material, producing less heat-affected zone (HAZ) during cutting(Llanto *et al.*, 2021c). Due to its ability to prevent heat distortion and maintain the structural integrity of the material, AWJ is especially well suited for use with aluminium.

ii. Versatility in Material Thickness(Gupta *et al.*, no date): AWJ provides versatility in cutting aluminium blocks of varying thicknesses. AWJ can cut through a variety of thicknesses effectively and efficiently, whether they are narrow sheets or heavy slabs. This adaptability streamlines the machining process by eliminating the need for multiple cutting methods or tool swaps.

iii. Minimal Material Waste: The limited kerf width of AWJ results in minimal material waste. Material utilisation is maximised when cutting is performed with high precision and minimal material waste. This benefit is particularly significant when working with expensive materials such as aluminium, as it reduces expenses and maximises resource efficiency.

iv. No Heat-Affected Zones(Singh, Srinivasu and Ramesh Babu, 2020; Llanto *et al.*, 2021a): As AWJ is a non-thermal procedure, it prevents the formation of heat-affected zones and recast layers on the block's cut surface. This benefit guarantees the material retains its original properties and reduces the need for secondary machining or post-processing.

v. Environmentally Friendly: AWJ is a cutting procedure for aluminium blocks that is environmentally beneficial. The process generates no hazardous vapours, gases, or particles. In addition, AWJ typically utilises recycled water, reducing water consumption and minimising its environmental impact.

2.4 Cutting surface quality.

Surface quality is an essential aspect of abrasive waterjet cutting (AWJM) procedures, which relates to the characteristics of the cut surface after machining. It includes aspects such as surface texture, integrity, burr, and other visual and functional characteristics. The surface quality obtained in AWJM is affected by a number of parameters and factors, including cutting parameters, material properties, nozzle design, abrasive type and size, standoff distance, and cutting path strategy(Hi T Hi R A I Po, El V A and Sachidananda, no date). In AWJ, surface irregularity is one of the most important indicators of surface quality. Typically, it is measured with parameters such as Ra (average roughness) or Rz (mean peak-to-valley height)(Kovacevic, no date). Optimising cutting parameters such as jet pressure, abrasive flow rate, traverse speed, and standoff distance is necessary to achieve the desired level of surface roughness(Chithirai Pon Selvan, Mohana Sundara Raju and Sachidananda, 2012b).

Integrity is another essential aspect of surface quality, which refers to the absence of flaws such as fractures, delamination, or thermal damage on the cut surface. Controlling cutting parameters, such as jet pressure and traverse speed, is crucial for preserving the integrity of the cut surface. Additionally, the appropriate selection of abrasive type and size can prevent excessive material removal and surface injury to the workpiece. It is essential to note that attaining a high surface quality in AWJ frequently necessitates a trade-off with other process objectives, such as cutting speed and precision. Finding the optimal equilibrium between these factors is essential for attaining the desired surface quality for a particular application. Figure 2.4 show the example of surface finish produce by combination of the parameter used.

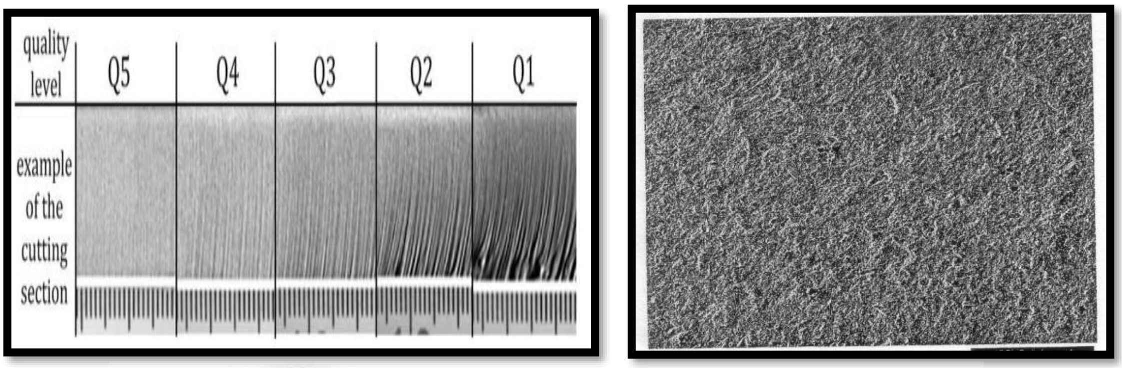


Figure 2. 4 Surface quality example

2.5 Taper angle cutting

The taper angle is the deviation of the cut from a perpendicular orientation in abrasive waterjet cutting (AWJ). It is the angular difference between the top and bottom surfaces of the workpiece that is caused by the deviation of the waterjet as it travels through the material. Taper angle is a crucial factor in AWJ, as it can influence the dimensional accuracy and surface quality of the cut.

The taper angle in AWJ is determined by a number of variables, including nozzle geometry, fluid pressure, standoff distance, material thickness, and cutting speed. Figure 2.5 show the schematic that represent the formation of the kerf taper.(Gupta *et al.*, no date) Higher jet pressures and shorter standoff distances have a tendency to increase the taper angle, whereas lower pressures and longer standoff distances can help decrease it. Additionally, the material's thickness plays a role, with denser materials generally exhibiting larger taper angles.

Controlling and minimising taper angle is important for applications requiring precision dimensional accuracy, such as those in the aerospace and automotive industries. To reduce taper angle, various strategies can be employed, such as modifying the cutting parameters, optimising the nozzle design, employing compensation techniques, or utilising multi-pass cutting techniques.

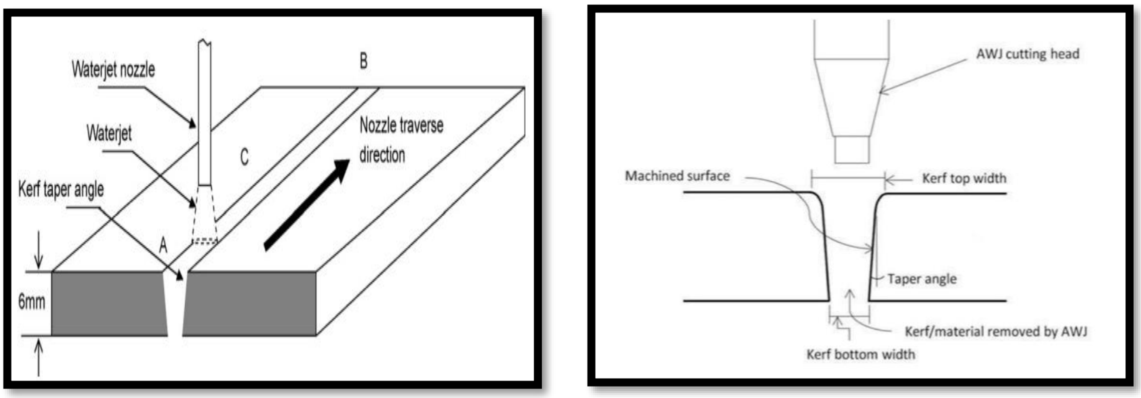


Figure 2. 5 Schematic represent the formation of kerf taper

2.6 Design of experimental using Taguchi Method

The Taguchi method, developed by Dr. Genichi Taguchi, is a powerful statistical technique utilised in product design and manufacturing for quality improvement and process optimisation(Chithirai Pon Selvan, Mohana Sundara Raju and Sachidananda, 2012b) .It provides a method that is both systematic and efficient for identifying and minimising the effects of numerous factors and sources of variation, resulting in improved product quality, performance, and dependability.

One of the key principles of the Taguchi method is employing orthogonal arrays in experimental design. Orthogonal arrays permit a balanced and efficient distribution of experimental trials, thereby reducing the number of experiments necessary to identify significant factors and their interactions. This method saves time, effort, and resources while yielding valuable insights into the effects of various factors on the quality characteristics of a product or process.

In addition, the Taguchi method incorporates a loss function that quantifies the cost or loss associated with deviations from the intended target value. By minimising the loss function, the Taguchi method aims to optimise parameter settings and reduce variation, resulting in cost savings and improved product quality

In conclusion, the Taguchi method is an effective and systematic technique for enhancing and optimising quality. By utilising orthogonal arrays, engineers and researchers can determine the optimal combination of factors and parameter settings that result in improved performance and quality. Taguchi provides a framework for achieving consistent and reliable outcomes in product design and manufacturing processes.

2.7 Process parameter optimization

Optimising process parameters is essential for enhancing surface quality and taper angle in abrasive waterjet cutting (AWJ) of aluminium blocks. Several published studies have investigated the effects of various parameters and their optimisation on the achievement of improved results. Table 2.1 show the effect of various parameter and their optimisation.

Table 2. 1 Effects of various parameters and their optimisation

no	parameter	description
1	Standoff distance	standoff distance, which is the distance between the nozzle and the workpiece surface, is a crucial parameter that influences both surface quality and taper angle(Anu Kuttan, Rajesh and Dev Anand, 2021). Experimentation has examined the effects of various standoff distances and their optimal values for optimising performance a standoff distance of 1-2mm is recommended for most materials(Ramalingam *et al.*, 2015a). AWJM is capable of producing a rough finish, particularly on thick materials. Using a lower water pressure, a slowed cutting speed, or a finer abrasive may reduce this effect.(Deaconescu and Deaconescu, 2021b)
2	Abrasive flow rate	Surface quality is significantly impacted by the abrasive particle flow rate in AWJ. It is essential that by increasing the abrasive flow rate excessively can result in a decrease in surface quality,(Madara *et al.*, 2021) and an increase in cost.
3	Traverse Speed	Researchers have studied the relationship between traverse speed and these parameters to determine the

		optimal traverse speed that minimizes taper angle and enhances surface finish(Anu Kuttan, Rajesh and Dev Anand, 2021). By Increased traverse speed can result in a surface with a rougher finish while the lower of travel speed, the taper angle decreases and will lead to narrow cut(Li *et al.*, 2019).
4	Nozzle Diameter	Surface quality and taper angle are influenced by the diameter of the cutting nozzle. Researchers have investigated the effects of various nozzle diameters on these parameters and have optimized the nozzle diameter to obtain better results. a study published in the journal "Journal of Manufacturing Processes" found that a nozzle diameter of 0.2 mm produced the best surface quality and taper angle for cutting aluminium alloy.
5	Abrasive Type and Size	Smaller abrasive particles create a smoother surface with a smaller taper angle, whereas larger abrasive particles create a rougher surface with a larger taper angle.

It is worth noting that the optimal process parameters for AWJM on aluminium blocks may vary depending on the specific equipment, workpiece material, and desired surface characteristics. Therefore, it is essential to consider the findings from multiple studies and conduct further research or experimentation to fine-tune the parameters for a particular application.

2.8 Challenges and limitations

The issue of enhancing surface quality and taper angle in abrasive waterjet cutting (AWJC) on aluminium blocks is challenging and has limitations. Here a few common challenges and limitations using this process

i. Surface Roughness(Deaconescu and Deaconescu, 2021b): AWJM faces difficulty in obtaining the desirable surface quality on aluminium blocks. Due to the erosive effect of the abrasive particulates on the material, a natural capacity of abrasive waterjet cutting can cause surface irregularity. It may be necessary to perform additional post-processing stages, such as sanding, refining, or secondary machining, to achieve a finer surface finish.

ii. Taper Angle Control: Controlling the taper angle in AWJM is a further difficulty, particularly when aiming for minimal taper. The taper angle relates to the deviation about a perpendicular cut, which results in a conical form. Influencing the taper angle are variables such as nozzle design, material thickness, and cutting parameters. The waterjet nozzle is capable of cutting at an angle, resulting in a tapered cut edge. This can be mitigated by decreasing the standoff distance or modifying the water pressure and cutting speed. Achieving a consistent and low taper angle throughout the entire cutting process requires meticulous optimisation of process parameters and control of cutting conditions.

iii. Kerf Width Variation: Variation in Kerf Width AWJM can exhibit variations in the kerf width, which is the width of the waterjet's cutter. Inconsistent kerf width can affect the cut's dimensional accuracy and lead to deviations from the specified parameters. Variations in kerf width can be caused by variables including material thickness, traverse speed, and abrasive flow rate. Maintaining a consistent and accurate kerf width necessitates vigilant monitoring and adjustment of process parameters.

iv. Material Deformation: Aluminium is known for its relatively low melting point and high thermal conductivity, which contribute to its deformation. During AWJM, the cutting process's intense energy and pressure can cause localised heating and thermal deformation of the material. Minimising material deformation and maintaining dimensional stability when cutting thin or complex aluminium components can be difficult. Controlling the cutting parameters, such as water pressure, traverse speed, and nozzle selection, with care is required to prevent material deformation. The waterjet is capable of deforming materials, particularly delicate thin materials. This can be mitigated by reducing the water pressure or slowing the cutting pace.

v. Equipment Cost and Maintenance: The cost and maintenance of AWJM apparatus, such as high-pressure compressors, cutting heads, and abrasive delivery systems, can be expensive. In addition, the process's abrasive particulates can cause equipment wear and tear, necessitating regular maintenance and replacement. When implementing AWJM to improve the surface quality and taper angle of aluminium blocks, the initial investment and ongoing maintenance costs should be considered.

2.9 Summary

In summary, the parameters of abrasive waterjet cutting (AWJM are crucial in determining the quality, efficiency, and accuracy of the cutting process(Deaconescu and Deaconescu, 2021b) By controlling and optimising these parameters, it is possible to accomplish desirable results and improve the machining of a variety of materials, such as aluminium blocks.

The traverse speed, or cutting speed, affects both the overall cutting time and the cut's precision. To accomplish precise cuts with minimal taper and surface irregularities, it is necessary to strike a balance between rapidity and quality. Adjusting the traverse speed based on the material's thickness and properties will ensure efficient cutting and high-quality results.

Water pressure is another essential AWJM parameter. It directly influences the cutting performance and efficacy by determining the waterjet's energy and force. Higher water pressures can lead to speedier cutting rates, but they must be carefully managed to prevent excessive taper, material deformation, and surface damage. For delicate materials or intricate designs requiring precision control, a lower water pressure may be appropriate. Other variables such as abrasive flow rate, nozzle design, and standoff distance also influence the cutting procedure. Adjusting these parameters enables customization according to material characteristics, intended surface quality, and dimensional precision. Proper selection and optimisation of these parameters contribute to the reduction of surface irregularity, control of taper angles, minimization of material waste, and enhancement of overall productivity(Keshav Kumar Jha, Rai and Kumar Jha, no date).

However, it is essential to recognise the challenges and limitations of AWJM parameters. Surface imperfection, taper angle control, kerf width variation, material deformation, edge quality, and productivity are among the obstacles that must be overcome. To accomplish the desired surface quality and dimensional accuracy, these constraints necessitate cautious process optimisation, monitoring, and possibly post-processing.

In the end, it is essential to comprehend and optimise AWJM parameters in order to achieve high-quality aluminium block machining. By adjusting traverse speed, water pressure, and other relevant parameters, it is possible to improve surface quality, control taper angles, reduce material waste, and boost overall productivity. Continued research and development in AWJC parameter optimisation will advance the capabilities and industrial applications of this cutting method.

In conclusion, this literature review of previously published research papers reveals that the majority of researchers cited the same parameter as affecting surface roughness and taper angle. Therefore, this parameter is crucial for abrasive waterjet cutting (AWJM). From the stated parameters, my investigation will concentrate on only a few which s standoff distance, material thickness and the pressure of water jet to determine the surface roughness and taper angle. The surface imperfection will be evaluated using a surface rouhness machine, yielding more accurate and precise results.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Surface quality and taper angle play a crucial role in the precision manufacturing of aluminium blocks. Achieving high surface quality and minimising taper angle are crucial for assuring dimensional accuracy, decreasing post-processing needs, and enhancing the overall quality of machined parts(Qian *et al.*, 2023). Optimising the cutting parameters in the context of abrasive waterjet cutting (AWJ) is crucial for improving surface quality and taper angle during single-pass cutting of aluminium blocks.

This section explains the methods used to improve surface quality and taper angle in AWJC on pure aluminium blocks. The methodology describes the material used, the equipment used, the experimental setup, parameter selection, experimental design, fix factors, and surface quality and taper angle characterization. By following this systematic strategy, a full understanding of the major process factors that impact surface quality and taper angle may be achieved in order fulfil the objective project.

3.2 Process flow chart

Select investigations may be repeated or additional tests may be conducted to corroborate the findings and validate the results. The parameter values are optimised for surface quality and taper angle enhancements based on data analysis. As necessary, additional iterations or adjustments can be made to the cutting procedure to achieve the intended results. This methodology offers a systematic method for investigating and improving surface quality and taper angle during single-pass abrasive waterjet cutting of aluminium blocks. By selecting and optimising the cutting parameters with care, it is possible to improve the surface quality, taper angle, and dimensional accuracy of a machined part. The subsequent sections will present results, analyses, and discussions based on the methodology employed as shown in figure 3.1.

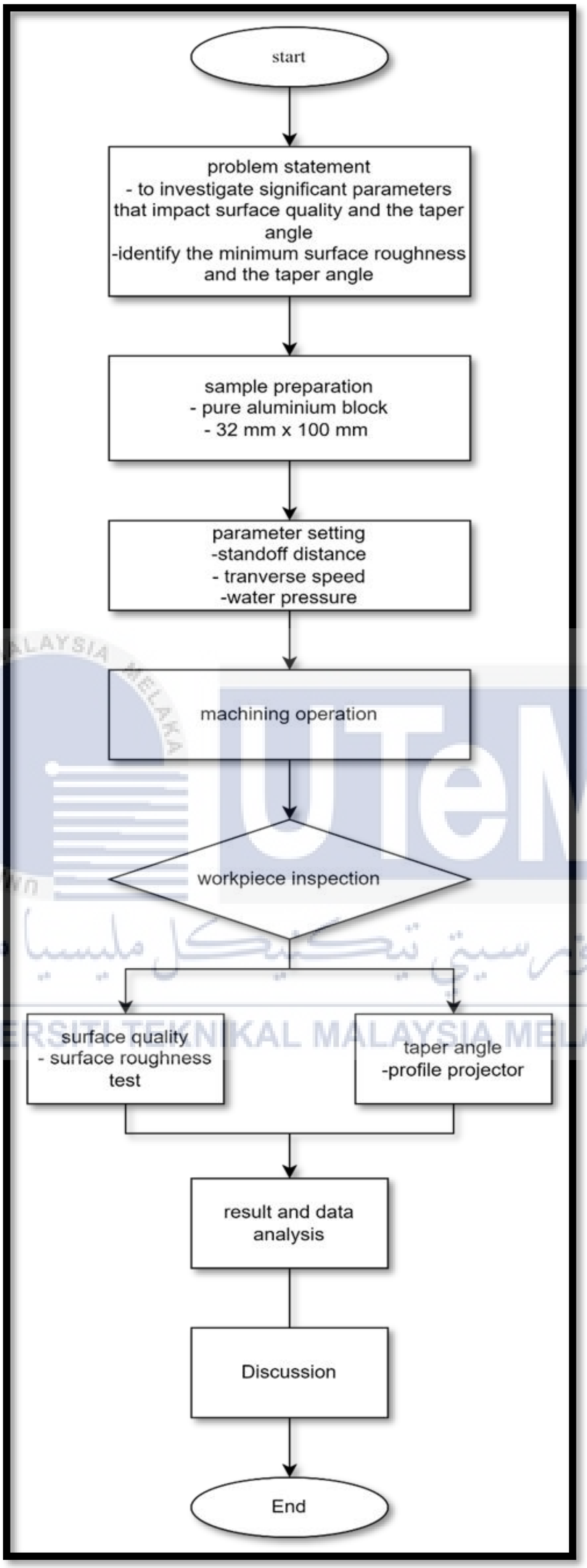


Figure 3. 1 Methodology flowchart

3.3 Material

3.3.1 Pure aluminium block

The mineral bauxite is used to produce aluminium. The Bayer Process converts bauxite to aluminium oxide (alumina). Using electrolytic cells and the Hall-Heroult Process, the alumina is subsequently transformed to aluminium metal.

A pure aluminium block refer to figure 3.2, measuring 32 mm in thick and 100 mm in wide shows the lightweight metal's flexibility and utility. The block's clean and uniform surface highlights the intrinsic characteristics that make aluminium so valuable in a variety of sectors. Pure aluminium is a fundamental material in the construction of a wide range of goods due to its superior conductivity, corrosion resistance, and malleability. The exact measurements of 32 mm x 100 mm highlight its usefulness for applications requiring a balance of strength and weight. The use of pure aluminium has particular advantages. Because of its malleability, it is possible to make delicate cuts and shapes without risk of cracking or shattering. Furthermore, the absence of iron contamination makes it perfect for industries requiring rust-free purity, such as food processing or medical equipment production.

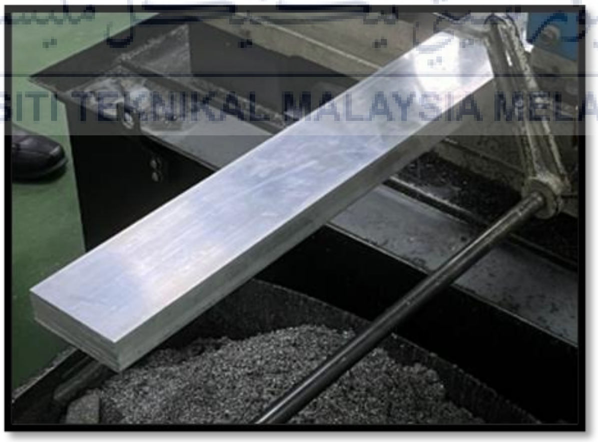


Figure 3. 2 Pure aluminium block

3.3.2 Abrasive

IMG Garnet is a not made of metal, naturally occurring mineral abrasive extracted from Almandine mineral deposit sources in Indian River and coastal bed mines. Almandine Garnet is the heaviest and hardest garnet type in its own group, making it a perfect abrasive grain for a variety of industrial applications. IMG Garnet is a genuine virgin almandine garnet from the gemstone family. Mesh 80 is the most common grade used for abrasive waterjet cutting. Abrasive waterjet cutting can cut any object such as steel, aluminium, marble, granite glass, rubber, plastic, and so on.

Ever Blast Systems SDN BHD located at 5A Jalan Panglima Hitam M 35/M , Alam Impian, Seksyen 35, 40470 Shah Alam, Selangor, is the company that manufactures this abrasive mesh.The abrasive used got from Edutech Supply & Services (supplier) located at No. 34, Jalan Lingkaran Mitc, Melaka International Trade Centre, 75450 Ayer Keroh, Melaka.

Figure 3. 3 Abrasive mesh 80

3.4 Equipment

3.4.1 Machine specification

Many academics choose abrasive waterjet (AWJ) because of its environmental friendliness, extensive processing flexibility, and cold processing(Wan *et al.*, 2023). Many researchers have undertaken abrasive jet processing tests on materials such as titanium alloys(Rabani *et al.*, 2016), brass(Hlaváč *et al.*, 2017), aluminium alloys(Ahmed *et al.*, 2018), engineered ceramics(Zhang *et al.*, 2022), carbon fibres(Sambruno *et al.*, 2019), and so on in recent years. A waterjet is a sort of cutting device that uses a high-pressure stream of water that is usually paired with an abrasive material to cut through a range of materials. The size and qualities of a waterjet might differ based on the model used and the company that makes it. Waterjets frequently run at high pressures, up to 50 000 psi (peak). This pressure range is referred to by the term "psi." Cutting speeds and the capacity to cut through tougher materials may both be boosted as pressure is increased. The waterjet system is dependent on the nozzle, which is a critical component. It is in charge of calculating the width of the water stream as well as the cutting precision. The nozzles diameter using by this waterjet machine is 1.0 mm. The detail specification of machine used to conduct this research are shown in table below

Machine	Waterjet cutting machine
Brand	Flow
Model	FLOW MACH 2 1313B
Table size	Width: 1,310.6 mm Length: 1,310.6 mm
Water cutting pressure	50 000 psi (max)
Nozzle	1.0 mm (diameter)
Software	• Flow Path – design software • Flow Cut – machine cutting software

Table 3. 1 Waterjet cutting machine specification

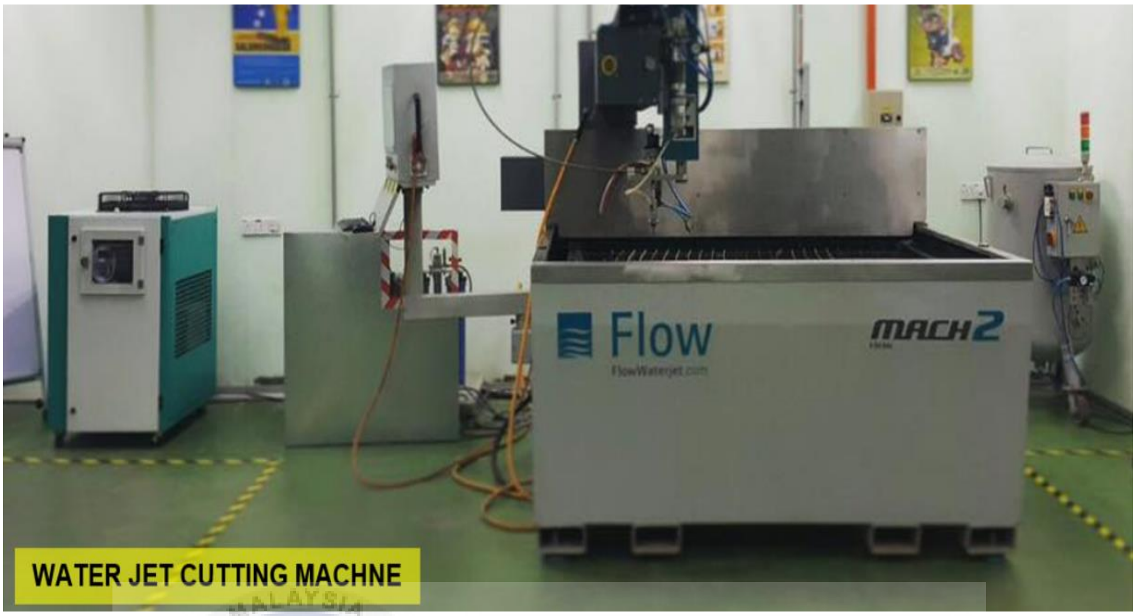


Figure 3. 4 Waterjet cutting machine

3.1.2 Work process abrasive waterjet

The work process of AWJM is follow the step below:

1 clamp the pure aluminium block on the table of the waterjet machine and make sure the block is tight.

2 set the nozzle position above the aluminium block to be cut which is X and Y value.

3 the distance cutting is set to 90 mm only to ensure that the finished sample does not fall into the machine.

4 insert the value of the parameter.

5 press X and Y home then click set current position as user home.

6 Click the low-pressure button then pump on

7 Wait for 10 seconds then click high pressure button.

8 wait until the meter's needle attach number 5 then click the cutting start button.

9 Wait until the process of cutting finish.

10 After the cutting process finish, make sure that nozzle is at home position by click x and y home then choose “go to the latest used defined home”.

11 Wait until the nozzle at home position.

12 To run next sample, offset the previous sample by adding 30 mm to x and y value.

13 Set the traverse speed, water pressure(thickness) and standoff distance according to the table of experiment.

14 Repeat step 4 to step 12 until all samples needed are done as figure 3.5 shown below.

Figure 3. 5 Sample cutting

3.5 Experiment setup

3.5.1 MINITAB version

Because parameter optimisation in abrasive waterjet is critical to achieving desired results, multiple approaches are employed to establish a link between experiment parameters and results. The statistical design of experiment (DOE) approach has proven a significant tool in this context for understanding the link between parameters and results. Even though it has been used in a variety of study fields, its application to abrasive waterjet of aluminium blocks remains an important area of study. In this research, the version of MINITAB used as shown in figure 3.6 below

Figure 3. 6 MINITAB version

3.5.2 Orthogonal arrays (2 level)

Lots of engineers today organise industrial trials utilising Taguchi's catalogue of orthogonal arrays. However, Taguchi offers either no or insufficient details on the procedures employed to generate these arrays. Furthermore, Taguchi shows orthogonal arrays in ways that differ from how these arrays are often shown in statistical literature. As a result, it is difficult to see the connections between Taguchi's arrays and the comparable ones published elsewhere. Recent ads and testimonials on the success of Taguchi's orthogonal array experiments add to the confusion by creating the idea that these arrays are anything other than fractional factorials and classical experiment designs. In this research, only 2 level use which is low level and high level.

3.5.2.1 Creating of orthogonal arrays

To choose sample locations for creating response surfaces to be employed in the optimisation process, orthogonal arrays were used. Orthogonal arrays can be utilised directly to determine design variables in the discrete design space. Design variables must have discrete values. In this part, we will look at how to utilise orthogonal arrays to generate a discrete design from a set of discrete data.

The uncontrolled optimisation issue of minimising surface roughness and kerf angle is considered. Consider a problem with three design variables to show the method. Let the variables' values be shown in Table x; that is, we have three design variables, each with two levels.

Variables / level	Thickness	Standoff distance	Traverse speed
Low	35	3	40
high	45	6	80

Table 3. 2 Variables value

The $L_8(2^3)$ orthogonal array can be used for the situation of three design variables. In this technique, just 8 design variable combinations are used shown in figure 3.7 to determine the number of experiments.

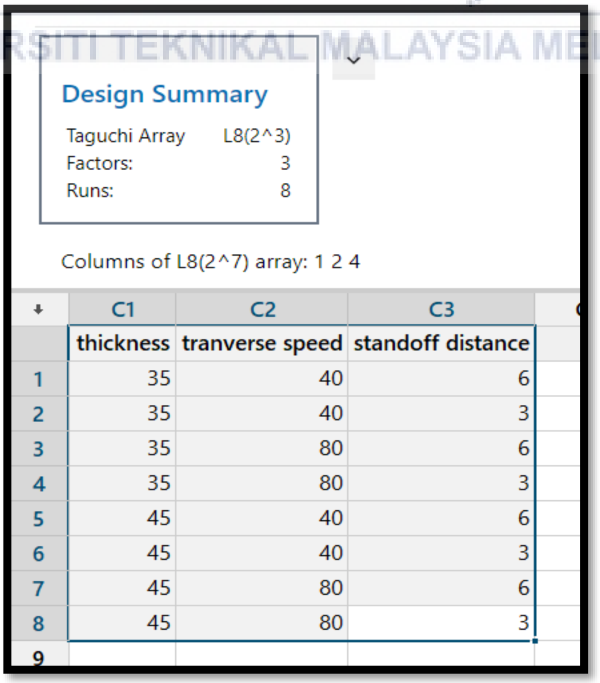
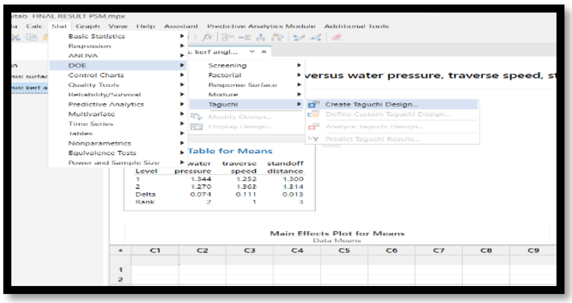
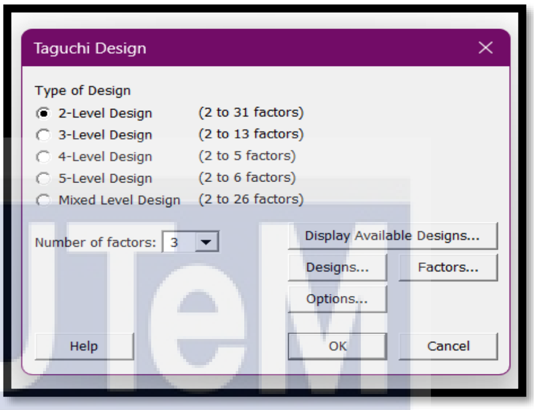
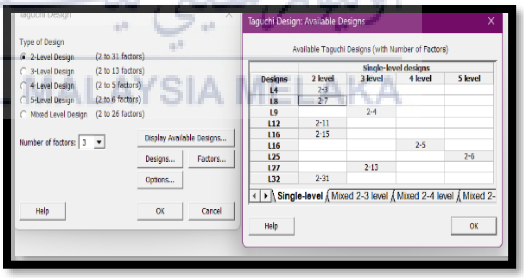
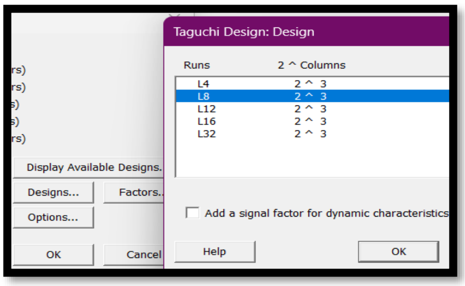


Figure 3. 7 Taguchi design of orthogonal array

3.5.2.2 Work process of creating orthogonal array

<table>
<tr><th></th><th>Instruction</th><th>picture</th></tr>
<tr><td>1</td><td>Open MINITAB, select stat, choose DOE, choose Taguchi then click create Taguchi design</td><td></td></tr>
<tr><td>2</td><td>This display will pop-out after step 1 is done. For type of design select 2-level design and make sure number of factors is 3 according to the number variable.</td><td>
</td></tr>
<tr><td>3</td><td>Click display available design and chose l8 (2-7) then click ok.</td><td></td></tr>
<tr><td>4</td><td>Click design then select L8 (2^3) then ok.</td><td>
</td></tr>
</table>

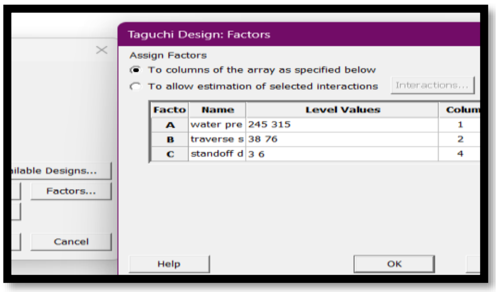
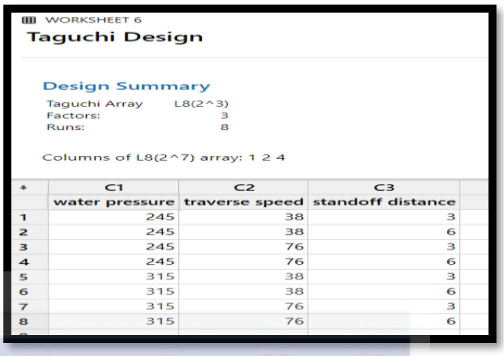
<table>
<tr><td>5</td><td>Click factor and insert all variable and value of the level, then click ok.</td><td>
</td></tr>
<tr><td>6</td><td>The orthogonal array will display</td><td>
</td></tr>
</table>

Table 3. 3 Work process of orthogonal array

3.5.3 Variable

Achieving excellent quality of surface and accurate kerf angles in the complex realm of abrasive waterjet machining necessitates careful consideration of several variables. These factors, which are critical in determining the process's result, have an independent impact on both surface roughness and kerf angle. The interaction of various elements, from standoff distance to waterjet pressure and traversal speed, carefully forms the final outcome. Understanding how each variable affects surface quality and kerf geometry is critical for operators seeking the delicate balance of cutting speed and precision.

The variable use for this research is water pressure, traverse speed and the last is standoff distance. This variable was selected based on the reading of the article published by the researchers before that related to the most parameter that impact the process output. Figure below shown the weighted distribution of the AWJ cutting input process parameters

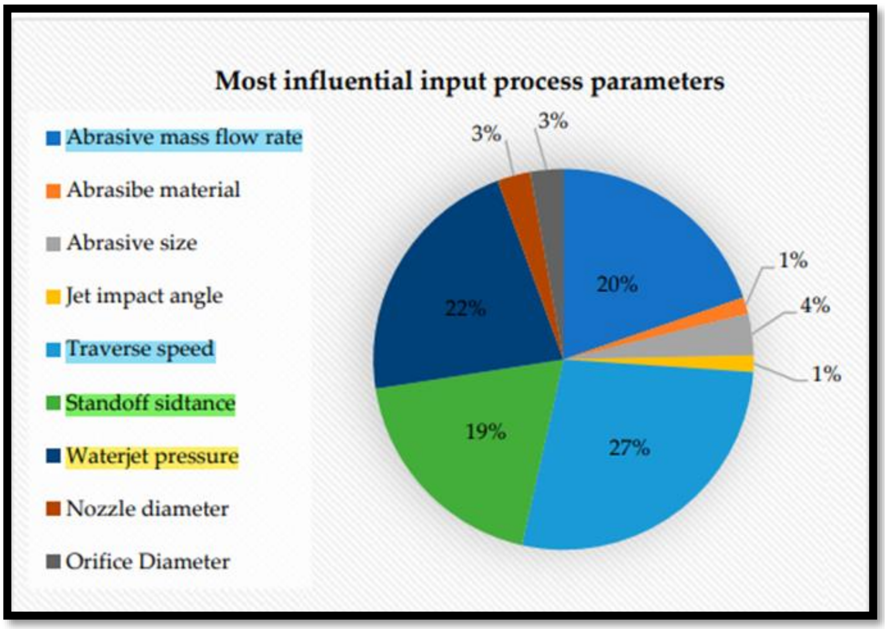


Figure 3. 8 Survey of identified most influential AWJ cutting input process parameters reviewed publications from 2017 to 2020 (Llanto *et al.*, 2021c)

The most significant factors in abrasive waterjet cutting, according to the pie chart above, are traverse speed, waterjet pressure, standoff distance, and abrasive mass flow rate. However, just three variables were chosen for this thesis. Finding the correct combination between these factors is a complex task, requiring operations to achieve the desired surface quality and kerf geometry adapted to specific material characteristics and machining requirements.

The traversal speed of a waterjet nozzle determines its route across the material's surface, leaving behind a narrow channel known as the kerf. However, unlike a tightrope's predetermined span, the topography of the cut is a ballet of accuracy and force, with traversal speed playing a critical part in shaping the ultimate output. Increased traversal speeds reduce the amount of time each abrasive particle spends etching into the material. This results in a smoother overall surface with no deep grooves or gouges.

Water pressure, a crucial factor, determines the force with which abrasive particles are driven into the material surface. The sheer force of high pressure can create unsightly markings on the surface. This might result in a harsher surface quality, particularly on softer materials. Higher pressure can cause the kerf at the bottom to widen, resulting in less accurate cuts and perhaps impacting dimensional accuracy.

The standoff distance, or the distance that lies between the nozzle and the workpiece, influences the focus and dispersion of the jet. An proper standoff distance is critical for balancing cutting efficiency and surface quality. An ideal standoff distance keeps the abrasive-laden water firmly bundled, maximising its cutting power. Maintaining the proper distance also prevents the jet from splattering or losing concentration, so reducing the destructive force on the material's surface. This results in a smoother surface finish, which is especially important for fragile materials.

3.5.4 Fix factor

By exploiting certain fixed factors, this thesis grounds its study inside carefully set limitations. These main factors, namely nozzle diameter, abrasive flow rate, and abrasive size, serve as the basis close to which the investigation of abrasive waterjet machining is built, offering a systematic framework for detailed analysis.

The first fixed component, nozzle diameter, affects the size of the waterjet stream and hence effects the precision and complexity of the cuts. A smaller nozzle diameter may result in finer details, but it can also affect the velocity of material removal. The nozzle diameter use in this experiment is 1.0 mm.

The number of abrasive particles driven by the waterjet is governed by the second fixed component, abrasive flow rate. This setting has a direct influence on cutting efficiency and material removal. Controlling the abrasive flow rate precisely is critical for achieving best outcomes in terms of surface quality and productivity.

The third fixed component is abrasive size, which relates to the diameters of the abrasive particles. The size of these particles has a considerable impact on their cutting capacity and the surface roughness that results. Finer finishes are produced by smaller abrasive particles, although bigger particles may be more efficient for quick material removal. The abrasive size use is abrasive mesh 80.

By keeping these elements constant throughout the thesis, this study attempts to determine the variables contributions while also understanding their influence on the abrasive waterjet machining process.

3.6 Characterization

3.6.1 Surface roughness

Evaluation of surface quality entails measuring surface roughness with appropriate instruments, such as profilometers or surface roughness analysers. For representative results, measurements are collected at multiple locations along the cut surface. Profilometers or surface roughness analysers are used to measure the surface's structure. They supply quantitative data on parameters such as Ra (average roughness), Rz (average maximal height), and Rq (root mean square roughness), providing an objective measurement of surface quality.

Figure 3. 9 Surface roughness machine

This surface roughness machine brand is Mitutoyo, Surf test SJ-301, with code 178-602 and serial number 335250708, and it was manufactured in Japan. The tester machine does not require annual maintenance, but it must be calibrated before performing a surface test according to the value Ra shown in figure below. The test can be started after the calibration done when the value of Ra has been set.

Figure 3. 10 Calibration value of surf test

This surface roughness test used the standard of ISO 4287:1997. ISO 4287:1997 is the chosen standard for surface roughness testers because to its global acceptability, detailed parameter definitions, precise measurement standards, compatibility with instrument manufacturers, broad applicability across industries, and frequent updates. Its global acceptance provides uniformity in measurements, boosting commerce and collaboration. The standard covers a wide range of roughness characteristics, allowing for precise surface characterization for a variety of applications. It also establishes clear standards for measuring processes, providing consistent and comparable findings. Most surface roughness tests are built to comply with ISO 4287:1997, which promotes consistency. Furthermore, the standard is revised on a regular basis to integrate technology advances and address industry demands, assuring its continued relevance and the accuracy.

3.6.2 Profile projectile

Kerf angle evaluation is performed by measuring the angle at specific locations on the cut surface. These measurement systems are precise and dependable. Besides that, by projecting the profile of the cut surface onto a screen or digital display, profile projectors also may be used to measure the kerf angle. This method permits visual inspection and angle measurement.

A profile projector, also known as an optical comparator, is a precision measuring equipment used for inspecting and measuring microscopic objects with fine features. This optical comparator(vertical) machine is produced by S-T Industries, Inc and it was manufactured in united state. The model for this vertical optical comparator 20-4600. This machine required maintenance. This machine was purchased in 2002 and the last date calibration of this machine is 18/04/2017. The calibration of this machine performed by SENDI MAHIR SDN. BHD.

Figure 3. 11 Optical comparator(vertical)

Profile projectors, like any precision equipment, require routine maintenance to maintain precise and dependable performance. Here are some of the reasons why maintenance is required because maintenance include complete checks and changes to ensure appropriate alignment of the optical system and that the projected picture perfectly represents the characteristics of the measured part. Additionally, the light source must be calibrated to guarantee consistent and exact lighting, and the stage that holds the item must be calibrated on a regular basis to assure precision. Cleaning and inspection are required to eliminate dust and debris that might develop on the optics and negatively impact image quality. The focusing mechanism and magnification settings should be checked and changed on a regular basis. Because profile projectors are sensitive to environmental variables, keeping a regulated atmosphere is critical. Routine maintenance also includes lubrication of moving parts and inspections on digital components or software, if available. Overall, regular maintenance makes sure the profile projector performs properly, giving clear and dependable measurements for quality control and inspection.

3.7 Summary

In conclusion, the method employed to improve surface quality and kerf angle during single-pass abrasive waterjet cutting of an aluminium block is essential for achieving improved cutting outcomes. By employing a methodical methodology, the study was able to achieve its research objectives and provide valuable insights for optimizing the cutting process.

The experimental design included the identification of critical parameters that influence surface quality and taper angle, such as water pressure, material thickness, standoff distance, and traverse speed. The selection of these parameters was based on their prospective impact on the cutting performance.

An orthogonal array was selected to ensure a balanced and effective distribution of experimental trials. The selected values for the design parameters encompassed a meaningful range and were practically realizable, allowing for a thorough evaluation of their effects. Throughout the experiments, measurements of surface quality and taper angle were scrupulously recorded for each parameter combination. This diligent data collection enabled a precise and trustworthy analysis of the obtained results.

Finally, the methodology utilized in this study to improve surface quality and reduce taper angle in single-pass abrasive waterjet cutting of an aluminium block demonstrated a methodical and rigorous approach. The careful selection of design parameters, use of an orthogonal array, statistical analysis, optimization procedure, and validation steps all contributed to the achievement of the research goals. This study's findings provide valuable insights and recommendations for optimizing the abrasive waterjet cutting process on aluminium blocks, thereby paving the way for enhanced cutting efficiency and quality in industrial applications.

CHAPTER 4

RESULTS

4.1 Introduction

Due to its ability to precisely cut a broad variety of materials, abrasive waterjet cutting has become a versatile and effective cutting method in numerous industries. When applied to aluminium blocks, it offers several benefits, including enhanced surface quality and reduced taper angles compared to conventional cutting techniques. The results of this research section demonstrate a comprehensive analysis of surface development and kerf improvements obtained by single-pass abrasive waterjet cutting on an aluminium block. Because of its adaptability and efficiency in cutting a wide range of materials, abrasive waterjet technology is increasingly being used in machining operations. Understanding the details of the cutting process is critical for optimising the results of production in the context of aluminium, a material recognised for its lightweight and corrosion-resistant qualities.

Abrasive waterjet cutting, on the other hand, uses a high-pressure jet of water containing abrasive particulates to erode the material, resulting in a smoother surface finish. By the process parameters and optimizing the cutting conditions, we expect to significantly improve the aluminium block's surface quality. Due to its inherent precision and control, single-pass abrasive waterjet cutting has the potential to reduce taper angles in comparison to conventional cutting techniques. This enhancement would result in more precise dimension control and straighter incisions.

The goal of the study is to provide information on the unique mechanisms and consequences related with single-pass abrasive waterjet cutting on aluminium, with a focus on surface quality and kerf characteristics. This study's experimental technique includes are systematic research focused on characteristics such as waterjet pressure, traverse speed, and standoff distance. These characteristics are critical drivers of the cutting process's overall effectiveness and efficiency.

This section reveals significant insights into the influence of process factors on surface formation and kerf dimensions by diving into the outcomes of the abrasive waterjet cutting tests. The findings provided here not only add to our understanding of the complex interplay between cutting parameters and material reactions, but they also have important implications for optimising the abrasive waterjet cutting process on aluminium surfaces. As we dig further into the details, we'll get a deeper comprehension of the elements impacting surface quality and kerf characteristics, opening the path for developments in precision machining and manufacturing methods.

4.2 Parameter used

The parameter used for research to run the experiment is water pressure, standoff distance and traverse speed. Initially, traversal speed was expressed as a percentage, with 80% for high level and 40% for low level. To convert the percentage value to the real value of traverse speed, the value of traverse speed is collected when the sample is cut. When utilising a high-level percentage, the number for traverse speed is 76 mm/min, thus to find the value for 40%, divide 76 by 2. As a result, the traversal speed at the lowest level is 38 mm/min. For the water pressure value, we use a material thickness of 35 mm for low level and 45 mm for high level. during a cut of 45 mm, water pressure shows a value of 315 MPa. to get the value for low level, the value of 315 MPa must be divided by 45mm and then multiplied by 35 mm equal to 245 MPa and the value of standoff distance for low and high level is 3 mm and 6 mm respectively. Table 4.1 shows the value of low level and high level for each parameter used.

variables / level	Water pressure (MPa)	Standoff distance(mm)	Traverse speed (mm/min)
Low	245	3	38
High	315	6	76

Table 4. 1 Parameter value

4.3 Orthogonal array based on the parameters

Based on the value of parameter, the table of orthogonal array were generated to reduce the number of experiments. Table 2 below show the orthogonal array produced by Taguchi method.

Design of experimental Orthogonal array	Water pressure (MPa)	Traverse speed (mm/s)	Standoff distance (mm)
1	245	38	3
2	245	38	6
3	245	76	3
4	245	76	6
5	315	38	3
6	315	38	6
7	315	76	3
8	315	76	6

Table 4. 2 Orthogonal array produced by Taguchi method

4.4 Experimental result

4.4.1 Experimental result on surface roughness

Surface roughness is an important characteristic in manufacturing and materials science, impacting the quality and functioning of machined components. This section is focus on the surface roughness examination of eight different samples in this work, using a complete technique that includes the determination of average values generated from ten separate trials for each sample. The main objective of this comprehensive analysis is to provide an accurate and got a reliable data for generating very precise results.

The utilisation of many trials for each sample has been chosen to reflect the inherent variety in surface texture that may occur within a particular material. This method is especially useful for reducing the impact of abnormalities and ensuring that the estimated average surface roughness is a more trustworthy and accurate assessment of true surface quality. Averaging several trial measurements improves the statistical robustness of the data, providing a more thorough and precise value of surface roughness. The value for the surface roughness 10 trial for 8 sample are shown in table 4.3 below.

Sample / Trial	1	2	3	4	5	6	7	8
1	4.81	4.84	4.81	4.94	4.28	4.83	5.31	5.28
2	5.05	5.59	4.2	4.4	3.72	4.68	5.22	4.11
3	5.08	4.71	4.87	5.73	3.6	5.08	5.03	5.89
4	5.12	5.5	4.89	5.39	4.13	5.18	4.99	4.59
5	5.01	5.17	4.79	4.98	4.71	4.37	4.86	4.72
6	4.91	4.86	4.26	6.3	4.11	4.05	4.41	5.51
7	4.64	4.92	5.08	5.01	4.6	4.69	5.17	5.18
8	5.41	4.8	5.12	4.9	4.55	4.65	5.34	4.81
9	5.2	4.65	4.42	4.91	4.24	4.08	4.62	6.07
10	4.8	4.7	5.34	5.06	4.23	4.88	4.9	5.2
Average	5.003	4.974	4.778	5.162	4.217	4.649	4.985	5.136

Table 4. 3 Average value of surface roughness

From the average value obtain, the value was insert to MINITAB software as shown in table 4.4 below to analysis the result using Taguchi design. To analyse the data, click stat then choose DOE (design of experiment), choose Taguchi method and choose analyses Taguchi design.

Design of experimental Orthogonal array	Water pressure (MPa)	Traverse speed (mm/min)	Standoff distance (mm)	Surface roughness (Ra) µm
1	245	38	3	5.003
2	245	38	6	4.974
3	245	76	3	4.778
4	245	76	6	5.162
5	315	38	3	4.217
6	315	38	6	4.649
7	315	76	3	4.985
8	315	76	6	5.136

Table 4. 4 Inserted value of surface roughness in MINITAB

4.4.1.1 Taguchi analysis on surface roughness

Surface roughness is one of the most essential factors for determining how rough a workpiece material has been processed. The machined surface is smoother near the jet entry and gradually gets rougher towards the jet exit, according to all research. This is because as the particles go downward, they lose kinetic energy and their cutting ability deteriorates. By analysing the experimental data of all the selected materials, it was discovered that the optimal selection of the three basic parameters, namely, water pressure, nozzle traverse speed, and nozzle standoff distance, is critical in controlling process outputs such as surface roughness. Figure 4.1 show the effect of water pressure, traverse speed and the standoff distance on surface roughness.

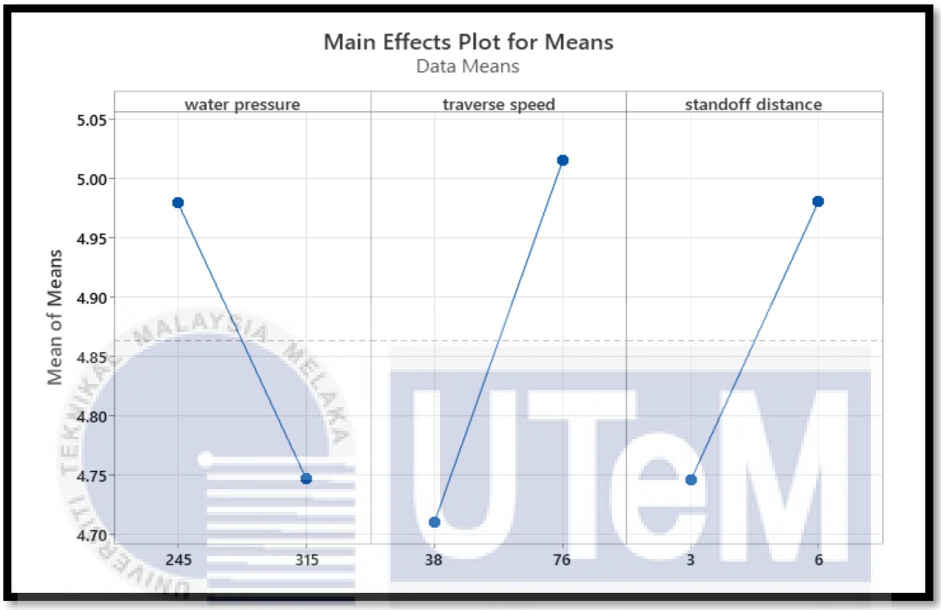


Figure 4. 1 Surface roughness versus water pressure traverse speed, standoff distance

4.4.1.2 Effect of water pressure on surface roughness

Figure 4.1 depicts the effect of water pressure as a process parameter. This evolution appears to be linear, as Ra decreases with increasing water pressure. This decrease in Ra can be attributed to the increased forces caused by the increased pressure. Therefore, greater pressure necessitates greater energy to eliminate surface irregularities, resulting in a superior surface quality. Surface roughness has a negative relationship with water pressure, as water pressure rises, the surface roughness decrease. This is the same of what we would expect in water jet cutting, where increased pressure should result in smoother surfaces.

4.4.1.3 Effect of traverse speed on surface roughness

Figure 4.1 depicts the relationship between traversal speed and surface quality. Surface roughness has a negative relationship with traverse speed, as traverse speed increases, surface roughness decreases. Slower rates enable the water jet more time to remove material efficiently and provide a smoother surface, which is an expected trend. The abrasive particulates have more time to act on the material at slower traverse velocities, resulting in a smoother surface. However, excessively slow traverse velocities may result in excessive attrition or material deformation, resulting in a rougher surface. Extremely high traverse speeds, on the other hand, can affect the cutting action, resulting in poor surface quality and increased irregularity.

4.4.1.4 Effect of standoff distance on surface roughness

Figure 4.1 demonstrates that this parameter has a significant impact on the surface roughness. Refer to figure 4.1, Ra changes from 4.75 µm to 4.98 µm with as little as a 3mm different in standoff distance. The surface roughness decreases dramatically as the standoff distance increases, with the increase being greater at larger standoff distances. Nonetheless, its influence is almost linear in nature. Therefore, a greater standoff distance necessitates that surface irregularities be removed with this reduced velocity and pressure, resulting in a rougher surface.

4.4.1.5 Variable ranking on surface roughness

Based on the figure 4.2, response table for mean analyses from Taguchi method for surface roughness, the most parameter that influence the cutting process is traverse speed, next is standoff distance and the last one is water pressure.

Response Table for Means

Level	water pressure	traverse speed	standoff distance
1	4.979	4.711	4.746
2	4.747	5.015	4.980
Delta	0.232	0.304	0.235
Rank	3	1	2

Figure 4. 2 Response table for surface roughness mean

Traverse speed has the largest Delta value (0.304), suggesting the biggest variance in average surface roughness across its levels (38 mm/min and 76 mm/min). This implies that adjusting the traverse speed has the greatest influence on average surface roughness. The second greatest Delta value (0.235) is for standoff distance, indicating that it has a moderate influence on average surface roughness. Increasing the standoff distance from 3 mm to 6 mm results in a significantly rougher surface and the last one is Water pressure has the least Delta value (0.232), suggesting the smallest variation in average surface roughness between its two levels (245 MPa and 315 MPa). This implies that within the studied range, altering the water pressure has the least significant effect on average surface roughness. Increasing the water pressure from 245 MPa to 315 MPa results in a somewhat smoother surface

4.4.2 Experimental result on kerf angle

The kerf angle, a critical parameter in abrasive water jet cutting, has a large impact on the precision and quality of machined components. The focus of this work is on the comprehensive evaluation of kerf angles in eight different samples, using a systematic technique that includes computing the average values based on five unique trials for each specimen. Through rigorous and frequent measurements, the major goal of this work is to get a very accurate approximation of the kerf angle shown by these materials. The value for the kerf angle 5 trial for 8 sample are shown in table 4.5 below.

Sample / Trial	1	2	3	4	5	6	7	8
1	1.14	1.55	1.48	1.26	1.03	1.27	1.26	1.18
2	1.18	1.11	1.5	1.1	1.05	1.41	1.37	1.38
3	1.23	1.37	1.43	1.51	1.06	1.29	1.4	1.36
4	1.27	1.43	1.55	1.32	1.24	1.34	1.43	1.25
5	1.33	1.27	1.45	1.4	1.26	1.2	1.35	1.27
Average	1.23	1.346	1.482	1.318	1.128	1.302	1.362	1.288

Table 4. 5 Average value of kerf angle

From the average value obtain, the value was insert to MINITAB software as shown in table 4.6 below to analysis the result using Taguchi design. To analyse the data, click stat then choose DOE (design of experiment), choose Taguchi method and choose analyses Taguchi design.

sample	Water pressure (MPa)	Traverse speed (mm/min)	Standoff distance (mm)	Kerf angle
1	245	38	3	1.23
2	245	38	6	1.346
3	245	76	3	1.482
4	245	76	6	1.318
5	315	38	3	1.128
6	315	38	6	1.302
7	315	76	3	1.362
8	315	76	6	1.288

Table 4. 6 Inserted value of kerf angle in MINITAB

4.4.2.1 Taguchi analysis on kerf angle

The kerf angle is critical to determining the geometry and accuracy of the cut. The angle at which the abrasive water jet contacts with the workpiece, known as the kerf angle, has a considerable impact on the ultimate form and quality of the machined material. Understanding and managing the kerf angle is critical for making precise cuts and maximising material utilisation in a wide range of industrial applications.

By analysing the experimental data of all the selected materials, it was discovered that the optimal selection of the three basic parameters, namely, water pressure, nozzle traverse speed, and nozzle standoff distance, is critical in controlling process outputs such as kerf angle. Figure 4.3 show the effect of water pressure, traverse speed and the standoff distance on kerf angle.

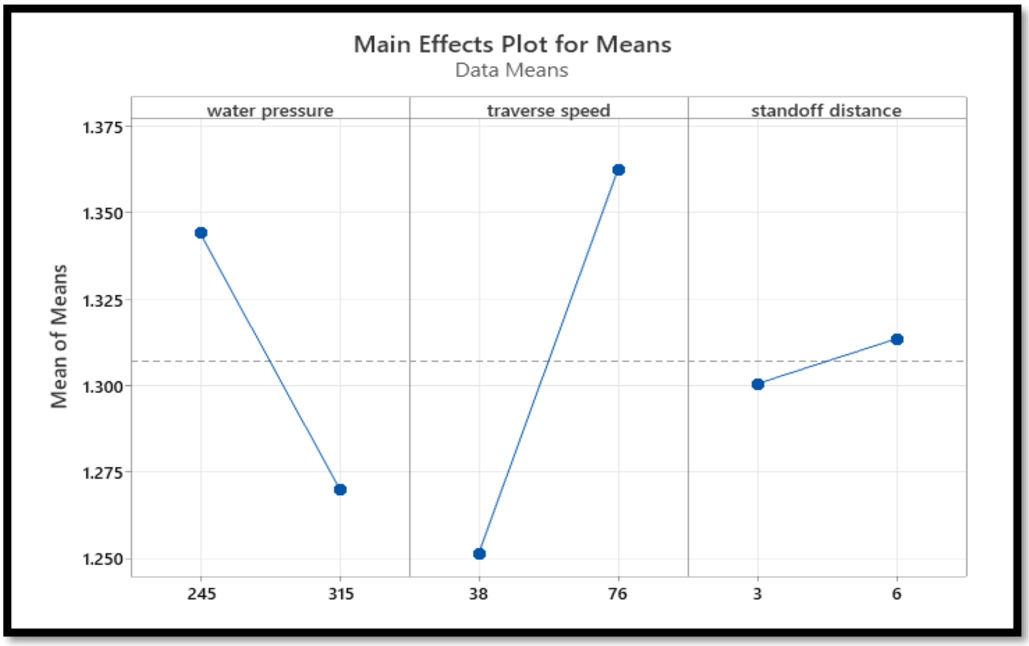


Figure 4. 3 Water pressure, traverse speed, and standoff distance vs kerf angle

4.4.2.2 Effect of water pressure on kerf angle

The effect of water pressure as a process parameter has negative relationship with kerf angle. Figure 4.3 indicates that, within the designated operating range, an increase in water pressure causes a decrease in kerf taper angles. When water pressure is increased, the jet kinetic energy increases that leads to a high momentum transfer of the abrasive leading to a decrease in kerf taper angle.

4.4.2.3 Effect of traverse speed on kerf angle

Lower traverse speed typically produced smoother cuts with decreased taper angles. This is because slower traverse rates give abrasive particulates more time to uniformly erode the material. As the cutting action becomes less precise and concentrated, higher traverse velocities can result in greater taper angles. Figure 4.3 indicated that at lower traverse speed the kerf angle also decreased.

4.4.2.4 Effect of standoff distance on kerf angle

In general, the kerf angle tends to increase as the standoff distance increases. As the distance between the nozzle and the surface of the workpiece increases, the stream of water and abrasive particulates spreads out and disperses more. From the figure 4.3, when the distance of standoff is 3 mm, the kerf angle is about 1.300 degree then increase to 1.314 degree when the standoff distance is 6mm. This value also show in figure 4.4 response table for means for the lowest and the highest value plotted.

4.4.2.5 Variable ranking on kerf angle

Based on the figure 4.4, response table for mean analyses from Taguchi method for kerf angle, the most parameter that influence the cutting process is traverse speed, next is water pressure and the last one is standoff distance.

Response Table for Means

Level	water pressure	traverse speed	standoff distance
1	1.344	1.252	1.300
2	1.270	1.363	1.314
Delta	0.074	0.111	0.013
Rank	2	1	3

Figure 4. 4 Response table for surface roughness mean

The data shows that the greatest change is in traversal speed, followed by a moderate change in water pressure and a tiny change in standoff distance. Traverse Speed is ranked first with a delta of 0.111, indicating that the difference in traverse speed between the two levels is the greatest of the three variables. Water Pressure ranks second with a delta of 0.074, suggesting a moderate difference in water pressure across levels. This indicates a noticeable, but not drastic, difference in pressure and standoff distance is ranked third with a delta of 0.013, indicating a minor difference in standoff distance across levels. This shows that there is little to no change in the distance maintained between items.

4.6 Result discussion

Our examination into the parameters that have a significant influence on surface quality and kerf angle during abrasive waterjet cutting on aluminium blocks produced interesting results. Water pressure, traversal speed, and standoff distance all played important roles in altering surface quality and kerf angle, according to extensive research and analysis. Understanding these essential factors serves as the foundation for later optimisation attempts and gives vital insights into the machining process's complexities.

Using the Taguchi method's orthogonal matrix, we systematically optimised the discovered key factors to improve both surface quality and taper angle. The Taguchi method's robust design of trials enables us to quickly examine a wide variety of parameter combinations. The optimised settings produced from this methodology not only increased surface quality but also reduced taper angles, demonstrating the Taguchi method's usefulness in reaching optimal cutting conditions. The organised character of the Taguchi approach allowed for a thorough investigation of the parameter space, which resulted in enhanced machining results.

This study discovered the optimum attainable surface roughness and taper angle on the cutting surface of aluminium blocks. This phase was critical in demonstrating that the optimised parameters produced from the Taguchi approach did indeed result in improved machining results. The scope study established benchmarks for future optimisation efforts and industry standards by providing a quantitative estimate of the top bounds of possible surface quality and minimal taper angles. This thorough assessment leads to a more nuanced knowledge of the capabilities and limitations of the abrasive waterjet cutting process on aluminium.

4.6.1 Combination parameter on surface roughness

Based on table 4.4, the best combination of 315 MPa water pressure, 38 mm/min traverse speed, and 3 mm standoff distance appears to give the lowest surface roughness (Ra) in this experiment. The average Ra value for this combination is 4.217 µm, which is lower than the average Ra value for all other combinations.

Based on the table 4.4, the worst parameter combination for surface roughness (highest Ra) appears to be is experimental number 4 with combination of 245Mpa water pressure, 76 mm/min traverse speed and 6mm standoff distance. This combination has an average Ra value of 5.125 µm, which is the highest among all eight runs in the table. Here's why these parameters contribute to worse surface roughness.

It should be noted that these results are based on a small sample of eight runs only. More tests with a wider variety of parameter values may be required to confirm the observed patterns and develop stronger conclusions.

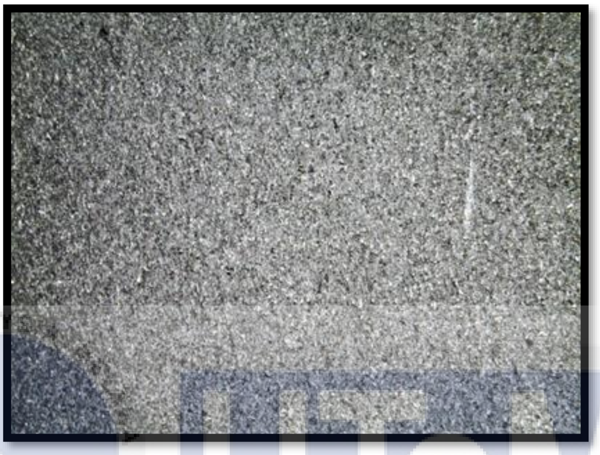


Figure 4. 5 The best surface roughness (4.217 µm)

Figure 4. 6 The worst surface roughness (5.162 µm)

4.6.2 Combination parameter on kerf angle.

Based on table 4.6, the best combination of 315 MPa water pressure, 38 mm/min traverse speed, and 3 mm standoff distance appears to give the lowest kerf angle in this experiment. The average kerf angle value for this combination is 1.128 degree, which is lower than the average angle value for all other combinations.

The worst parameter combination for kerf angle (highest number of degree) appears to be is experimental number 3 with combination of 245Mpa water pressure, 76 mm/min traverse speed and 3mm standoff distance. This combination has an average angle value of 1.482 degree, which is the highest among all eight runs in the table. Here's why these parameters contribute to worse surface roughness.

It should be noted that these results are based on a small sample of eight runs only and this result is also different with other research because the value will not same depend to the machine used, material used and other variables. More tests with a wider variety of parameter values may be required to confirm the observed patterns and develop stronger conclusions.

4.5 Summary

These expected outcomes may differ depending on variables such as the cutting system used, the qualities of the aluminium block, and the required cutting settings. To achieve the desired surface quality and taper angle, as well as to enhance the process, experimental testing and optimisation are usually necessary. Furthermore, when assessing the effectiveness of the cutting technique, it is critical to consider the application-specific needs. A machined part's appropriate surface roughness and taper angle values are determined by its intended application, standard practices, and cost factors. It is feasible to produce increased surface quality and lower taper angles during single-pass abrasive waterjet cutting of an aluminium block by carefully adjusting the water pressure, traverse speed, and standoff distance.

CHAPTER 5

CONCLUSION

5.1 Introduction

As we approach the finish line of our investigation into the complicated topic of single-pass abrasive waterjet cutting on aluminium blocks, this final segment provides a chance to synthesise a variety of insights and discoveries that have emerged throughout the course of our study. The focus on surface formation and kerf improvements has led us to a thorough analysis of the relationship between process factors and the final characteristics of machined aluminium surfaces. This journey has been distinguished by an in-depth analysis of the complexities involved in obtaining accuracy and efficiency in the cutting process.

5.2 Parameters that significant impact surface quality and the kerf angle

Through a systematic investigation, the crucial factors that have a significant effect on surface quality and kerf angle during abrasive waterjet cutting of aluminium blocks has been determined. Our findings highlight the complex link between process factors and machining characteristics. Traverse speed has emerged as a critical contributor to the observed variances in surface quality and kerf angle. This comprehension creates the framework for focused optimisation and improvement in future goals.

5.3 Optimize the parameters using an orthogonal matrix of Taguchi method

There effectively improved the identified significant parameters using the Taguchi method's advanced design of experiments tool. The orthogonal matrix allowed for a systematic investigation of the parameter space, which resulted in the identification of optimal settings for improved surface quality and reduced kerf angle. Our findings demonstrate the Taguchi method's usefulness in achieving robust optimisation, opening the door for increased efficiency and precision in abrasive waterjet cutting operations.

5.4 The best achievable surface roughness and kerf angle on cutting surface.

I successfully identified the best achievable surface roughness (4.127 µm) and kerf angle (1.128 degree) on the cutting surface of aluminium blocks using an analytical analysis. This goal served as a critical validation step, verifying the efficacy of the Taguchi method-determined optimised parameters. The scope analysis results give a clear grasp of the top limits of possible surface quality and kerf angle, acting as helpful benchmarks for future efforts to optimise abrasive waterjet cutting operations. the best parameter by using high level of water pressure and low level for traverse speed and standoff distance.

5.5 Summary

In this conclusion, machinability of the pure aluminium block material is experimented for desired machining quality. The effects of key parameters such as water pressure, traverse speed, and standoff distance which are controlling the surface quality and kerf angle are studied. In this conclusion, we explore the key objectives that guided our research and track the progress of our understanding of surface development and kerf improvements. This study's findings not only provide insight on the hidden dynamics of abrasive waterjet cutting on aluminium, but they also have larger implications for the manufacturing and material processing sectors. The combination of these crucial elements serves to distil the core of our study, creating a cohesive narrative that explains the relevance of our findings.

Attaining all these goals not only improves our understanding of the intricate mechanics of abrasive waterjet cutting on aluminium blocks, but also gives practical insights for optimising settings and producing improved machining results. This work is a notable contribution to the field of materials processing and precision machining because of its synergistic approach to parameter discovery, optimisation, and validation.

5.6 Recommendation

Several recommendations arise from the complete analysis into surface quality and kerf angle optimisation during single-pass abrasive waterjet cutting on aluminium blocks to guide future research and practical applications.

5.6.1 Deepen the dive.

Firstly, deepen the dive, which is provide more study into the complex relationships between many parameters impacting surface quality and kerf taper angle is required to advance our understanding of abrasive waterjet cutting processes. Further investigation may reveal hidden synergies or trade-offs, offering significant insights that can lead to even more accurate and efficient cutting results. Exploring the complicated interaction of various elements can help to optimise the overall optimisation approach and raise the level of complexity of abrasive waterjet cutting procedures.

5.6.2 Expand studies.

Second, expand studies to include a greater variety of parameter combinations and their respective affects is critical for obtaining complete optimisation. Researchers can find the ideal cutting settings by investigating a broader range of situations. For example, make 4 variables at 3 level design. This method not only improves awareness of ideal process conditions, but it also helps to develop a solid framework for getting superior outcomes in abrasive waterjet cutting applications.

5.6.3 Material used.

Next, variables the material used such as aluminium and composite. This reason is to take a wider look, researchers ought to expand their study beyond a particular aluminium alloy to better understand how diverse materials react to waterjet cutting. This extensive investigation will allow cutting procedures to be tailored to the specific properties of various materials, providing a versatile and adaptable methodology for a wide range of tasks.

5.6.4 Alternative method

Besides, is consider other alternative method such as laser cutting. While abrasive waterjet cutting is a strong technology, experimenting with other cutting methods such as laser or plasma cutting may provide significant insights into the advantages and disadvantages of each method. Comparative studies help researchers choose the best strategy for certain applications by providing a full overview of cutting-edge technology.

In conclusion, the recommendations for study and optimisation of abrasive waterjet cutting operations on aluminium blocks highlight the detailed character of this complex machining approach. In essence, these recommendations would accelerate the study and optimisation of abrasive waterjet cutting on aluminium blocks, directing future efforts towards accuracy, adaptability, sustainability, and the continuous progress of machining processes. The synergistic implementation of these ideas has the potential to not only improve our understanding of abrasive waterjet cutting, but also to influence the trajectory of machining technologies in the wider field of materials processing.

REFERENCES

Ahmed, T.M. *et al.* (2018) 'Improving surface roughness of abrasive waterjet cutting process by using statistical modeling', *CIRP Journal of Manufacturing Science and Technology*, 22, pp. 30–36. Available at: https://doi.org/10.1016/j.cirpj.2018.03.004.

Anu Kuttan, A., Rajesh, R. and Dev Anand, M. (2021) 'Abrasive water jet machining techniques and parameters: a state of the art, open issue challenges and research directions', *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. Springer Science and Business Media Deutschland GmbH. Available at: https://doi.org/10.1007/s40430-021-02898-6.

Chen, L., Siorest, $ E and Wong, W.C.K. (1996) *0890-6955(95)00108-5 KERF CHARACTERISTICS IN ABRASIVE WATERJET CUTTING OF CERAMIC MATERIALS, Int. J. Mach. Tools Manufact*.

Chithirai Pon Selvan, M., Mohana Sundara Raju, N. and Sachidananda, H.K. (2012a) 'Effects of process parameters on surface roughness in abrasive waterjet cutting of aluminium', *Frontiers of Mechanical Engineering*, 7(4), pp. 439–444. Available at: https://doi.org/10.1007/s11465-012-0337-0.

Chithirai Pon Selvan, M., Mohana Sundara Raju, N. and Sachidananda, H.K. (2012b) 'Effects of process parameters on surface roughness in abrasive waterjet cutting of aluminium', *Frontiers of Mechanical Engineering*, 7(4), pp. 439–444. Available at: https://doi.org/10.1007/s11465-012-0337-0.

Dadgar, M. *et al.* (2023) 'Reduction of Taper Angle and Jet Trailback in Waterjet Cutting of Complex Geometries by a Revised Model of the Process Control', *Procedia CIRP*, 117, pp. 20–25. Available at: https://doi.org/10.1016/j.procir.2023.03.005.

Deaconescu, A. and Deaconescu, T. (2021a) 'Response surface methods used for optimization of abrasive waterjet machining of the stainless steel x2 crnimo 17-12-2', *Materials*, 14(10). Available at: https://doi.org/10.3390/ma14102475.

Deaconescu, A. and Deaconescu, T. (2021b) 'Response surface methods used for optimization of abrasive waterjet machining of the stainless steel x2 crnimo 17-12-2', *Materials*, 14(10). Available at: https://doi.org/10.3390/ma14102475.

Gupta, V. *et al.* (no date) *Analysis of Kerf Taper Angle in Abrasive Water Jet Cutting of Makrana White Marble*. Available at: www.trp.org.in.

Hi T Hi R A I Po, M.C., El V A, S. and Sachidananda, H.K. (no date) 'AN INVESTIGATION ON SURFACE ROUGHNESS IN ABRASIVE WATER JET CUTTING OF BRASS', *Global Journal of Advanced Engineering Technologies* [Preprint].

Hlaváč, L.M. *et al.* (2017) 'Precision comparison of analytical and statistical-regression models for AWJ cutting', *Precision Engineering*, 50, pp. 148–159. Available at: https://doi.org/10.1016/j.precisioneng.2017.05.002.

Jegaraj, J.J.R. and Babu, N.R. (2005) 'A strategy for efficient and quality cutting of materials with abrasive waterjets considering the variation in orifice and focusing nozzle diameter', *International Journal of Machine Tools and Manufacture*, 45(12–13), pp. 1443–1450. Available at: https://doi.org/10.1016/j.ijmachtools.2005.01.020.

Karmiris-Obratański, P. *et al.* (2021) 'On the effect of multiple passes on kerf characteristics and efficiency of abrasive waterjet cutting', *Metals*, 11(1), pp. 1–14. Available at: https://doi.org/10.3390/met11010074.

Kechagias, J., Petropoulos, G. and Vaxevanidis, N. (2012) 'Application of Taguchi design for quality characterization of abrasive water jet machining of TRIP sheet steels', *International Journal of Advanced Manufacturing Technology*, 62(5–8), pp. 635–643. Available at: https://doi.org/10.1007/s00170-011-3815-3.

Keshav Kumar Jha, E., Rai, N. and Kumar Jha, K. (no date) *Experiment of Input Parameters on Abrasive Water Jet Machining A Real Time Engine Oil Monitoring System for Diagnosis of Lubricant using IoT Network View project Vehicle Anti-Theft Tracking System Based on Internet of Thing(IoT) View project Experiment of Input Parameters on Abrasive Water Jet Machining*. Available at: https://www.researchgate.net/publication/351587459.

Kovacevic, R. (no date) *Surface Texture in Abrasive Waterjet Cutting*.

Li, M. *et al.* (2019) 'Effects of processing parameters on kerf characteristics and surface integrity following abrasive waterjet slotting of Ti6Al4V/CFRP stacks', *Journal of Manufacturing Processes*, 42, pp. 82–95. Available at: https://doi.org/10.1016/j.jmapro.2019.04.024.

Liu, H. *et al.* (2004) 'A study of abrasive waterjet characteristics by CFD simulation', *Journal of Materials Processing Technology*, 153–154(1–3), pp. 488–493. Available at: https://doi.org/10.1016/j.jmatprotec.2004.04.037.

Liu, H.T. (2017) '"7M"advantage of abrasive waterjet for machining advanced materials', *Journal of Manufacturing and Materials Processing*, 1(1). Available at: https://doi.org/10.3390/jmmp1010011.

Llanto, J.M. *et al.* (2021a) 'Recent progress trend on abrasive waterjet cutting of metallic materials: A review', *Applied Sciences (Switzerland)*. MDPI AG. Available at: https://doi.org/10.3390/app11083344.

Llanto, J.M. *et al.* (2021b) 'Recent progress trend on abrasive waterjet cutting of metallic materials: A review', *Applied Sciences (Switzerland)*. MDPI AG. Available at: https://doi.org/10.3390/app11083344.

Llanto, J.M. *et al.* (2021c) 'Recent progress trend on abrasive waterjet cutting of metallic materials: A review', *Applied Sciences (Switzerland)*. MDPI AG. Available at: https://doi.org/10.3390/app11083344.

Madara, S.R. *et al.* (2021) 'Modelling of surface roughness in abrasive waterjet cutting of Kevlar 49 composite using artificial neural network', in *Materials Today: Proceedings*. Elsevier Ltd, pp. 1–8. Available at: https://doi.org/10.1016/j.matpr.2020.02.868.

Melentiev, R. and Fang, F. (2018) 'Recent advances and challenges of abrasive jet machining', *CIRP Journal of Manufacturing Science and Technology*. Elsevier Ltd, pp. 1–20. Available at: https://doi.org/10.1016/j.cirpj.2018.06.001.

Mohankumar, V., Kanthababu, M. and Velayudham, A. (2021) 'Abrasive waterjet cutting of boron carbide particles reinforced Al 6063 MMCs – A semi empirical modeling approach in the prediction of kerf angle', *Measurement: Journal of the International Measurement Confederation*, 181. Available at: https://doi.org/10.1016/j.measurement.2021.109492.

Qian, Y. *et al.* (2023) 'The cylindrical surface characteristics of AA7075 aluminum alloy machined by abrasive waterjet with circular cuts', *Journal of Materials Research and Technology*, 26, pp. 4975–4988. Available at: https://doi.org/10.1016/j.jmrt.2023.08.261.

Rabani, A. *et al.* (2016) 'An approach for using iterative learning for controlling the jet penetration depth in abrasive waterjet milling', *Journal of Manufacturing Processes*, 22, pp. 99–107. Available at: https://doi.org/10.1016/j.jmapro.2016.01.014.

Ramalingam, A. *et al.* (2015a) *APPLICATION OF RESPONSE SURFACE METHODOLOGY IN ABRASIVE WATERJET MACHINING OF HIGH SPEED STEEL Machining of Hard Meterials View project APPLICATION OF RESPONSE SURFACE METHODOLOGY IN ABRASIVE WATERJET MACHINING OF HIGH SPEED STEEL*, *Article in International Journal of Applied Engineering Research*. Available at: https://www.researchgate.net/publication/286451517.

Sambruno, A. *et al.* (2019) 'Kerf Taper Defect Minimization Based on Abrasive Waterjet Machining of Low Thickness Thermoplastic Carbon Fiber Composites C/TPU', *Materials*, 12(24), p. 4192. Available at: https://doi.org/10.3390/ma12244192.

Saravanan, S. *et al.* (2020) 'A review on recent progresses in machining methods based on abrasive water jet machining', in *Materials Today: Proceedings*. Elsevier Ltd, pp. 116–122. Available at: https://doi.org/10.1016/j.matpr.2019.05.373.

Sasikumar, K.S.K. *et al.* (2018) 'A study on kerf characteristics of hybrid aluminium 7075 metal matrix composites machined using abrasive water jet machining technology', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 232(4), pp. 690–704. Available at: https://doi.org/10.1177/0954405416654085.

Shanmugam, D.K., Wang, J. and Liu, H. (2008) 'Minimisation of kerf tapers in abrasive waterjet machining of alumina ceramics using a compensation technique', *International Journal of Machine Tools and Manufacture*, 48(14), pp. 1527–1534. Available at: https://doi.org/10.1016/j.ijmachtools.2008.07.001.

Singh, N.P., Srinivasu, D.S. and Ramesh Babu, N. (2020) 'A study on the interaction of jet with constituent layers of multilayered structure in through kerfing with abrasive waterjets', *Journal of Manufacturing Processes*, 60, pp. 117–133. Available at: https://doi.org/10.1016/j.jmapro.2020.10.046.

Singh, N.P., Srinivasu, D.S. and Ramesh Babu, N. (2021) ‘Modelling of abrasive waterjet kerf in a double-layered structure’, *Journal of Manufacturing Processes*, 69, pp. 514–531. Available at: https://doi.org/10.1016/j.jmapro.2021.07.053.

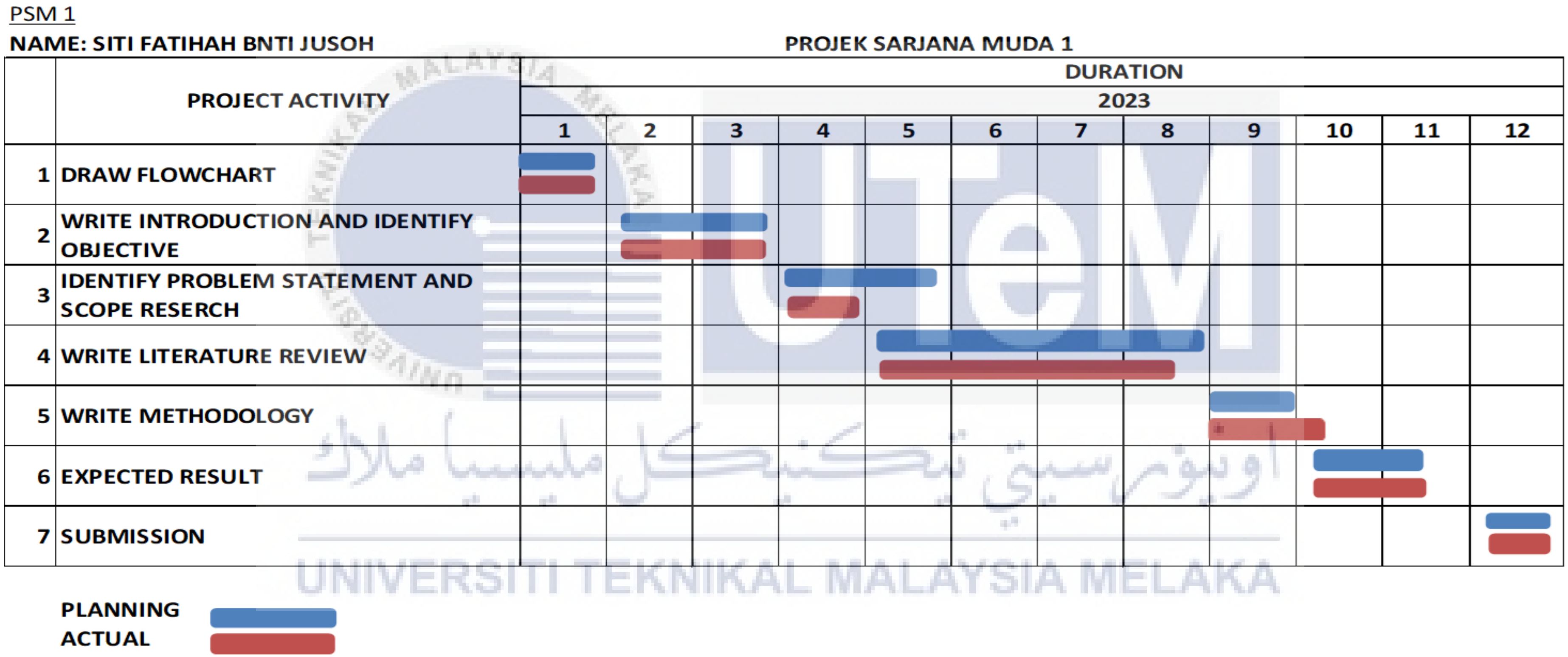
Siores, E. *et al.* (no date) *Enhancing Abrasive Waterjet Cutting of Ceramics by Head Oscillation Techniques*.

Wan, L. *et al.* (2023) ‘Feasible study on the sustainable and clean application of steel slag for abrasive waterjet machining’, *Journal of Cleaner Production*, 420. Available at: https://doi.org/10.1016/j.jclepro.2023.138378.

Zhang, Y. *et al.* (2022) ‘Hole characteristics and surface damage formation mechanisms of Cf/SiC composites machined by abrasive waterjet’, *Ceramics International*, 48(4), pp. 5488–5498. Available at: https://doi.org/10.1016/j.ceramint.2021.11.093.

APPENDICES

APPENDIX A 1 Gantt chart process activity PSM 1



APPENDIX A 2 Gantt chart process activity PSM 2