A STUDY OF PROCESS PARAMETERS DURING ABRASIVE WATER JET MACHINING ON BOROSILICATE GLASS

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

It is due to the development of new materials that has led to the evolution of new manufacturing processes. The current era in manufacturing is concentrating on modern manufacturing methods which can machine difficult-to-cut materials and are economically feasible as well. The modern manufacturing has led to the development of the latest non-conventional manufacturing methods that can process hard and brittle materials with extraordinary properties such as high specific stiffness, high strength and heat resistance, high hardness, and resistance to corrosion. Some of the main areas of study, development, and innovation in this technology includes Electrochemical slurry jet machining, AWJM using ice particles as media, improvements in nozzle design, blending polymer additives in abrasives, process parameter optimization, etc.

The cutting technology by a jet of water (high-pressure water erosion) was first introduced in the middle of the 1800s to cut rocks and for mining applications. Many years later around 1950, this technology was used for cutting soft materials like paper. Abrasives as media were first used in water jets in the 1980s to increase process effectiveness. The two biggest advancements in this technology in 1990 were Motion control systems and process flexibility. Since then, to now a series of developments to accomplish the machining of hard and brittle materials, manufacturing typical shapes and micro-products, cleaning and polishing, and for developing biomedical, scientific, and electronic components [1].

1.1 MANUFACTURING PROCESS AND ITS CLASSIFICATION

Manufacturing processes can be broadly divided into two groups:

a) Primary Manufacturing Processes: These provide basic shape and size to the workpiece.

b) Secondary Manufacturing Processes: These provide the final shape and size with tighter control on the dimension, surface characteristics, etc. of the workpiece.

Material removal process that comes under Secondary manufacturing processes can be further divided into two groups, and they are **"Conventional or Traditional Machining Processes"** and **"Non-Conventional or Non-Traditional or Advanced Machining Processes"**.

Conventional machining is a secondary manufacturing process in which a wedge-shaped cutting tool (harder than the work material) is used to remove excess material from the workpiece in the form of chips in order to get the desired shape, size, and surface finish of the workpiece, while Non-Conventional machining processes, on the other hand, are defined as a group of processes that remove excess material by various techniques which involve mechanical, thermal, electrical, or chemical energy or combinations of these energies but do not use a sharp cutting tool, which is required for the traditional manufacturing processes.

1.2.1 Need for Non-Conventional / Non-Traditional / Advanced Machining Processes

It is a well-established fact that during conventional machining processes, an increase in the hardness of work material results in a decrease in economic cutting speed. It is no longer possible to find tool materials that are sufficiently hard and strong to cut (at economic cutting speeds) materials like stainless steel, titanium, and similar other high strength temperature resistant (HSTR) alloys, ceramics, fibre-reinforced composites, and difficult to machine alloys [2]. That's the reason why non-conventional machining processes were introduced and in today's scenario they are in high demand due to their following advantages which are given below -

a) Extremely hard and brittle materials are difficult to machine by traditional machining processes as either the tool undergoes extreme wear or the workpiece material gets damaged.

b) When the workpiece is too flexible or slender to support the cutting forces, it is preferable to use non-conventional machining processes to avoid any accidents.

c) When the part shape is too complex with internal or external profiles or small holes, then the processing and production of such parts using conventional machining methods are difficult, uneconomical, and time-consuming.

d) When high surface finish and tolerance are required in the final job, then non-conventional machining processes are preferred, as these processes do not require a physical tool for cutting the workpiece, which may leave marks or imperfections on the workpiece surface.

e) As conventional machining produces heat affected zones, so where the temperature rise or residual stresses are undesirable or unacceptable, non-conventional machining processes have to be used.

f) Non-conventional processes are preferred in industries where high and continuous production is required, as they can work continuously with very little downtime.

1.2.2 Types of Non-Conventional / Non-Traditional / Advanced Machining Processes

The source of energy used categorizes the non-conventional machining into mechanical, thermoelectric, electrochemical, and chemical machining, and a brief description of each process is given below:

- **Mechanical Machining:** The process in which kinetic energy of either abrasive or water jet (or both) is utilized to remove excess material from the workpiece and the removal of material occurs mainly by abrasion is known as Mechanical Machining. Some of its examples are abrasive jet machining (AJM), abrasive water jet machining (AWJM), ultrasonic machining (USM), etc.
- **Thermoelectric Machining:** The process in which the energy supplied to the workpiece is in the form of heat, light, or electron bombardment, and the input

energy is concentrated over a small area of the workpiece, causing that portion to be removed by fusion and/or vaporization of the material, is known as Thermoelectric Machining. Some of its examples are electric discharge machining (EDM), plasma arc machining (PAM), laser beam machining (LBM), etc.

- **Electrochemical & Chemical Machining:** The process in which controlled anodic dissolution (conversion of electrical energy into chemical energy) occurs is known as Electrochemical Machining (ECM), and in this process, the mechanism of material removal is the reverse of electroplating. On the other hand, the process in which chemicals selectively remove material from portions of the workpiece, while other portions of the work surface are protected by a mask is known as Chemical Energy Based Processes, and one of their examples is chemical machining (ChM) [2].

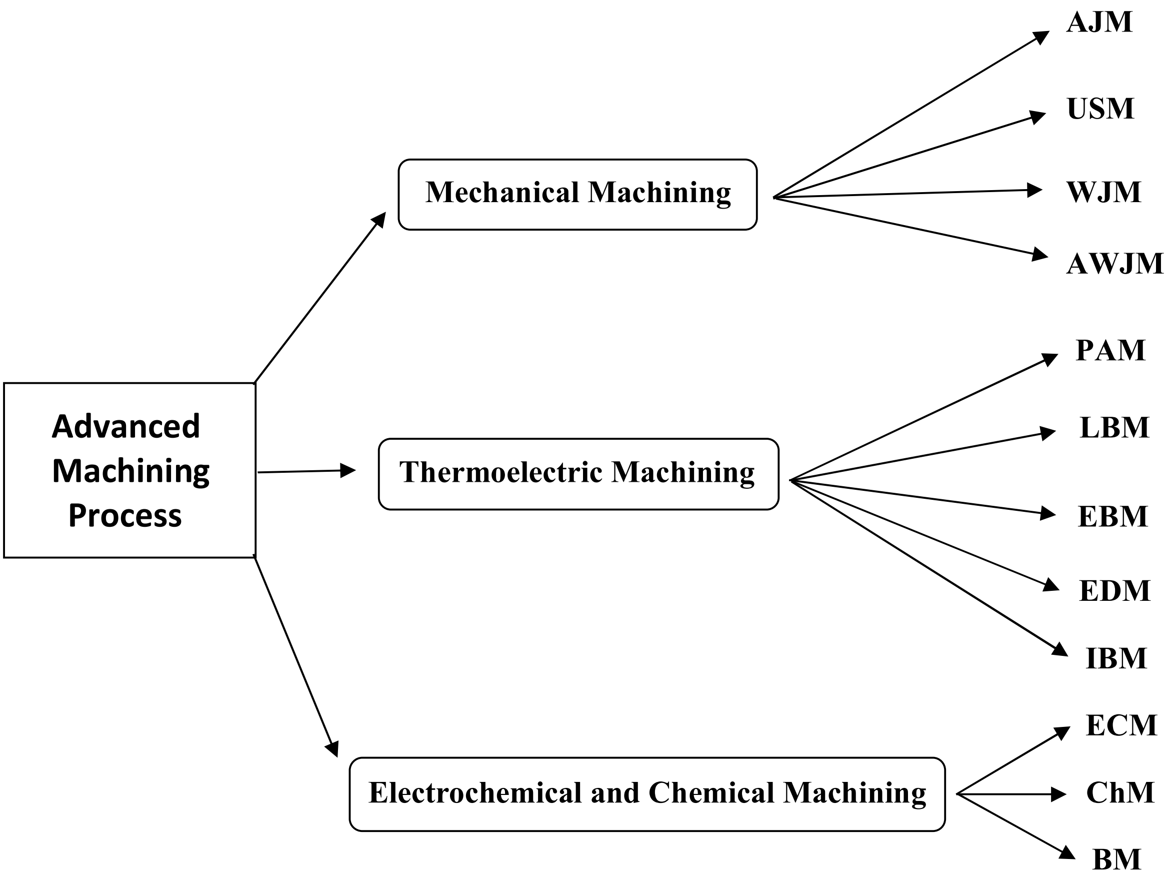


Fig 1.1 Classification of Advanced Machining Process [2]

1.2 ABRASIVE WATER JET MACHINING (AWJM)

1.2.1 Introduction

Abrasive water jet machining is one of the most widely used non-traditional methods of machining which is extensively used for the cutting and processing of almost all engineering materials because of its advantages such as less heat affected zone, better surface finish, etc. It is also regarded as a cold-working process as it generates almost negligible heat during machining operations. It is a stochastic process, so its efficiency, economy, and quality are influenced by a large set of parameters. Hashish (1997), on the basis of the characteristics of parameters, divides the process parameters into three groups such as static variables, quasi-static variables, and dynamic variables. The static variables include abrasive material and its size and mixing tube length, while the quasi-static variables include orifice size and the internal diameter of the focusing tube. The dynamic variables include water jet pressure, abrasive flow rate, traverse rate, and jet impingement angle. Dynamic variables among these parameters were controllable, whereas quasi-static variables were uncontrollable. According to earlier researches, dynamic variables played a substantial effect on cutting performance, which was expressed in terms of depth of cut, material removal rate, kerf geometry, and surface topography of the cut. With the continuous operation of the AWJM process, the quasi-static variables undergo variation in the geometry, and that occurs due to the wearing out of the material. This variation affects the mixing of abrasive particles, energy, and coherency of the jet, which in turn affects the cutting results significantly. Hence, it is difficult to control the AWJ cutting process to achieve the best quality results [3].

1.2.2 Basic Principle of AWJM

When a high pressure water jet and a stream of abrasives coming from two different directions are mixed and passed through the abrasive jet nozzle, a part of the momentum of the water jet is transferred to the abrasives, due to which the velocity of the abrasives rises rapidly. Thus, a high-velocity stream of a mixture of abrasives and water impinges on the workpiece to remove its material. The removal of material from the uppermost portion of a kerf is governed by erosive action while that at the depth is governed by deformation wear [2].

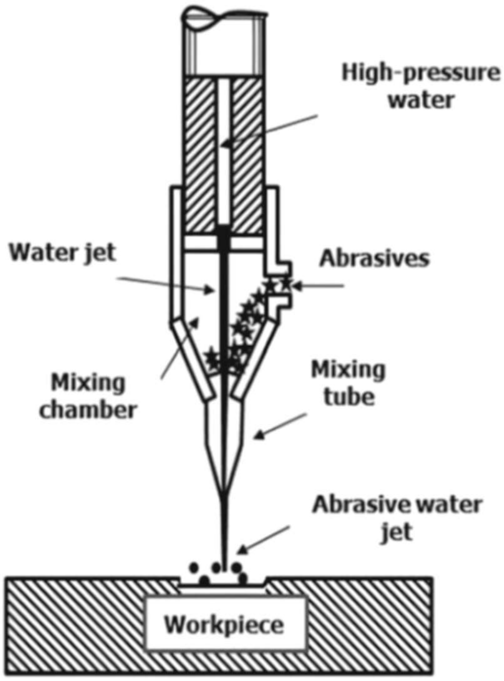


Fig 1.2 Schematic Diagram of AWJM [1,3]

1.3.3 Material Removal Mechanism

The material removal in abrasive water jet machining occurs through the continuous impact of abrasive particles in a high velocity liquid medium. Traditionally, it was seen that abrasive particles were using a combination of four sub-mechanisms, which are cutting, fatigue, melting, and brittle fracture [6]. It was also found that two major modes of material removal as a result of micro-cutting were cutting and deformation/ploughing deformation erosive wear mechanism [7]. The different features of the AWJ machined surface are shown in Fig 1.3. The sharp-edged angular particles were responsible for cutting deformation whereas ploughing deformation was significant for spherical abrasive particles [8] as shown in Fig 1.4(a). A combination of cutting wear and deformation wear mechanism causes ductile erosion. In the cutting wear zone, abrasive particles impinge on the target material at a low angle of attack, thus producing a smooth cutting zone [4]. On the other hand, deformation wear (Fig 1.4(b)) produces a rough surface with striation marks in the cutting zone as it occurs at a high angle of attack

[9,10]. The material removal in the brittle erosion process occurs through crack propagation and chipping as a result of contact stresses developed due to the impact of abrasive particles [11]. It was also seen that jet impact angles had an influence on material removal and in the target materials, oblique jet impact angle was associated with a highly effective ductile shearing action that limited the appearance of fracture traces and insufficient chip removal on the machined surface [12,13].

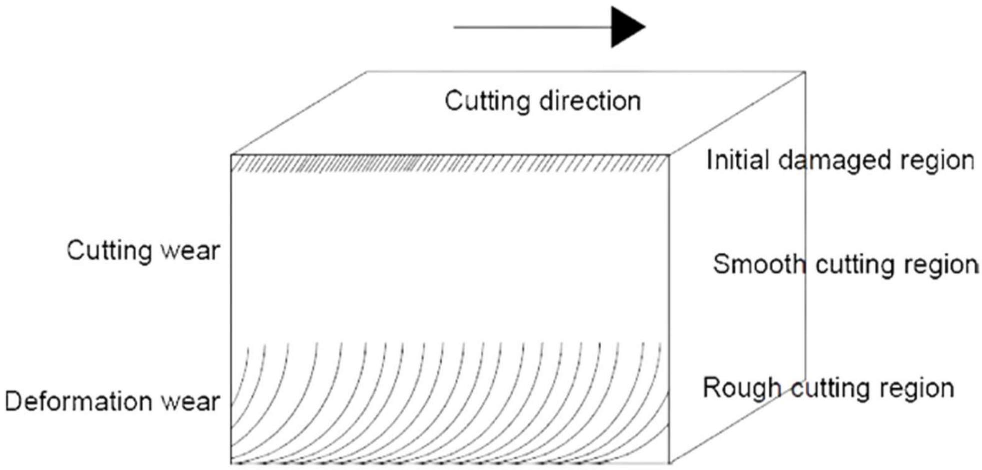
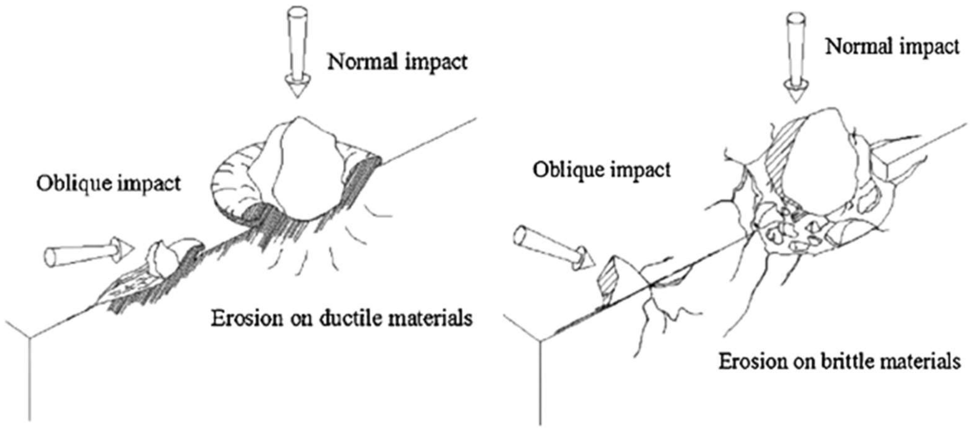


Fig 1.3 Various terms of the AWJ machined surface



(a) (b)

Fig 1.4 Erosion process on (a) ductile materials (b) brittle materials [5]

1.3.4 Theory of Abrasive Water Jet Generation

In abrasive water jet machining, high-speed water jets are produced by the acceleration of a certain volume of pressurized water through an orifice. When high-pressure water passes through an orifice, it is converted into a high-velocity stream of water jet. Now, applying Bernoulli's equation between the entry and exit of the nozzle, we can write

$$\mathbf{P + \rho_w \frac{v_{pipe}^2}{2} + \rho_w g h_2 = P_{atm} + \rho_w \frac{v_o^2}{2} + \rho_w g h_1} \tag{1}$$

where P is the pump pressure, P_{atm} is the pressure at the exit of the nozzle, v_{pipe} and v_o are the velocities of water jet at the entry and exit of the nozzle respectively, ρ_w is the density of water.

Now, considering $h_1 = h_2$ and $v_o >> v_{pipe}$, the approximate velocity of the exit water jet is given by

$$\mathbf{v_{oth} = \sqrt{\frac{2P}{\rho_w}}} \tag{2}$$

In practice,

$$\mathbf{v_o = \mu\, v_{oth} = \mu \sqrt{\frac{2P}{\rho_w}}} \tag{3}$$

where μ is the efficiency coefficient that characterizes the loss of momentum occurring due to wall friction, fluid flow disturbances, and compressibility of the water. The velocity of fluid at the entry of the orifice is very much less when compared to the velocity of fluid at the exit of the orifice. The pressure at the nozzle exit is atmospheric pressure which is very less when compared to the water pressure at the entry of the orifice.

The flow rate of water 'Q' can be obtained as

$$\mathbf{Q = A_o v_o = A_o \mu \sqrt{\frac{2P}{\rho_w}}} \quad \textbf{(4)}$$

where A_o is the cross-sectional area of the orifice. The overall efficiency coefficient μ includes the coefficient of velocity (C_v), coefficient of contraction (C_c) and the compressibility factor.

Now, as the jet emerges out of the orifice, it interacts with the surrounding air and forms a thin film of air, which is carried along the walls of the focusing nozzle and creates waviness in the jet surface, which results in a decrease in pressure inside the mixing chamber. This partial vacuum inside the mixing chamber aids in entraining abrasives into the jet. Then, the momentum transfer from the high velocity jet to the abrasive particles occurs in the mixing chamber and focusing nozzle, and finally, a high velocity stream of a mixture of abrasives and water is formed whose velocity is obtained as

$$\mathbf{v_{awj} = \eta \frac{v_o}{1+\frac{\dot{m}_a}{\dot{m}_w}} = \eta \frac{v_o}{1+R}} \quad \textbf{(5)}$$

where v_{awj} is the velocity of abrasive water jet mixture, η is the momentum-transfer parameter which is a function of process parameters such as pump pressure, abrasive flow rate (AFR), abrasive size, along with the orifice and focus geometry. **R** is the ratio of abrasive mass flow rate to the mass flow rate of water [3].

1.3.5 AWJM Process Parameters

The effectiveness, performance, and efficiency of the AWJM process are influenced by a number of crucial processing parameters. The following are the key AWJM parameters:

- **Abrasive Type:** The type of abrasive is the most important parameter in abrasive water jet machining process as it is directly linked with the material removal rate and machining accuracy. When choosing an abrasive type, hardness is the deciding factor, and thus, the harder the material, the harder the abrasive particles. In general, some of the most widely used abrasive types in abrasive water jet machining process are garnet, silicon carbide, glass beads, silica, sodium bicarbonate, aluminium oxide, crushed glass, etc. The most commonly used materials for polishing, cleaning, and etching operations are dolomites and glass beads. It was found that surface roughness was reduced substantially with the use of harder abrasive materials, while on the other hand, it increased the rate of material removal, which in turn reduced the processing time.

Garnet   Aluminium Oxide   Silicon Carbide

Fig 1.5 Types of Abrasives

- **Abrasive Grain Size:** The size of the abrasive particles, or grain size, played a significant role in abrasive water jet machining process. The coarse grain particles are normally used for the cutting process, while on the other hand, fine grain particles are employed during polishing and finishing operations. Additionally, smaller mesh number abrasives typically had larger average particle sizes and much less particles per unit weight.
- **Water Jet Pressure:** The pressure at which the water jet is coming is one of the important parameters in abrasive water jet machining process. The flow of abrasives directly depends on the pressure of the jet, and with a rise in pressure, the kinetic energy of abrasive particles tends to rise, which consequently raises the particle’s ability to remove material from the workpiece. Thus, with the rise of water jet pressure, both surface roughness and overall process duration are reduced, thus improving surface quality. But there is a limit to which water jet

pressure can be increased, beyond that, it may have a detrimental effect on the surface quality of the workpiece.

- **Stand-off Distance:** The space between the work surface and the nozzle tip is known as Stand-off distance and is again a significant parameter in the abrasive water jet machining process. As the standoff distance is increased, the jet gets the opportunity to expand before impinging on the work surface, which results in an increase in jet diameter during the cutting process. Now, with an increment in jet diameter, the kinetic energy of the jet at impingement gets reduced, which ultimately leads to ineffective cutting and poor part quality. It is thus more preferable to keep the stand-off distance value low, as it will yield a smoother surface due to an increase in kinetic energy, which finally increases the cutting process efficiency.
- **Abrasive Mass Flow Rate**: The cutting efficiency in abrasive water jet machining process is directly linked with the abrasive mass flow rate. As the mass flow rate is increased, the depth of cut increases and the jet can easily cut through the workpiece as well, which results in an increase in surface smoothness and material removal rate.
- **Traverse Speed:** The rate at which a nozzle head moves across the workpiece to achieve the process of machining is known as Traverse speed. As traverse speed is increased, less abrasive particles can attack the surface per unit time, which results in a decrease in material removal rate and reduced machining action (improper contact of abrasive particles with the work surface). Thus, both surface roughness and machining time are increased [1].

1.3.6 Advantages of AWJM

- It is a versatile process suitable for a wide range of materials.
- It produces no heat affected zone, unlike other advanced machining processes such as plasma arc machining, electric discharge machining, etc.
- Since the mechanical properties of the workpiece remain unchanged, so the process is suitable for heat-sensitive materials such as plastics and composites.

- This process provides a very good surface finish as no physical tool is required, which may leave marks or imperfections on the work surface.
- The process is ideal for laser reflective materials for which laser beam machining cannot be applied.
- The process produces no toxic fumes while machining, and thus it is regarded as a green or environmental friendly process.
- Cooling oil or lubrication is generally not required in this process as they do not produce heat while cutting.
- The process is highly flexible and independent of material hardness and conductivity.
- This process requires low machining force.
- Since there is no direct contact between the tool and workpiece in non-conventional machining processes so no cutting tool is required, which helps in saving the tool cost.

1.3.7 Limitations of AWJM

- Initial capital investment in this process is quite high.
- During machining, high noise is produced.
- Material removal rate in this process is low.
- Nozzle wear rate is high.

1.3.8 Applications of AWJM

The versatility and ability to cut a wide range of materials with high precision make abrasive water jet machining a valuable tool in various industries where precise cutting, shaping, and profiling are required. It can be used extensively in the aerospace, automotive, electronics industries, etc. Some of the applications of abrasive water jet machining are given as

- It is extensively used for cutting various metals, including steel, aluminium, titanium, copper, ceramic, etc., and is particularly useful for those materials that are difficult to machine using traditional methods, such as heat-sensitive alloys or those with high hardness.

- It is widely employed in the stone and tile industry for cutting and shaping natural stone, granite, marble, ceramic tiles, and other similar materials.
- In the aerospace industry, abrasive water jet machining can be used for cutting and shaping various components, such as engine parts, turbine blades, interior cabin parts, and aircraft panels. It offers the advantage of precise cutting without producing any heat-affected zones or inducing mechanical stresses.
- It can be used for cutting and extracting rocks and minerals in mining and quarrying operations, thus providing a precise and controlled method for material extraction.
- In the automotive industry, abrasive water jet machining is used for cutting and shaping parts made of different materials, including metals, plastics, and composites. It is used to make parts such as interior trim components (headliners, door panels, trunk liners), cutting gaskets, body panels, bumpers, and other automotive parts.
- In various industries, abrasive water jet machining is used for surface cleaning and preparation as it can effectively remove coatings, oxides, rust, and contaminants from metal surfaces.
- This process is capable of producing intricate and precise cuts with minimal material wastage, thus finding its applications in industries where high precision is required, such as electronics, medical device manufacturing, jewellery, etc.
- The process is also applicable in deburring (AWJD), sharpening of grinding wheels, and surface strengthening to increase the fatigue strength.

1.4 THEORY OF OPTIMIZATION

Optimization is necessary for any problem that involves decision-making, whether in engineering, economics, or any other field. The task of decision-making means choosing between the various alternatives and our desire to make the “best” selection drives us to make the decision. The measure of goodness of the alternatives is described by an objective function or performance index [14]. Optimization theory and methods deal with selecting the best alternative for a given objective function. The area of optimization has received enormous attention in recent years, primarily because of the rapid progress in computer technology, including the development and availability of user-friendly software, and artificial neural networks. An example of this is the wide accessibility of optimization software tools such as the Optimization Toolbox of MATLAB and many other commercial software packages. There are various types of optimization methods, like Gradient descent optimization, Simulated annealing optimization, Particle swarm optimization (PSO), etc. But for our present study, two optimization methods, namely "Single-objective optimization" and "Multi-objective optimization" are used, and these are discussed below in brief.

1.4.1 Single-objective Optimization

Single-objective optimization refers to the process of finding the optimal solution for a problem with a single objective function. The objective is to find out the optimal combination of factors that maximizes or minimizes the response variable predicted by the response surface model independently.

The steps involved in single-objective optimization using RSM typically include:

- **Experimental Design:** Design and conduct a set of experiments to obtain data on the response variable for different combinations of input variables. The experimental design should be efficient and cover the relevant input variable space.
- **Response Surface Model Development:** Fit a response surface model to the experimental data using regression techniques such as linear regression, polynomial regression, or other regression methods. The response surface model relates the input variables to the response variable and provides an equation or model that approximates the relationship.
- **Model Validation:** Assess the adequacy of the response surface model by checking for model fit, statistical significance, and lack of fit. Validation ensures

that the model accurately represents the relationship between the input variables and the response variable.

- **Optimization Algorithm Selection:** Choose an appropriate optimization algorithm to search for the optimal values of the input variables based on the response surface model. Common optimization algorithms include gradient-based methods (e.g., gradient descent) or derivative-free methods (e.g., genetic algorithms, particle swarm optimization).
- **Objective Function Definition:** Define the objective function that quantifies the optimization goal, whether it is to maximize or minimize the response variable. The objective function is typically based on the predicted response values obtained from the response surface model.
- **Optimization Procedure:** Apply the selected optimization algorithm to iteratively search for the optimal values of the input variables that maximize or minimize the objective function. The algorithm adjusts the input variables according to a search strategy until convergence or the desired level of optimization is achieved.
- **Optimal Solution Evaluation:** Once the optimization algorithm converges, evaluate the optimal solution by simulating or testing it with the actual system or process. This step ensures that the predicted optimal values are feasible and can be practically implemented.
- **Sensitivity Analysis:** Perform sensitivity analysis to assess the robustness of the optimal solution and understand how variations in the input variables affect the response variable.

1.4.2 Multi-objective Optimization

Multi-objective optimization is applied to a problem that involves more than one objective function that are to be maximized or minimized. Thus, it involves finding the optimal combination of factors that simultaneously optimize the multiple responses predicted by the response surface models.

A lot of steps involved in multi-objective optimization using RSM typically are same as that required for single-objective optimization. So, the further extra steps are only discussed below:

- **Multi-Objective Optimization Algorithm Selection:** Choose an appropriate multi-objective optimization algorithm to search for the optimal values of the input variables based on the response surface models. Common multi-objective optimization algorithms include genetic algorithms, particle swarm optimization, and evolutionary algorithms. These algorithms aim to find a set of solutions known as the Pareto front, representing the trade-offs between the different objectives.
- **Optimization Procedure:** Apply the selected multi-objective optimization algorithm to iteratively search for the optimal values of the input variables that optimize the defined objective functions. The algorithm adjusts the input variables according to a search strategy and generates a set of solutions that represent the Pareto front.
- **Pareto Front Analysis:** Analyze the generated Pareto front to identify the trade-offs between the different objectives. Explore the solutions on the Pareto front to understand the relationship between the input variables and the multiple response variables and gain insights into the optimization problem.
- **Optimal Solution Selection:** Select the optimal solution from the Pareto front based on decision-maker preferences or additional criteria. The decision-maker can use subjective judgment, preference elicitation techniques, or decision analysis methods to choose a solution that best suits the desired trade-offs between the objectives.

CHAPTER 2

LITERATURE REVIEW AND RESEARCH OBJECTIVES

2.1 LITERATURE REVIEW

The rapid development of science and technology and the demands for higher machining efficiency and quality are increasing day by day in many sectors, such as aerospace, electronics, optical components, precision instruments, medical apparatus, etc. The manufacturing sector is becoming more and more conscious of the global economy and thus to reduce the time needed for tooling and for fast conversion of raw materials into useful products, the use of new and cutting-edge technologies is becoming inevitable, and the most popular method for transforming raw materials into their final shape is machining [15].

Abrasive water jet machining (AWJM) is an extended version of water jet machining where the rate of increase of material removal beyond that of a water jet machine occurs by incorporating abrasive particles such as aluminium oxide, silicon carbide, or garnet within the water jet [16,17]. This process has the ability to cut a variety of materials, ranging from soft to hard, like rubber, plastics, polymers to titanium, inconel, etc.

There are so many process parameters that affect the quality of machined surface cut by the AWJM process and the important process parameters are traverse speed, hydraulic pressure, stand-off distance, abrasive flow rate, and types of abrasive. This process provides some advantages over other machining processes in the cutting of composite materials, like no thermal effect, small cutting forces, and high machining versatility. In this process, the material removal from the workpiece is done by impinging a highly accelerated abrasive jet, which causes the cutting of material through the sharp edges of the abrasives [18].

The versatility of abrasive water jet machining can only be enhanced by doing a comprehensive study of the previous work, and the researchers investigated this process from different points of view and came to a number of conclusions regarding the different aspects of the process. In this process, experiments and studies were conducted with a focus on parametric effects on the surface quality of the work piece, material removal rate, depth of cut, kerf taper angle, process optimization, performance evaluation, and other relevant topics. In the following paragraphs, a comprehensive literature survey has been put forward.

Waheed Sami Abushanab et al. [19] studied the influences of input process parameters on surface roughness (R_a) and topography of the cut surface for Ti6Al4V alloy, after which process optimization was carried out using an L9 orthogonal array. It was concluded that the abrasive flow rate contributed 29.32 % and the stand-off distance contributed 61.77 % in controlling surface roughness as compared to other process parameters.

The experiments were carried out on high-strength aluminum 7068 alloy using garnet 80 mesh abrasive and Bharath Reddy et al. [20] observed that the greatest significant parameter for maximum MRR and lower surface roughness is traverse speed succeeded by abrasive feed rate and SOD.

C. Joel et al. [21] used the Grey-Taguchi method for determining the predicted optimal parametric combinations and finally, the experiment was conducted based on optimized parameters and the cutting accuracy was evaluated. It was found that the abrasive feed rate contributed 46.52% in abrasive cutting operation which is followed by nozzle speed with 36.76% contribution and finally comes the stand-off distance with 15.05% contribution.

K. Karthik et al. [22] used three different levels of input parameters to generate a design table using an L27 orthogonal array and the optimum values of the parameters were found using Grey Relational Analysis and Response Surface Methodology. It was concluded that material removal rate was influenced by water jet pressure and feed rate while the influencing factors for kerf top width were feed rate and abrasive flow rate.

R. Selvam et al. [23] developed a hybrid laminated composite material with Carbon and S-Glass fibers as primary reinforcement and SiC nano particles as filler material. They empirically correlated the effect of process parameters on experimentally obtained quality characteristics, (R_a and K_t) values by generating response surface graphs, and then they optimized the parameters within the tested range based on the desirability approach of RSM. Kerf Taper was found to be decreasing with a decrease of both traverse speed and SOD at moderate water pressure and Abrasive flow rate and Water pressure played a significant role in obtaining better average surface roughness.

Vootkuri Naveen et al. [24] performed the drilling operation on GLARE under different conditions of input parameters such as stand-off distance, traverse rate, abrasive mass flow rate, and water jet pressure. The impact of the input parameters on response variables, such as delamination and surface roughness was assessed using the Response Surface Methodology technique and ANOVA (Analysis of Variance) and it was found that the most significant parameters to control the Surface roughness were water jet pressure and traverse rate while delamination and fiber pull out occurred at low water jet pressure and high SOD.

M. Chithirai Pon Selvan et al. [25] investigated the performance analysis of process parameters by machining Ti-6Al-4V using abrasive water jet technology. They developed mathematical equations using Regression Investigation Method (RIM) and Artificial Neural Network (ANN) procedures in order to select appropriate parameters and based on the input and output data collected from the experiments, modelling was done and tested for the different sets of data to ensure the accuracy. It was observed that pressure and abrasive mass flow rate were proportional to DOC while nozzle stand-off distance and traverse speed were inversely proportional to DOC.

Arghya Bagchi et al. [26] observed the influence of jet pressure, standoff distance, and cutting speed on surface roughness and material removal rate during abrasive water jet cutting of Nimonic C263 super alloy and it was found that MRR increases with the increase of jet pressure but shows various patterns with respect to SOD while low SOD and high jet pressure were found to be suitable for high surface quality.

K. Ravi Kumar et al. [27] performed machining on aluminum/ tungsten carbide composites with 2, 4, 6, 8, and 10 wt. % tungsten carbide reinforced fabricated by stir casting technique. They employed Response surface methodology to explore the influence of input parameters and their relations on the responses. The material removal rate was found to be greatly influenced by transverse speed followed by % reinforcement and standoff distance respectively, while surface roughness was highly influenced by % tungsten carbide followed by transverse speed and standoff distance.

The influence of jet impingement angle on the cutting of alumina ceramics was investigated by Wang et al. [28]. They found that with a decrease in jet impingement angle, penetration depth and surface finish increased. The result also indicated a greater contribution of an oblique jet impingement angle to the cutting performance than the normal impingement angle (90°).

Deepak et al. [29] studied the AWJ cutting of D2 steel (thickness equal to 8 mm) through variations in the effects of the traverse rate and stand-off distance. They analyzed the response parameters namely kerf width and surface roughness under single pass and multi pass (two) cutting operations and the result indicated that with an increase in top kerf width (18 %), stand-off distance increases in a single pass cutting whereas there was a decrease in bottom kerf width (25 %) with the formation of results in kerf taper.

Manu & Babu [30] studied the effect of jet impingement angle on the depth of penetration and surface topography of 6061-T6 parts geometry in AWJ turning. They found more penetration depth and a better material removal rate in normal jet impingement angle (90°), while the jet impingement angle of 30°yielded a lower material removal rate and better surface finish when a higher water jet pressure was employed.

Selvan et al. [31] performed the abrasive water jet machining on aluminium by varying the levels of water jet pressure, abrasive mass flow rate, traverse rate, and stand-off distance and found that water jet pressure and abrasive mass flow rate were directly proportional to the surface roughness.

The influence of multi abrasive particle impact on erosion during AWJ machining of Ti-6Al-4V was simulated by Kumar & Shukla [32] using finite element analysis. They observed an increase in the erosion rate at a lower jet impingement angle value of 45^0 and at a jet impingement angle of 90^0, they discovered that the maximum crater depth could be reached. In the simulation results, the jet impingement angle of 45^0 revealed the highest erosion rate for the titanium alloy. The findings matched the expectations for ductile material's behaviour and it was indicated that the type of material determines the jet impingement angle at which maximal erosion occurred.

Akkurt et al. [33] examined the geometrical characteristics in AWJ cutting of brass-353 by varying thicknesses and developed the relationships between the depth of penetration, traverse rate, and deflection of cutting edge geometry. It was found that water jet pressure was producing a deformation effect on the thinner section. Lateral deflection of the jet happens due to material and cutting types. Higher water jet pressure and abrasive mass flow rate with lower traverse rate and stand-off distance increase the performance of the machining process. They discovered that the cutting mechanism in AWJ provided superior surface quality than the wear mechanism.

The AWJ machining of glass/epoxy composite laminate was researched by Azmir & Ahsan [34], and machining characteristics, including R_a and taper ratio were examined in the machined cut profile by varying water jet pressure and abrasive types. It was found that, for R_a and taper ratio, machining performance was unaffected by the cutting orientation, and also better quality cuts was reported as a result of increased kinetic energy.

Huang et al. [35] investigated the effect of high pressure AWJ cutting on granite, and it was found that the abrasive mass flow rate was directly proportional to water jet pressure, and the effect of other cutting parameters was not significant. They found a decrease in kerf taper angle and striation angle when a lower traverse rate and higher water pressure were employed during the cutting operation.

The surface roughness in AWJ machining of brass 360 was investigated by Naresh Babu et al. [36] and it was found that water jet pressure was the most influential factor that affected the surface roughness. The kinetic energy of the abrasive particles increases and reaches its maximum level with the increase in water jet pressure, which results in the removal of the maximum quantity of material from the work surface. This effect reduces the striations formed on the machined surface and, consequently, helps in providing a good surface finish with a reduction in the surface roughness value. The surface quality increases by 33% with an increase in water jet pressure of 25%.

The AWJ machining of armed fibre reinforced plastics composite was examined by Azmir et al. [37] and they found a decrease in kerf taper ratio and surface roughness with the use of higher water jet pressure. This occurred because the kinetic energy of the particles utilized to create the desired quality of cut profiles increases with an increase in water jet pressure.

It was found by Srinivas & Babu [38], that water jet pressure and traverse rate were the significant parameters that contributed for the high depth of penetration in trapezoidal shaped aluminum-silicon carbide particulate metal matrix composites of 70 mm thickness. They performed modelling for AWJ cutting of target material with various SiC percentages and indicated that careful selection of traverse rate and abrasive mass flow rate was necessary rather than water jet pressure in order to achieve greater depth of jet penetration.

Selvan & Raju [39] investigated the surface roughness of grey cast iron of 100 mm thickness in AWJ cutting and found that water jet pressure was playing a vital role in surface roughness, and as the water jet pressure increases, the surface becomes smoother because brittle abrasives disintegrate into smaller elements, resulting in a reduction in the abrasive size.

Iqbal et al. [40] investigated the AWJ cutting of 4340 tool steel and Aluminium 2219 of thicknesses 20 mm and 40 mm, respectively. They found a decrease in the surface roughness in the cutting wear zone with a decrease in the traverse rate, and it occurred because of sufficient contact time between the abrasives and target material. Kerf width was found to be a major problem in thicker and softer work materials, and it can be reduced by increasing the traverse rate. The result also indicated that the most influencing factors for hardened material were the thickness of the work material and traverse speed.

The AWJ machining process was used by Pal & Choudhury [41] to create blind pockets on Ti-6Al-4V alloy, and the results were found to be consistent with those of previous researchers when high water jet pressure was used. The depth of cut and material removal rate were found to be increasing at higher water jet pressure because of the increase in kinetic energy of abrasive particles in the jet.

The AWJ milling of titanium alloy was carried out by Shipway et al. [42] by adjusting the jet impingement angles and abrasive mesh sizes, and the results show that the jet impingement angle of 60° produces a higher material removal rate and a better surface finish due to the generation of the normal jet impingement angle.

The types and geometric considerations of the orifice in the abrasive water jet cutting head were optimized by Powell et al. [43] because an improper alignment of the orifice in the cutting head not only generated wear in the mixing tube walls, leading to a short life of the orifice, but also resulted in an inefficient AWJ process. Also, with the optimum consideration of the orifice, a well-aligned and coherent AWJ stream was produced, which not only ensured the most efficient cutting but also enhanced the cutting power.

Jegaraj & Babu [44] investigated the surface roughness of machined AA6063–T6 aluminium alloy by varying the ratio of water jet orifice and focusing nozzle diameter in AWJ process, and the results indicated that the quality of the cut surface was not degraded much with the increase in the water jet orifice and focusing nozzle diameter.

The effect of the jet impingement angle on the AWJ cutting of ceramics was studied by Gudimetla et al. [45]. They found variations in tilting the cutting head between 15° and 20° from the normal jet impingement angle, and they concluded that there was an increase in depth of penetration while the deflection of the AWJ was reduced.

Karakurt et al. [46] investigated the taper angle in AWJ cutting of different compositions of granites, and they found traverse rate and stand-off distance to be the influencing factors for baltic brown, aksaray yaylak granite, and bergama grey granite, respectively. The kerf angle in granite materials was found to be increasing with an increase in the traverse rate.

The influence of the shape and hardness of the abrasive particle in the AWJ milling of Ti-6Al-4V was investigated by Fowler et al. [47]. In this study, they have chosen different types of abrasive particles like white and brown aluminium oxide, glass beads, garnet, and steel shot, and it was reported that the hardness of the abrasive particle had more influence on the process than its shape. Also, with the increase in the hardness of the abrasive particle, the surface roughness and material removal rate increased. The relation between the hardness of the abrasive and work material becomes important in AWJ milling operations as hard abrasive particles produce stronger indentation with the work material compared to the softer particles.

An algorithm for compensating the wear effect of the focusing nozzle in the AWJ cutting of hard and tough materials was developed by Zohoor & Nourian [48]. The goal of this study was to increase the cut surface quality and decrease the kerf width in hard and tough materials that were machined. A controlling algorithm was developed by them to compensate for the effect of increasing nozzle diameter on cut surface quality and kerf width for cutting hard and tough materials. They reported that traverse rate and nozzle diameter were the parameters that were influencing the surface quality and kerf geometry.

The surface integrity of AA 7475 aluminium alloy using the impact of the plain water jet cutting process was studied by Boud et al. [49]. The findings indicated that the generation of compressive residual stress induced by the plain water jet improved the fatigue life of the aluminium alloy.

Jiuan-Hung Ke et al. [50] examined the machining characteristics of the self-made magnetic abrasive in abrasive water jet machining. It was found from the Taguchi method that the flexible magnetic abrasive particles provide a better material removal rate and surface roughness than conventional abrasives.

The Injection and suspension type AWJ machining processes were studied by Putz et al. [51], and they proved the effectiveness of AWJ suspension type by machining ceramics. The results showed that the suspension-type AWJ method produced surfaces with improved quality and geometrical accuracy. The potential of the suspension-type procedure to reduce jet stream diameter as a result of the absence of an air phase in the abrasive water mixing stream was also reported. The larger air phase concentration in the Injection type process, however, led to a faster jet expansion which resulted in a reduction in kinetic energy that caused the target materials to produce poor kerf geometry.

2.2 SCOPE AND OBJECTIVES OF THE PRESENT WORK

Abrasive water jet machining has been finding extensive use in the manufacturing sector for machining a variety of materials, including both metals and non-metals. There are various reasons behind the selection of this process, and two of the most important are that it generates very less heat at the cutting zone while machining hard materials, and the second is its ability to cut all kinds of materials such as metals, non-metals, composites, ceramics, etc. The other reasons include that, it produces a higher material removal rate than the Wire EDM process and also has better surface integrity than the laser machining process. It can cut thick components in the range of 250 mm (depending on materials) and has the ability to cut intricate shapes without producing thermal distortion. Also, the existence of the minimum cutting force on the work materials yields better dimensional accuracy due to insignificant deformation. Thus, the scope of work in the field of abrasive water jet machining is very high.

2.2.1 Objectives of the Present Work

A lot of research has been carried out on abrasive water jet machining by considering the effects of various factors on the different responses. However, little work has been done on the effect of four factors on the different responses. So, keeping in mind previous research works and the current necessity in the study of abrasive water jet machining on borosilicate glass, the aims of the current work are as follows:

- To conduct the experiments on the AWJM setup and analyze the process on borosilicate glass.
- To identify the effects of process parameters such as water pressure, abrasive flow rate, traverse speed, and stand-off distance on the depth of cut and taper

angle of the kerf by performing the response surface methodology (RSM) and analysis of variance (ANOVA).

- To perform the optimizations in order to get the optimal values of the factors for the predicted desired values of the responses.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 AWJ MACHINE SYSTEM

The photographic view of the experimental setup used in the present research work is shown in the figure. The Flow MACH 3 (1313b) is used as a machine for our experimental work.

Fig 3.1 Experimental Setup of AWJ Machine System

3.2 TECHNICAL SPECIFICATIONS OF AWJ MACHINE

Working specifications of the machine	
Machine	Flow MACH 3 (1313b)
Maximum Traverse Speed	12700 mm/min
Orifice Diameter	0.254 mm

<table>
<tr><td>Focusing / Mixing Tube Diameter</td><td colspan="2">0.762 mm</td></tr>
<tr><td>Maximum Working Pressure</td><td colspan="2">6,500 bar (94,000 psi)</td></tr>
<tr><td colspan="3">Standard Specifications of the Machining Centre</td></tr>
<tr><td>X-Y cutting travel</td><td colspan="2">722 mm x 725 mm</td></tr>
<tr><td>Z- axis travel</td><td colspan="2">178 mm</td></tr>
<tr><td>No. of Axis for motion</td><td colspan="2">5</td></tr>
<tr><td>Table Size</td><td colspan="2">1300 mm x 1300 mm</td></tr>
<tr><td rowspan="2">Accuracy of motion</td><td>Linear Straightness</td><td>0.0381 mm per 1 m</td></tr>
<tr><td>Repeatability</td><td>0.050 mm</td></tr>
</table>

3.3 COMPONENTS OF ABRASIVE WATER JET MACHINING SYSTEM

An experimental setup for Abrasive Water Jet Machining (AWJM) typically involves several key components and subsystems. Here is a detailed description of the components and their functions:

- **Pump / Intensifier:** The pump or intensifier is an important component of the AWJM setup which is responsible for pressurizing the water to the desired level, typically ranging from 30,000 to 90,000 psi. It utilizes hydraulic pressure amplification to increase the pressure of the incoming water, thus producing high-pressure water at its outlet. The pump is typically powered by an electric motor. The intensifier unit consists of various sub-systems such as hydraulic, pressure control, and safety systems. The intensifiers may have different designs and configurations based on the specific requirements and applications.
- **Abrasive Feed System**: The abrasive feed system in abrasive water jet machining (AWJM) is responsible for delivering and mixing abrasive particles with the high-pressure water stream. The abrasive particles are introduced into the high-pressure water stream through an abrasive hopper, which is typically a container where the abrasive particles are stored. The hopper is designed to

hold a sufficient quantity of abrasive material, ensuring a continuous supply during the cutting process. It may have a feed mechanism such as a screw or gravity feed to control the amount of abrasive being supplied to the cutting head, which is known as abrasive metering system. The abrasive particles, such as garnet, aluminum oxide, or silicon carbide, are mixed with water to form an abrasive slurry. The design and configuration of the abrasive feed system can vary based on the specific requirements and application, but the general purpose remains consistent which is to deliver a controlled and consistent, supply of abrasive particles to the high-pressure water stream for effective cutting.

- **Cutting Head:** The cutting head is a crucial component of AWJM setup which is responsible for focusing and directing the mixture of high-pressure water jet and abrasive particles onto the workpiece to perform the cutting operation. It consists of several components:

a) **Nozzle:** The nozzle is a primary component of the cutting head, which is specially designed to accelerate the abrasive slurry into a high-velocity jet. It is the tip of the cutting head, and it shapes the mixture of abrasive water jet into a precise and coherent stream. It is typically made of a hard and wear-resistant material such as tungsten carbide, sapphire, or diamond to withstand high erosive forces and maintain its shape. The nozzle size and shape can be selected based on the desired cutting performance.

b) **Orifice:** The orifice is a small opening located at the end of the nozzle. It is located where the high-pressure water and abrasive mixture exits the cutting head. The diameter of the orifice affects the flow rate and velocity of the abrasive water jet stream, which in turn influences the cutting speed and accuracy.

c) **Mixing Chamber:** It is a chamber inside the cutting head where thorough mixing of abrasive particles and the high-pressure water jet occurs. The mixing chamber helps to create a coherent and concentrated abrasive water jet by effectively distributing the abrasive particles within the water stream. It may incorporate internal features like baffles or swirl inducers to enhance the mixing process.

- **Motion Control System**: A motion control system often employs computer numerical control (CNC) technology, which is commonly used to automate and control the AWJM process. The CNC system receives instructions from a computer program or operator interface specifying the cutting path and coordinates of movement and then translates them into commands for the cutting head and other machine components. It controls parameters such as cutting speed, cutting path, feed rate, and water jet pressure, thus allowing for precise control and repeatability of the cutting process.
- **Control and Monitoring Instruments**: Various instruments and sensors are used to monitor and control the AWJM process. These may include pressure gauges, flow meters, temperature sensors, workpiece support, and other monitoring devices. The data from these instruments can be used to optimize cutting parameters and ensure safe and efficient operation.
- **Catcher tank:** The catcher tank is typically positioned beneath the work area and is designed to capture the water jet and abrasive particles after they have interacted with the workpiece. The water is separated from the abrasive particles through settling or filtration processes. The separated water can be recycled and reused in the system, while the abrasive particles are collected for disposal or recycling. It also acts as a barrier, thus absorbing and dissipating some of the kinetic energy of the jet, which results in a reduction in noise levels.

CHAPTER 4

DESIGN OF EXPERIMENT AND OPTIMIZATION TECHNIQUES

In the field of statistics and research, the design of experiment (DOE) is defined as a systematic approach of planning, conducting, analyzing, and interpreting the possible outcome of an experiment by considering the input process parameters at different levels. It is an efficient method that enables us to study the relationship between factors (input variables) and responses (output variables), thus helping in the optimization of process parameters with the help of which we can take data-driven decisions. This information is useful for building statistical models to predict the process performance. Thus, it defines the specific setting levels of the combinations of elements at which the different runs in the experiment are to be done.

In statistics, a full factorial experiment is an experiment whose design consists of two or more factors each at different possible levels, and whose experimental design takes all possible combinations of these levels across such factors. Such experimental designs allow researchers to examine both the main effect (independent effects of each factor) and the interaction effect (combined effects of factors) on the response variable. Thus, this design provides a comprehensive understanding of how different factors interact with each other and impact the response variable.

If the number of combinations in a full factorial design is too high, then a fractional factorial design may be considered in which some of the combinations can be omitted. For example, say, if there are, 8 factors at two levels, then $2^8 = 256$ combinations would be generated. It is not feasible to perform such a large number of experiments due to high cost or resource constraints. In such cases, fractional factorial designs may be used. These designs select a subset of factor combinations to be tested, providing information about the main effects and some interaction effects while reducing the number of experimental runs. But this design is less attractive if a researcher wishes to consider more than two levels. Attempts are made to employ the full factorial design of experiments and analysis of variance approach for studying the influence of process parameters on output response parameters.

4.1 HISTORY OF DESIGN OF EXPERIMENT (DOE)

The history of DOE can be traced back to the early 20th century when statisticians and scientists recognized the need for a more efficient and structured approach to experimentation. However, in the year the 1920s and 1930s, Ronald A. Fisher, a British statistician, invented the design of experiments at the Roth Amsted Experimental Station which was located 25 miles north of London. He made significant contributions to the development and popularization of DOE and his work laid the foundation for modern DOE. The most well-known of a group of Japanese scientists, Genichi Taguchi, is known for his quality-improvement techniques. Toyota was one of the first firms to implement Taguchi's techniques. Some basic concepts of the design of experiments were described by Ronald A. Fisher and those fundamental principles are

- **Randomization:** It is a technique for preventing an unknown bias from affecting the outcomes of an experiment and it also ensures that the groups are comparable. It helps in controlling the effects of extraneous variables and allows for valid statistical inferences.
- **Replication:** It involves running multiple independent experimental runs or observations for each treatment combination with identical experimental conditions. It helps in estimating the experimental error, assessing the variability, and obtaining more precise and reliable results. When the noise comes from uncontrollable nuisance variables, replication improves the signal-to-noise ratio.
- **Blocking:** It is a technique used to reduce variability in the experimental units caused by sources that are not of primary interest. It involves grouping similar experimental units together and randomly assigning treatments within each group.
- **Orthogonality:** Orthogonal designs are those in which the effects of different factors are uncorrelated or independent of each other. It thus helps in the efficient estimation of the main effects and interaction between factors. They

help in obtaining clear and unambiguous information about the effects of individual factors on the response variable.

4.2 APPLICATIONS OF DOE

DOE finds applications in various fields, including manufacturing, engineering, healthcare, agriculture, and social sciences. Some common uses of DOE include:

- **Process optimization:** DOE helps identify the critical process factors that affect the outcome of a process and determine the optimal levels for these factors, thus optimizing the manufacturing processes. By systematically varying the factors and measuring the response, researchers can uncover the optimal settings that lead to improved product quality, efficiency, or cost savings.
- **Product development:** DOE is used to optimize product formulations or designs by studying the effect of various factors, such as materials, design parameters, or production methods, on the final product's quality or performance. This helps in creating better products with reduced development time.
- **Quality improvement:** DOE can be employed to identify the critical process parameters and their optimal settings that have the most significant impact on product quality. By reducing variability and understanding the impact of different factors, organizations can enhance product reliability and consistency, reduce defects, and ensure customer satisfaction.
- **Root cause analysis:** When troubleshooting a process or system, DOE can be used to systematically investigate the potential causes of a problem. By varying the factors suspected of contributing to the issue, researchers can determine the root cause and develop appropriate solutions.
- **Sensitivity analysis:** DOE allows for the evaluation of the sensitivity of a process or system to different factors. By systematically varying the factors, researchers can assess which ones have the most significant impact and focus resources on those that matter the most.
- **Robustness testing:** DOE helps in testing the robustness of a process or product design by intentionally introducing variations in operating conditions

or component specifications. This helps in identifying the range of conditions within which the process or product performs reliably.

- **Cost optimization:** DOE aids in optimizing costs by identifying the key factors that contribute to cost variations and determining their optimal levels. This helps in achieving cost savings without sacrificing quality or performance.
- **Scientific research:** In scientific studies, DOE helps researchers investigate hypotheses, explore relationships between variables, and determine cause-and-effect relationships. It allows for controlled experimentation, reducing bias and confounding factors, and enabling more reliable conclusions.

4.3 RSM APPROACH TO DESIGN OF EXPERIMENTS

Response Surface Methodology (RSM) is a statistical and mathematical technique used for modeling and optimizing complex processes. It involves the design of experiments, data analysis, and the development of mathematical models to understand the relationship between input variables and output responses. RSM aims to find the optimal combination of input variables that maximizes or minimizes the desired response. It is a widely used approach in the design of experiments (DOE) to efficiently explore and model the relationships between input variables and output responses. RSM aims to develop mathematical models that can predict and optimize the response variables based on the input variables.

Here's an overview of the RSM approach to the design of experiments:

- **Define the Objective:** Clearly define the objective of the experiment, including the response variables of interest and the desired optimization goals (e.g., maximizing yield, minimizing cost, etc.).
- **Selection of Factors:** Identify the input factors that may potentially affect the response variables. These factors can be categorical (e.g., type of material) or continuous (e.g., temperature, pressure).
- **Experimental Design:** The next step is to design a set of experiments by selecting appropriate levels for each input variable. The design can be a central composite design, Box-Behnken design, factorial design, or other designs depending on the number of variables and desired precision. The selected design should cover a wide range of input variable values.

- **Run Experiments:** Conduct the experiments according to the chosen experimental design by systematically varying the levels of the input factors. Randomization and replication are often employed to minimize the effects of uncontrolled factors and assess experimental error.
- **Data Collection:** Collect data for both the input factors and the corresponding response variables for each experimental run. It is important to ensure accurate and reliable data collection methods.
- **Model Development:** Use statistical techniques to develop mathematical models that describe the relationship between the input factors and the response variables. Regression analysis is commonly employed to estimate the model coefficients, including main effects and interaction terms. The model can be linear, quadratic, or higher order, depending on the complexity of the relationship.
- **Model Validation:** Validate the developed model using statistical tests to ensure its accuracy and reliability. This involves comparing the predicted values from the model with the actual experimental results. Residual analysis, analysis of variance (ANOVA), and diagnostic plots are often used to assess model adequacy.
- **Model Optimization:** Use optimization techniques to identify the optimal combination of input factors that maximizes or minimizes the response variables. Optimization methods, such as gradient-based algorithms or evolutionary algorithms, can be employed to find the settings that optimize the desired objectives.
- **Sensitivity Analysis:** Perform sensitivity analysis to assess the robustness of the optimized solution. This involves evaluating the impact of small variations in the input factors on the response variables to understand the stability and reliability of the optimization results.
- **Confirmation Experiment:** Conduct a confirmation experiment using the optimized settings obtained from the previous step to validate the optimized solution. This experiment helps ensure that the desired response is achieved under the optimized conditions.

CHAPTER 5

EXPERIMENTAL PLAN AND PROCEDURES

5.1 EXPERIMENTAL PLAN

The present experimental study has been performed as per the following plan:

- '31' work specimens of borosilicate glass material with each of size 20 × 13 × 33 mm^3 are taken to perform the experiment.
- Arrangement for experimental setup is required to perform the abrasive water jet machining.
- A mechanical clamping device is used to keep the work specimen at the desired position.
- Conducted Abrasive Water Jet Machining using five different levels for each process parameter which are water pressure, abrasive flow rate, traverse speed, and stand-off distance. The machining is conducted using proper combinations of input process parameters as designed by the central composite design (CCD) of the RSM technique.
- Observe and measure the depth of cut (DOC) in the work specimen by using a vernier caliper.
- Taper angle (TA) is measured by measuring the kerf wall inclination i.e., measuring the top and bottom kerf width, and then using the mathematical equation.

5.2 WORK AND ABRASIVE MATERIAL

In the present research work, 31 work specimens of borosilicate glass material with each of size 20 × 13 × 33 mm^3 are taken to perform the experiment.

5.2.1 Borosilicate Glass

Borosilicate glass is a type of glass that is composed mainly of silica (SiO_2) and boron trioxide (B_2O_3). It is known for its high resistance to thermal shock, which means it can withstand rapid temperature changes without breaking. This property makes borosilicate glass suitable for a wide range of applications. One of the most well-known brands of borosilicate glass is Pyrex, which has been used for laboratory glassware and kitchenware for many years. Borosilicate glass is preferred in scientific and industrial settings because of its ability to withstand high temperatures and resist chemical corrosion. The mechanical and thermal properties of the borosilicate glass and the figure of the work specimen is given in Table 5.1 and Fig 5.1 respectively.

Fig 5.1 Work Specimen

Table 5.1: Mechanical and thermal properties of the borosilicate glass

Tensile Strength (MPa)	81.6
Thermal Conductivity (W/m-K)	1.15
Melting Point (℃)	1252
Density (gm/cc)	2.23
Young's modulus (GPa)	64

5.2.2 Abrasive Material

Garnet is a widely used abrasive material due to its excellent properties like hardness, toughness, and chemical inertness, thus suitable for various applications. It can be used for abrasive blasting, water jet cutting, grinding and polishing applications for achieving precise and smooth finishes on surfaces, etc. In the present study, Garnet (#80) has been used whose physical and chemical properties are given in table 5.2.

Table 5.2: Physical and Chemical properties of Garnet (#80)

Properties	**Values**
Hardness	7.5-8 (on Mohs scale)
Melting Point (°C)	1320
Specific Gravity	4.1
Density (gm/cc)	2.2

5.3 EXPERIMENTAL DETAILS

5.3.1 Selection of Process Parameters

Four independently controllable process parameters, namely: water pressure, abrasive flow rate, traverse speed, and stand-off distance are considered as input parameters to carry out the experiments.

5.3.2 Finding the limits of Process Parameters

Trial runs are carried out by changing one of the process parameters at a time while keeping the others constant. The working range is decided by inspecting the weld seam for a smooth appearance and the absence of any visible defects. The upper and lower limits are coded as +2 and -2 respectively. The selected process parameters, their limits, notations, and units are given in Table 5.3.

Table 5.3: Parameters with notations, units and levels

Parameters	**Notations**	**Units**	**Levels**				
			-2	**-1**	**0**	**+1**	**+2**
Water pressure	WP	bar	1000	1125	1250	1375	1500
Abrasive flow rate	AFR	g/min	18	27	36	45	54
Traverse speed	TS	mm/min	200	250	300	350	400
Stand-off distance	SOD	mm	30	37.5	45	52.5	60

5.3.3 Experimental Design

In our present study, water pressure, abrasive flow rate, traverse speed, and stand-off distance are selected as controllable process parameters (or factors) with five levels, and depth of cut, and taper angle of the kerf were selected as responses. Garnet (#80) with a mesh size of 80 has been used as an abrasive which is kept fixed in our study. The design of experiment is formed by using central composite design (CCD) of response surface methodology (RSM) using statistical software. Analysis of variance (ANOVA) is used to see the influence of individual parameters and their interactions on the responses, which is obtained using the statistical software. The acceptability of the established models is tested using the sequential F-test and lack-of-fit test. The statistical software which is used for preparing DOE and ANOVA is MINITAB. The coded design matrix and uncoded design matrix are given in Tables 5.4 and 5.5 respectively.

Table 5.4: Coded Design Matrix

Exp. No.	Water pressure (bar)	Abrasive flow rate (g/min)	Traverse speed (mm/min)	Stand-off distance (mm)
1	-1	-1	-1	-1
2	+1	-1	-1	-1
3	-1	+1	-1	-1
4	+1	+1	-1	-1
5	-1	-1	+1	-1
6	+1	-1	+1	-1
7	-1	+1	+1	-1
8	+1	+1	+1	-1
9	-1	-1	-1	+1
10	+1	-1	-1	+1
11	-1	+1	-1	+1
12	+1	+1	-1	+1
13	-1	-1	+1	+1
14	+1	-1	+1	+1
15	-1	+1	+1	+1

Exp. No.	Water pressure (bar)	Abrasive flow rate (g/min)	Traverse speed (mm/min)	Stand-off distance (mm)
16	1	+1	+1	+1
17	-2	0	0	0
18	+2	0	0	0
19	0	-2	0	0
20	0	+2	0	0
21	0	0	-2	0
22	0	0	+2	0
23	0	0	0	-2
24	0	0	0	+2
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0
28	0	0	0	0
29	0	0	0	0
30	0	0	0	0
31	0	0	0	0

Table 5.5: Uncoded Design Matrix

Exp. No.	Water pressure (bar)	Abrasive flow rate (g/min)	Traverse speed (mm/min)	Stand-off distance (mm)
1	1125	27	250	37.5
2	1375	27	250	37.5
3	1125	45	250	37.5
4	1375	45	250	37.5
5	1125	27	350	37.5
6	1375	27	350	37.5
7	1125	45	350	37.5
8	1375	45	350	37.5
9	1125	27	250	52.5

Exp. No.	**Water pressure (bar)**	**Abrasive flow rate (g/min)**	**Traverse speed (mm/min)**	**Stand-off distance (mm)**
10	1375	27	250	52.5
11	1125	45	250	52.5
12	1375	45	250	52.5
13	1125	27	350	52.5
14	1375	27	350	52.5
15	1125	45	350	52.5
16	1375	45	350	52.5
17	1000	36	300	45
18	1500	36	300	45
19	1250	18	300	45
20	1250	54	300	45
21	1250	36	200	45
22	1250	36	400	45
23	1250	36	300	30
24	1250	36	300	60
25	1250	36	300	45
26	1250	36	300	45
27	1250	36	300	45
28	1250	36	300	45
29	1250	36	300	45
30	1250	36	300	45
31	1250	36	300	45

5.4 EXPERIMENTAL PROCEDURE

Following a review of the literature and the machine's feasibility, a trial experiment was conducted, and process parameters and their ranges were identified, as shown in Table 5.3. Then, a large specimen of borosilicate glass is cut into 31 specimens each of size 20 × 13 × 33 mm^3 by performing abrasive water jet machining. Now, by using the design matrix of DOE as shown in the above table, the experiment was conducted by varying the input parameters at all the levels and the values of the responses were noted down.

5.5 TESTING EQUIPMENT

In this section, the equipment which is used to measure the values of the desired responses using the machined workpiece is discussed here. The depth of cut and taper angle of the kerf are to be measured.

5.5.1 Vernier Caliper

A vernier caliper is used to measure both the depth of cut and kerf widths (to measure the taper angle of the kerf). It is a mechanical instrument used to accurately measure linear dimensions with high precision. It consists of a main scale and a sliding vernier scale that allow for more precise measurements than a regular ruler or measuring tape. The main scale is a graduated ruler on the main body of the caliper, which provides the primary measurement readings. The sliding jaw is the movable part of the caliper that slides along the main scale. It is attached to the vernier scale and can be locked in place once the measurement is taken. The vernier scale is a secondary scale that is mounted on the sliding jaw. It consists of a series of equally spaced marks or divisions. The length of the vernier scale is slightly smaller than the main scale and is calibrated to provide more precise measurements.

The least count of a vernier caliper refers to the smallest measurement that can be read or determined using the instrument. It is a measure of its precision. It can be measured by using the below given formula

$$\text{Least Count} = \frac{(\text{Smallest division on the main scale})}{(\text{Total number of divisions on the vernier scale})}$$

The main scale on a typical metric vernier caliper usually has divisions of 1 mm, while the vernier scale has 10 divisions that cover a distance equal to 9 divisions on the main scale.

Therefore, applying the formula:

$$\text{Least Count} = \frac{1\ \text{mm}}{10} = 0.1\ \text{mm}$$

Thus, the least count of a metric vernier caliper is 0.1 mm (or 0.01 cm).

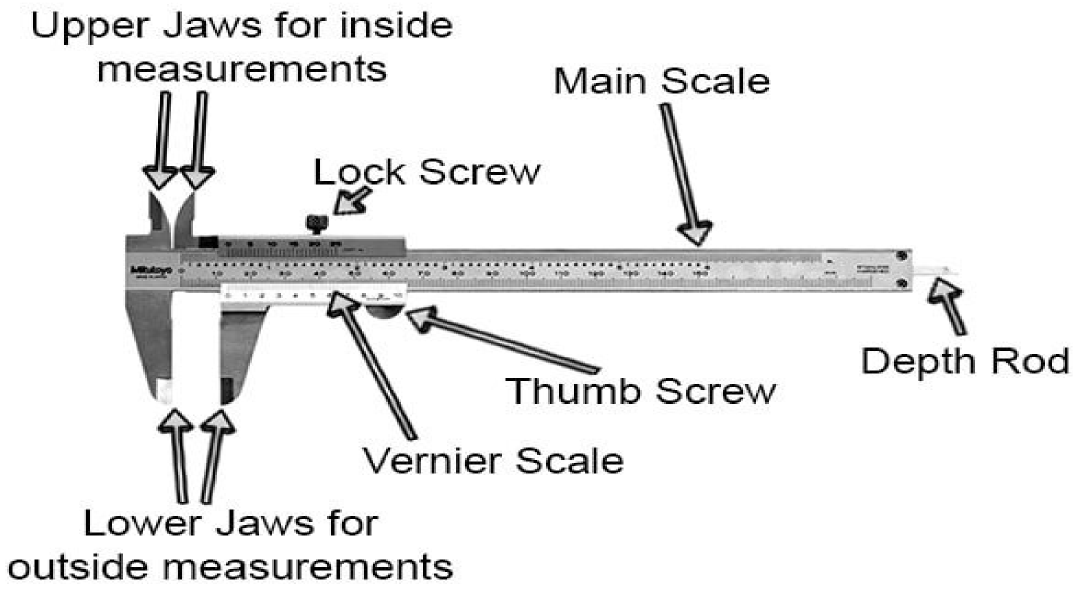


Fig 5.2 Schematic Diagram of Vernier Caliper

5.6 MEASUREMENT OF THE TAPER ANGLE OF THE KERF

In abrasive water jet machining, the taper angle of the kerf refers to the angle formed between the sidewall of the cut and the vertical axis. The measurement of the taper angle is important as it has a significant impact on the cutting efficiency and surface quality of the work surface. It can be measured by various methods and instruments. In our present study, it has been measured by measuring the kerf wall inclination $(W_t - W_b)$ as shown in the Fig 5.3. The taper angle of the kerf is calculated by using equation 4.

$$\tan\theta = \frac{(W_t - W_b)}{2T} \quad (4)$$

where θ = taper angle of the kerf

W_t = top kerf width

W_b = bottom kerf width

T = thickness of the sample

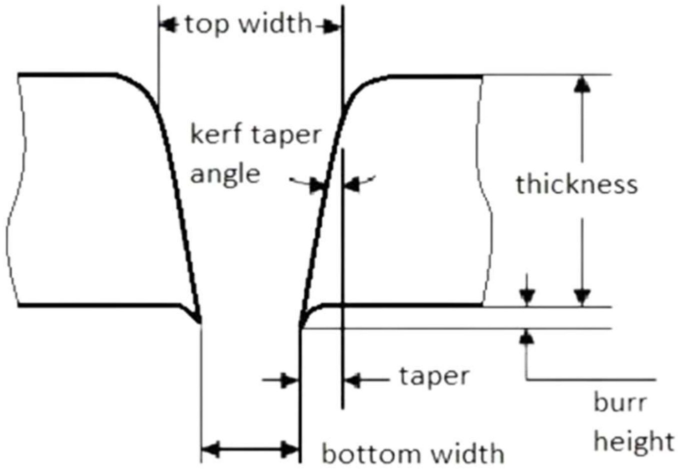


Fig 5.3 Schematic definition of the kerf geometry

CHAPTER 6

EXPERIMENTAL INVESTIGATION AND OPTIMIZATION

This chapter includes an experimental observation or the results of the experiments and the influence of process factors on the responses. This chapter analyses the observed data for mathematical modelling, response surface plots, and optimization. The link between the process parameters and responses is established by developing the regression equations and analysis of variance (ANOVA) tables using statistical software. ANOVA tables are analyzed to find out the contribution of the different factors on the responses. Moreover, the optimization is also performed to know the optimal values of the factors at the desired predicted values of the responses, which will also help in the validation experiment.

6.1 EXPERIMENTAL RESULTS

The procedure for the selection of appropriate process parameters and the development of design matrix for the experiment using MINITAB software have already been outlined. The abrasive water jet machining experiment is performed for the correct combinations of input process parameters as designed by the central composite design of the RSM technique, and the measurements were taken. The values of the responses corresponding to the factors are given in Table 6.1

Table 6.1: Design matrix and measured experimental results

Exp. No.	Factors			Responses		
	Water pressure (bar)	Abrasive flow rate (g/min)	Traverse speed (mm/min)	Stand-off distance (mm)	Depth of cut (mm)	Taper angle (degree)
1	1125	27	250	37.5	9.03	11.25
2	1375	27	250	37.5	11.41	9.69
3	1125	45	250	37.5	11.12	10.89
4	1375	45	250	37.5	12.65	8.45
5	1125	27	350	37.5	7.03	11.89
6	1375	27	350	37.5	9.71	10.41
7	1125	45	350	37.5	10.07	11.25

Exp. No.	Factors			Responses		
	Water pressure (bar)	Abrasive flow rate (g/min)	Traverse speed (mm/min)	Stand-off distance (mm)	Depth of cut (mm)	Taper angle (degree)
8	1375	45	350	37.5	11.85	9.1
9	1125	27	250	52.5	8.77	12.15
10	1375	27	250	52.5	10.96	10.76
11	1125	45	250	52.5	9.56	11.13
12	1375	45	250	52.5	11.35	8.94
13	1125	27	350	52.5	7.11	12.46
14	1375	27	350	52.5	10.08	10.99
15	1125	45	350	52.5	9.98	11.83
16	1375	45	350	52.5	11.76	9.74
17	1000	36	300	45	7.12	12.52
18	1500	36	300	45	11.69	9.34
19	1250	18	300	45	8.86	11.39
20	1250	54	300	45	12.14	9.81
21	1250	36	200	45	12.09	10.15
22	1250	36	400	45	9.42	11.14
23	1250	36	300	30	11.5	10.15
24	1250	36	300	60	8.52	10.93
25	1250	36	300	45	10.29	10.41
26	1250	36	300	45	10.25	10.35
27	1250	36	300	45	10.56	10.02
28	1250	36	300	45	10.39	10.36
29	1250	36	300	45	10.01	10.12
30	1250	36	300	45	10.52	10.39
31	1250	36	300	45	10.16	10.05

6.2 DEVELOPMENT OF MATHEMATICAL MODELS USING RSM

The mathematical models that predict the responses for a set of factors are developed by using RSM. To acquire the best-fit models, the constructed models are checked for their adequacy by using the analysis of variance (ANOVA) method. The development of relationships between the input and output parameters is required to understand the process behaviour, and it has been done using ANOVA. Regression analysis is a powerful statistical tool that helps to examine the relationship between two or more variables of interest. The use of regression analysis helps to get a precise estimation of the most important factors, their interactions, and other factors that can be ignored.

6.2.1 Analysis of Depth of Cut (DOC)

Table 6.2 shows the ANOVA results for the depth of cut with a confidence level of 95%. It can be observed from Table 6.2 that the water pressure has the greatest contribution to the depth of cut, followed by the abrasive flow rate, traverse speed, and stand-off distance. The square and interaction terms are found to be insignificant. As a result, this equation is appropriate for quadratic equations with curvature on the response surface. The developed mathematical model for the depth of cut in terms of coded factors is given below:

$$DOC = -9.5 + 0.0470\ WP + 0.187\ AFR - 0.1079\ TS - 0.056\ SOD - 0.000015\ WP*WP + 0.000551\ AFR*AFR + 0.000043\ TS*TS - 0.00138\ SOD*SOD - 0.000186\ WP*AFR + 0.000013\ WP*TS + 0.000024\ WP*SOD + 0.000725\ AFR*TS - 0.00257\ AFR*SOD + 0.000640\ TS*SOD$$

Table 6.2: ANOVA results for the Depth of cut

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	63.08	4.51	31.28	0.00
Linear	4	56.90	14.23	98.75	0.00
WP	1	28.69	28.69	199.16	0.00
AFR	1	18.03	18.03	125.14	0.00
TS	1	6.62	6.62	45.92	0.00
SOD	1	3.57	3.57	24.80	0.00
Square	4	2.25	0.56	3.91	0.02
WP*WP	1	1.50	1.50	10.42	0.01
AFR*AFR	1	0.06	0.06	0.40	0.54
TS*TS	1	0.34	0.34	2.33	0.15
SOD*SOD	1	0.17	0.17	1.20	0.29
2-Way Interaction	6	3.92	0.65	4.54	0.01
WP*AFR	1	0.70	0.70	4.84	0.04
WP*TS	1	0.11	0.11	0.76	0.40
WP*SOD	1	0.01	0.01	0.06	0.82
AFR*TS	1	1.70	1.70	11.82	0.00
AFR*SOD	1	0.48	0.48	3.35	0.09
TS*SOD	1	0.92	0.92	6.40	0.02
Error	16	2.30	0.14		

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Lack-of-Fit	10	2.08	0.21	5.43	0.03
Pure Error	6	0.23	0.04		
Total	30	65.38			
Model Summary		S	R-sq	R-sq (adj)	R-sq (pred)
		0.37954	96.47%	93.39%	81.24%

The model adequacy measures, namely R^2, adjusted R^2, and predicted R^2 are found to be equal to 0.9647, 0.9339, and 0.8124, respectively, which are very close to unity. The very close agreement of R^2 values indicates that the developed model is adequate. The lack-of-fit F-value is not significant relative to the pure error which is desirable.

6.2.2 Analysis of the Taper Angle of the Kerf (TA)

Table 6.3 shows the ANOVA results for the taper angle of the kerf with a confidence level of 95%. It can be observed from Table 6.2 that the water pressure has the greatest impact on the taper angle of the kerf, followed by the abrasive flow rate, stand-off distance, and traverse speed. The square and interaction terms are found to be insignificant. As a result, this equation is appropriate for quadratic equations with curvature on the response surface. The developed mathematical model for the taper angle of the kerf in terms of coded factors is given below:

TA =37.03- 0.03135 WP+ 0.0967 AFR- 0.0244 TS - 0.0685 SOD + 0.000011 WP*WP + 0.001111 AFR*AFR+ 0.000041 TS*TS+ 0.001334 SOD*SOD- 0.000165 WP*AFR + 0.000004 WP*TS + 0.000033 WP*SOD+ 0.000085 AFR*TS - 0.001083 AFR*SOD - 0.000055 TS*SOD

Table 6.3: ANOVA results for the Taper angle of the kerf

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	29.49	2.11	61.00	0.00
Linear	4	27.58	6.89	199.64	0.00
WP	1	18.60	18.60	538.65	0.00
AFR	1	5.44	5.44	157.62	0.00
TS	1	1.70	1.70	49.26	0.00
SOD	1	1.83	1.83	53.03	0.00
Square	4	1.22	0.31	8.85	0.00

Source	DF	Adj SS	Adj MS	F-Value	P-Value
WP*WP	1	0.85	0.85	24.64	0.00
AFR*AFR	1	0.23	0.23	6.71	0.02
TS*TS	1	0.29	0.29	8.49	0.01
SOD*SOD	1	0.16	0.16	4.66	0.05
2-Way Interaction	6	0.69	0.12	3.34	0.03
WP*AFR	1	0.55	0.55	15.96	0.00
WP*TS	1	0.01	0.01	0.28	0.61
WP*SOD	1	0.02	0.02	0.43	0.52
AFR*TS	1	0.02	0.02	0.67	0.42
AFR*SOD	1	0.09	0.09	2.48	0.14
TS *SOD	1	0.01	0.01	0.20	0.66
Error	16	0.55	0.03		
Lack-of-Fit	10	0.38	0.04	1.28	0.40
Pure Error	6	0.18	0.03		
Total	30	30.05			
Model Summary		S	R-sq	R-sq (adj)	R-sq (pred)
		0.18584	98.16%	96.55%	91.99%

The model adequacy measures, namely R^2, adjusted R^2, and predicted R^2 are found to be equal to 0.9816, 0.9655, and 0.9199, respectively, which are very close to unity. The very close agreement of R^2 values indicates that the developed model is adequate. The lack-of-fit F-value is not significant relative to the pure error, and this is desirable.

6.3 EFFECTS OF PROCESS PARAMETERS ON RESPONSES

The effect of process parameters on the depth of cut and taper angle of the kerf are discussed here. The response surface plots have been drawn for each of the responses with respect to all the parameters, and the effects of the parameters are studied. It is very important to know the relationship between the factors and responses so that the concluded experimental work can be proved correct and further optimization can be done.

6.3.1 Effects of process parameters on the Depth of Cut

Fig. 6.1 shows the combined effect of water pressure and abrasive flow rate on the depth of cut. It can be observed that with the increase in water pressure, the depth of cut increases for all levels of abrasive flow rate, and this occurs because higher water pressure causes the kinetic energy of abrasive particles to increase, which results in a more powerful and concentrated abrasive water jet. This jet can effectively erode the workpiece material, thus penetrating to a greater extent, which results in an increase in the depth of cut.

It has also been observed from the same response plot that the depth of cut increases as the abrasive flow rate is increased for all the values of the water pressure. This is due to the fact that a high abrasive flow rate implies more abrasive particles are present in the water jet, due to which their impact on the workpiece material becomes more significant. Thus, abrasive particles can effectively assist in the erosion process by cutting and eroding the material, thereby increasing the depth of cut.

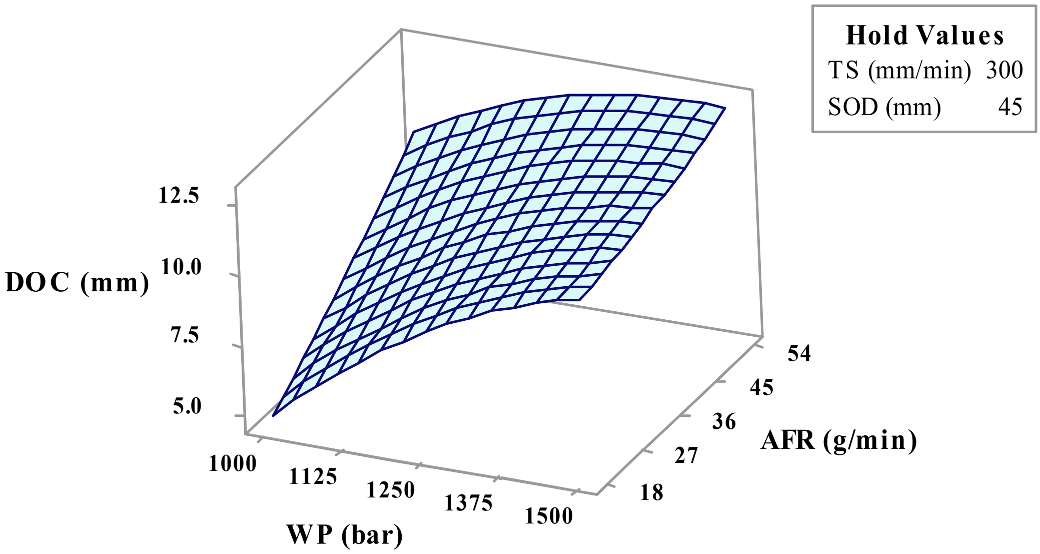


Fig. 6.1 Surface Plot of DOC (mm) vs WP (bar), AFR (g/min)

The effect of traverse speed and stand-off distance on the depth of cut is shown in Fig. 6.2. The surface plot shows that with the increase in traverse speed, the depth of cut decreases for all the values of stand-off distance. This is due to the fact that more traverse speed means the water jet and abrasive particles are moving faster across the workpiece surface, which implies they are spending less time in contact with the material. This short exposure produces less erosion effect, thus resulting in an increase in the depth of cut.

It can also be observed from the same surface plot that, with the increase in stand-off distance, the depth of cut increases, but after a certain distance, it starts decreasing for the higher values of traverse speed. This occurs because, with the increase in stand-off distance at higher values of traverse speed, sufficient passage will not be available for the abrasive particles to come out from the machining zone after impact which causes less dispersion of the jet. Thus, the jet gets more concentrated and its effectiveness is increased. Therefore, initially with the increase in stand-off distance, the depth of cut increases. But, at the lower values of traverse speed, the depth of cut starts decreasing as the stand-off distance is increased because the water jet and abrasive particles disperse over a larger area before reaching the workpiece. As a result, the energy concentration is reduced which decreases the effectiveness of the jet, leading to a decrease in the depth of cut.

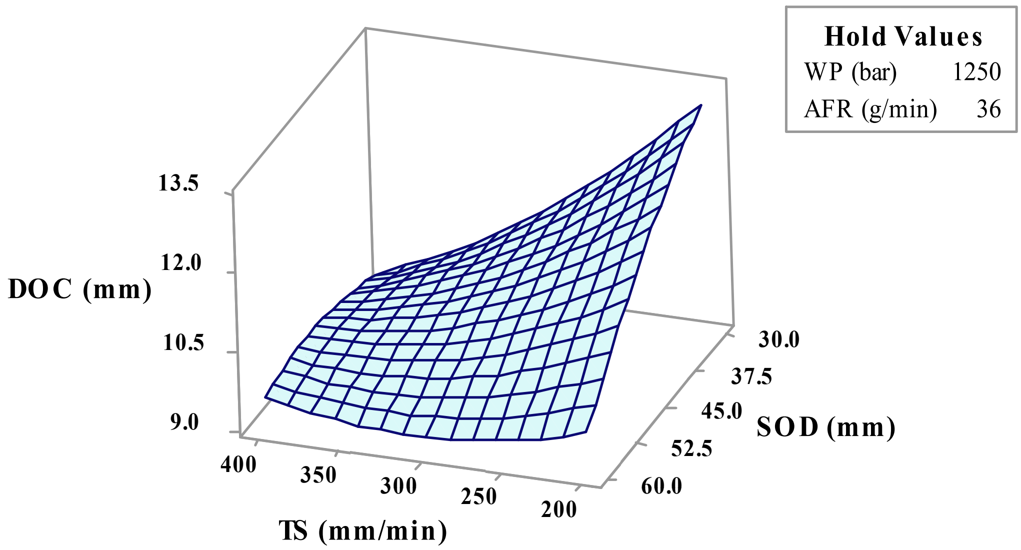


Fig. 6.2 Surface Plot of DOC (mm) vs TS (mm/min), SOD (mm)

6.3.2 Effects of process parameters on the Taper Angle of the Kerf

Fig. 6.3 shows the combined effect of water pressure and abrasive flow rate on the taper angle of the kerf. From the surface plot, it can be observed that, with the increase in water pressure, the taper angle of the kerf decreases for all the values of abrasive flow rate. This is due to the fact that the high-pressure water jet can erode the material more effectively because of its greater force. This results in a narrower and more precise cut, leading to a reduction in the taper angle of the kerf.

On the other hand, the same surface plot also shows that, with the increase in abrasive flow rate, the taper angle of the kerf decreases for the higher values of the water pressure. This occurs because at a higher abrasive flow rate, the concentration of abrasive particles in the water jet stream increases, which enhances the aggressiveness, thus aiding in more effective material removal. Thus, cutting efficiency is increased, which produces a narrow cut that causes a reduction in the taper angle of the kerf. But, as the abrasive flow rate is increased at the lower values of water pressure, the taper angle of the kerf decreases to some extent after which it increases slightly. This may be due to the fact that, initially the effect of the abrasive flow rate is significant due to which the taper angle of the curve decreases to some extent. However, after a certain period of time, the water pressure also becomes significant and the combined effect of both factors causes an slight increase in the taper angle of the kerf.

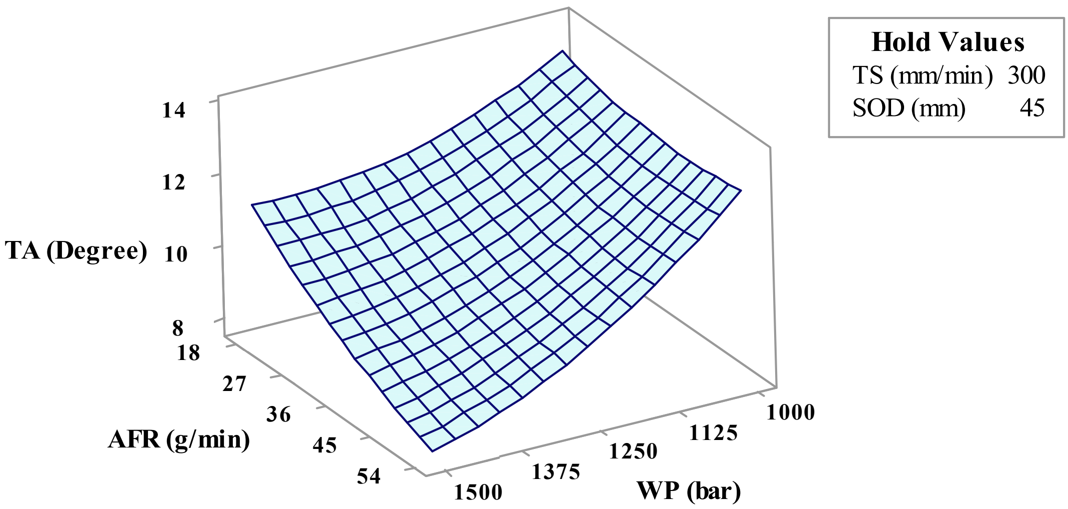


Fig. 6.3 Surface Plot of TA (degree) vs WP (bar), AFR (g/min)

The effect of traverse speed and stand-off distance on the taper angle of the kerf is shown in Fig. 6.4. It can be observed from the surface plot that, with the increase in the traverse speed, the taper angle of the kerf increases for all the levels of the stand-off distance. This is due to the fact that a faster traverse speed means that the cutting head moves quickly across the workpiece, thus spending less time in a specific area.

This reduces the dwell time, which may result in a relatively lower material removal rate and a wider cut, leading to a larger taper angle of the kerf.

On the other hand, the surface plot also shows that the taper angle of the kerf increases with the increase in stand-off distance. This occurs because a long stand-off distance increases the distance between the nozzle and the workpiece, allowing the water jet and abrasive particles to spread out over a larger area. This reduces the cutting action of the abrasive water jet, which results in a wider cut that increases the taper angle of the kerf.

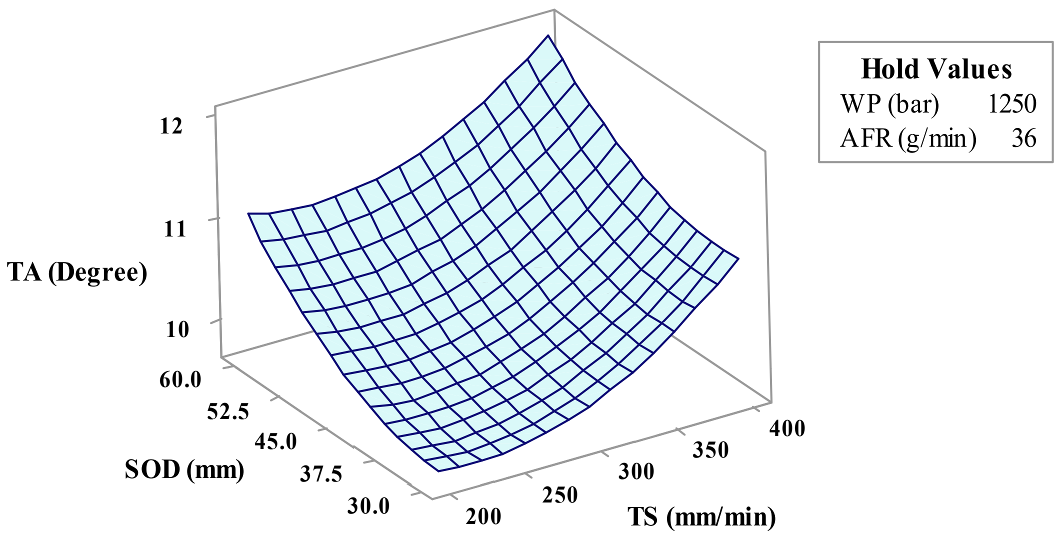


Fig. 6.4 Surface Plot of TA (degree) vs TS (mm/min), SOD (mm)

6.4 OPTIMIZATION OF PROCESS PARAMETERS

In this part, the effort has been made to optimize the depth of cut and the taper angle of the kerf for the abrasive water jet machining of borosilicate glass. Single-objective optimization and multi-objective optimization are used to optimize the process parameters so that we can get the desirable value of the responses.

6.4.1 Single-objective Optimization

In the present study, single-objective optimization has been carried out for the abrasive water jet machining of borosilicate glass. Here, the depth of cut and the taper angle of the kerf are optimized independently to find out the optimal combination of factors that maximizes or minimizes a response variable, and our aim is to maximize the depth of cut and minimize the taper angle of the kerf.

Fig 6.5 shows the individual optimization results for the depth of cut. In order to obtain the desired response, equal importance has been given to the lower, target, and upper bound of the linear desirability function. For linear desirability function (d), the value of the weight is considered as 1. MINITAB software has been used to obtain the optimum responses in abrasive water jet machining of borosilicate glass. The optimum depth of cut (14.4226 mm) has been obtained at a water pressure of 1358.3789 bar, abrasive flow rate of 53.9016 g/min, traverse speed of 212.2040 mm/min, and stand-off distance of 30.5072 mm.

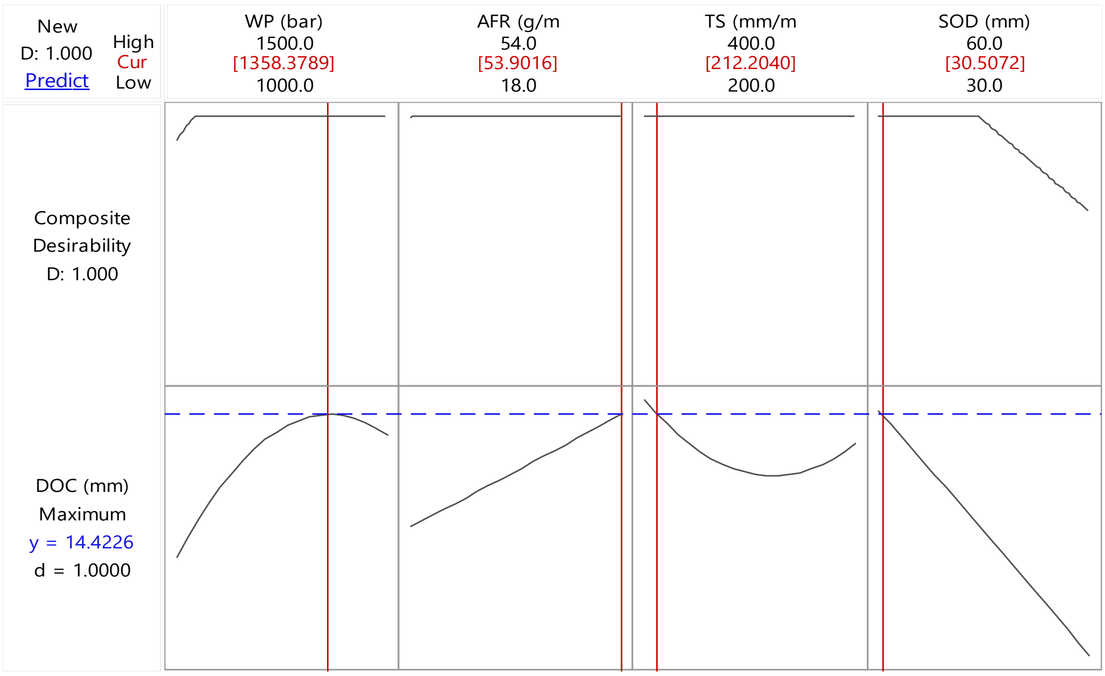


Fig 6.5 Optimization results for the depth of cut

Fig 6.6 shows the individual optimization results for the taper angle of the kerf. In order to obtain the desired response, equal importance has been given to the lower, target, and upper bound of the linear desirability function. For linear desirability function (d), the value of the weight is considered as 1. MINITAB software has been used to obtain the optimum responses in abrasive water jet machining of borosilicate glass. The optimum taper angle of the kerf (7.4794 degree) has been obtained at a water pressure of 1474.9545 bar, abrasive flow rate of 52.8525 g/min, traverse speed of 210.7468 mm/min, and stand-off distance of 32.8142 mm.

6.4.2 Multi-objective Optimization

In the present study, multi-objective optimization has been carried out for the abrasive water jet machining of borosilicate glass, and the optimization results of the depth of cut and taper angle of the kerf are shown in Fig 6.7. Here, these two responses are optimized together in one setting to find out the optimal combination of factors, and our aim is to maximize the depth of cut and minimize the taper angle of the kerf. This is due to the fact that the maximum taper angle can increase the material removal rate, which reduces the machining time and increases the productivity of the process. On the other hand, the taper angle of the kerf is minimized because it helps in increasing the accuracy and precision of the cut, which is important for machine parts that require tight tolerances or intricate designs. Each row of the graph corresponds to a response variable, and each column corresponds to one of the parameters considered during the abrasive water jet machining of borosilicate glass. Each cell of the graph shows the effect of one of the parameters on a response variable by keeping other parameters constant. The vertical line inside the graph represents the current parameter settings, and a horizontal dotted line represents the current response values. The numbers displayed at the top of a column show the current parameter level settings, the high value of that parameter, and the low value of that parameter setting in the experimental design. For linear desirability function (d), the value of the weight is considered as 1. On the left side of each row, the goal for the response (maximum for depth of cut and minimum for the taper angle of the kerf), the predicted response (y) at current parameter settings, and individual desirability scores are given. The current parameter settings are water pressure of 1449.4536 bar, abrasive flow rate of 49.7049 g/min, traverse speed of 238.4335 mm/min, and stand-off distance of 33.0328 mm for achieving the predicted minimum value of taper angle of the kerf (y_{TA}) of 7.8254 degree and maximum value of the depth of cut (y_{DOC}) of 13.4413 mm.

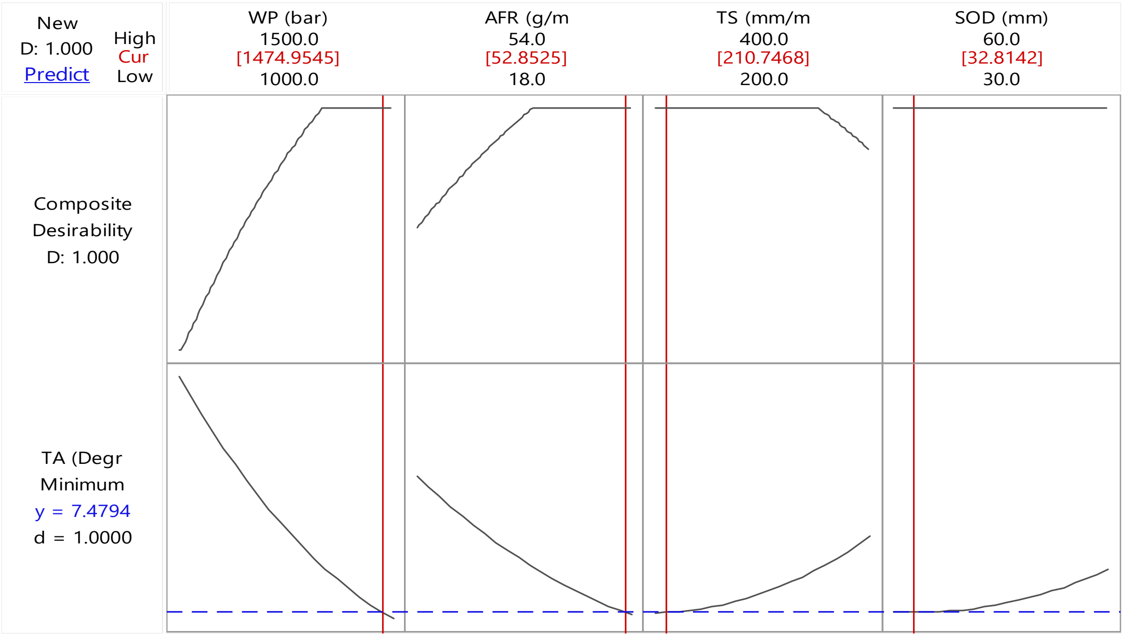


Fig 6.6 Optimization results for the taper angle of the kerf

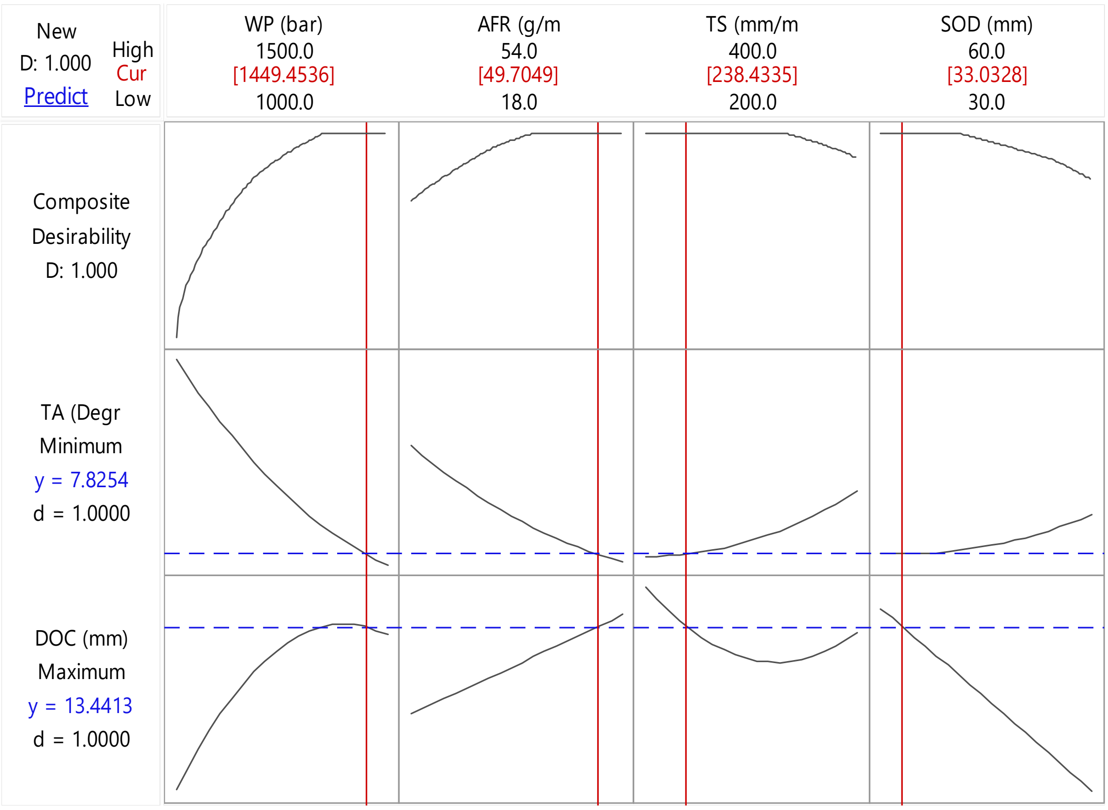


Fig 6.7 Multi-objective optimization results

6.5 FINAL VERIFICATION EXPERIMENTS

To verify the proposed mathematical models, three experiments have been carried out according to the parameter settings obtained from the optimization result for the maximum depth of cut, minimum taper angle of the kerf, and both responses together (i.e. maximum depth of cut, minimum taper angle of the kerf). These experimental results have been compared with the predicted optimum results of the responses and percentage errors in prediction are found which have been shown in Table 6.3. It was observed that the predicted value is quite close to the experimental result which is desirable.

Table 6.4: Final verification experiments

Responses	Parameter settings	Experimental results	Predicted Results	% Error in prediction
Maximum depth of cut (mm)	Water pressure 1358 bar, abrasive flow rate 54 g/min, traverse speed 212 mm/min, stand-off distance of 31 mm.	15.3442	14.4226	6.39
Minimum taper angle (degree)	Water pressure 1475 bar, abrasive flow rate 52.9 g/min, traverse speed 210.8 mm/min, stand-off distance 32.9 mm.	7.8705	7.4794	5.23
Maximum depth of cut (mm), minimum taper angle (degree)	Water pressure 1449.5 bar, abrasive flow rate 49.7 g/min, traverse speed 238.4 mm/min, stand-off distance 33 mm	14.1026, 8.2863	13.4413, 7.8254	5.89, 4.92

CHAPTER 7

CONCLUSION AND FUTURE SCOPE OF WORK

7.1 CONCLUSION

The present research carried out is an attempt to study and understand the effect of abrasive water jet machining on borosilicate glass. The principal objective of the present investigation is to understand the influence of different control parameters variation on the depth of cut and taper angle of the kerf. Based on the experimentation and investigations carried out, the following conclusions can be drawn:

- The RSM models that have been developed are adequate and can be used to accurately predict the responses for a set of parameters (minimum 95 percent confidence level).
- It is observed from the ANOVA table that for both the depth of cut and taper angle of the kerf, the most contributing factor is water pressure. However, the least contributing factor in the case of depth of cut is stand-off distance, while it is traverse speed for the taper angle of the kerf.
- It is also found that the depth of cut increases with an increase in both the water pressure and abrasive flow rate, while it decreases with an increase in both the traverse speed and stand-off distance. On the other hand, just the reverse relationship is found for the taper angle of the kerf.
- Both single-objective and multi-objective optimization have been carried out to find out the optimal values of the factors for achieving the predicted desired value of the responses. The optimum value of the two responses when predicted together are 13.4413 mm as the maximum value of the depth of cut, and 7.8254 degree as the minimum value of the taper angle of the kerf and are obtained at a water pressure of 1449.4536 bar, abrasive flow rate of 49.7049 g/min, traverse speed of 238.4335 mm/min, and stand-off distance of 33.0328 mm.
- Finally the proposed mathematical model has been verified by conducting a set of experiments according to the parameter settings obtained from the

optimization results and the percentage errors in prediction are calculated which is found within the desirable range.

7.2 FUTURE SCOPE OF PRESENT WORK

Apart from the present study that has been done, a lot of other work on abrasive water jet machining can be done as well. The following are the future scope of the present work as understood by the author:

- The use of AWJM for boring and turning could be researched.
- A better study of the effect of controlling parameters requires the modelling of the mean depth of cut and variation mean inclination angle.
- The effect of nozzle oscillation on kerf characteristics may be further studied.
- The pressure of water used in AWJM is very high, and at above 3800 bar pressure, water behaves as an incompressible fluid. So, in AWJM, water will act as a carrier fluid and will also erode the material. Hence, the combined effect of water and abrasive particles on both crystalline and amorphous materials should be studied.
- The burr formation in AWJM may be further studied.
- Apart from the technique used in the present study, several other techniques can be used for the design of experiment, and further optimization processes and comparisons can be made between the optimum parametric combinations determined by different techniques.

References

[1] Jagadish, Kapil Gupta, Abrasive Water Jet Machining of Engineering materials, Springer.

[2] Vijay K. Jain, Advanced Machining Processes, Allied Publishers Pvt. Ltd.

[3] T V K Gupta, In-Process Monitoring of Abrasive Water Jet Milling.

[4] Andreas W.Momber, Radovan Kovacevic, Principles of abrasive water jet machining, Springer Science & Business Media, 1998.

[5] Wang YF, Yang ZG, Finite element model of erosive wear on ductile and brittlematerials, Wear 265(5-6) (2008)871–8,

[6] H.C. Meng, K.C. Ludema, Wear models and predictive equations: their form and content, Wear 181–183 (2)(1995) 443-457, https://doi.org/10.1016/0043-1648(95)90158-2

[7] Mohamed Hashish, Visualization of the abrasive-waterjet cutting process, Exp. Mech. 28 (1998) 159–169, https://doi.org/10.1007/BF02317567

[8] Hutchings, IM, Mechanisms of the erosion of metals by solid particles. Erosion: prevention and useful applications, J ASTM Int (1979) 59–76.

[9] J.G.A. Bitter, A study of erosion phenomena part I, Wear 6 (1) (1963) 5–21,https://doi.org/10.1016/0043-1648(63)90003-6

[10]J.G.A. Bitter,A study of erosion phenomena: Part II, Wear 6 (3) (1963) 169–190,https://doi.org/10.1016/0043-1648(63)90073-5

[11] G. L. Sheldon, I. Finnie, The mechanism of material removal in the erosive cutting ofbrittle materials, J Manuf. Sci. Eng.88 (4) (1966)393–339, https://doi.org/10.1115/1.3672667

[12] Che CL, Huang CZ, Wang J, Zhu HT, Study of abrasive water jet polishing technology, Key Eng. Mater.487 (2011) 327–331,https://doi.org/10.4028/www.scientific.net/KEM.487.327

[13] NatarajanYuvaraj,MurugasenPradeep Kumar, Study and evaluation of abrasive water jet cuttingperformance on AA5083-H32 aluminum alloy by varying the jet impingementangles with different abrasive mesh sizes, Mach. Sci. Technol. 21 (3) (2017) 385–415,https://doi.org/10.1080/10910344.2017.1283958

[14]Xin-She Yang, Engineering Optimization: An Introduction with Metaheuristic Applications, John Wiley & Sons, (2010).

[15] Fengjun Chen, Yu. Jianliang Miao, Shaohui Yin Tang, Int. J. Adv. Manuf. Technol. 90 (2017) 785–799.

[16] M. Hashish, Cutting with abrasive water jets, Mech. Eng. 106 (3) (1984) 60-69.

[17] S. Bhowmik, Jagadish, A. Ray, Abrasive water jet machining of composite materials, inAdvanced Manufacturing Technologies, ed. by K. Gupta, Springer (2017)77–97.

[18] N. Yuvaraj, M. Pradeep Kumar, Multiresponse optimization of abrasive waterjet cutting process parameters using TOPSIS approach, Mater. Manuf. Process. 30 (7) (2015) 882–889, https://doi.org/10.1080/10426914.2014.994763

[19] Waheed Sami Abushanab, Essam B. Moustafa, Mooli Harish, S. Shanmugan, Ammar H. Elsheikh, Experimental investigation on surface characteristics of Ti6Al4V alloy during abrasive water jet machining process, Alexandria Engineering Journal 61 (10) (2022) 7529-7539, https://doi.org/10.1016/j.aej.2022.01.004

[20] Bharath Reddy Gunamgari, Manjeet Kharub, Experimental investigation on abrasive water jet cutting of high strength aluminum 7068 alloy, Mater. Today: Proc. 69 (2) (2022) 488-493, https://doi.org/10.1016/j.matpr.2022.09.180

[21] C. Joel, T. Jeyapoovan, Optimization of machinability parameters in abrasive water jet machining of AA7075 using Grey-Taguchi method, Mater. Today: Proc. 37 (2) (2021) 737-741, https://doi.org/10.1016/j.matpr.2020.05.741

[22] K. Karthik, David Smith Sundarsingh, M. Harivignesh, R. Gopi Karthick, M. Praveen, Optimization of machining parameters in abrasive water jet cutting of stainless steel 304, Mater. Today: Proc. 46 (2) (2021) 1384-1389, https://doi.org/10.1016/j.matpr.2021.02.489

[23] R. Selvam, N. Arunkumar, L. Karunamoorthy, An investigation on machining characteristics in abrasive water jet machining of hybrid laminated composites with SiC nano particles, Mater. Today: Proc. 39 (4) (2021) 1701-1709, https://doi.org/10.1016/j.matpr.2020.06.193

[24] Vootkuri Naveen Reddy, Bellam Venkatesh, Optimization of parameters in abrasive water jet machining of glass laminate aluminium reinforced epoxy

(GLARE), Mater. Today: Proc. 19(2) (2019) 890-894, https://doi.org/10.1016/j.matpr.2019.08.245

[25] M. Chithirai Pon Selvan, Divya Midhun chakkaravarthy, Rohan Senanayake, Swaroop Ramaswamy Pillai, Sahith Reddy Madara, A mathematical modelling of Abrasive Water jet Machining on Ti-6Al-4V using Artificial Neural Network, Mater. Today: Proc. 28 (2) (2020) 538-544, https://doi.org/10.1016/j.matpr.2019.12.215

[26]Arghya Bagchi, Madhulika Srivastava, Rupam Tripathi, Somnath Chattopadhyaya, Effect of different parameters on surface roughness and material removal rate in abrasive water jet cutting of Nimonic C263, Mater. Today: Proc. 27 (3) (2020) 2239-2242, https://doi.org/10.1016/j.matpr.2019.09.104

[27] K. Ravi Kumar, V.S. Sreebalaji, T. Pridhar, Characterization and optimization of Abrasive Water Jet Machining parameters of Aluminium /Tungsten carbide composite, Measurement 117 (2018) 57-66 https://doi.org/10.1016/j.measurement.2017.11.059

[28] Wang J, Kuriyagawa T, Huang CZ, An experimental study to enhance the cutting performance in abrasive waterjet machining, Mach Sci Technol7(2) (2003) 191–207, https://doi.org/10.1081/MST-120022777

[29] Deepak D, Anjaiah D, Shetty S, Optimization of Process Parameters in Abrasive Water Jet Drilling of D2 Steel to Produce Minimum Surface Roughness using Taguchi Approach, 6th International Conference on Electronics, Computer and Manufacturing Engineering (2017) 236–9, https://doi.org/10.17758/EAP.U0317104

[30] Manu R, RameshBabu N, Influence of jet impact angle on part geometry inabrasive waterjet turning of aluminium alloys, Int. J. Machining and Mach. of Mater. 3(1-2) (2008) 120–32, http://dx.doi.org/10.1504/IJMMM.2008.017629

[31] Selvan MC, Raju NM, Sachidananda HK, Effects of process parameters on surfaceroughness in abrasive waterjet cutting of aluminium, Front Mechn Eng. 7(4) (2012) 439–44.

[32] Kumar N, Shukla M, Finite element analysis of multi-particle impact on erosion inabrasive water jet machining of titanium alloy, J Comput Appl Math236(18)(2012) 4600–4610,

[33] Akkurt A, Cut front geometry characterization in cutting applications of brass withabrasive water jet, J Mater Eng Perform 19(4) (2010) 599–606,

[34] Azmir MA, Ahsan AK, A study of abrasive water jet machining process on glass/epoxy composite laminate, J. Mater. Process Technol. 209(20) (2009) 6168–73,

[35] Huang CZ, Hou RG, Wang J, Feng YX, The effect of high-pressure abrasive waterjet cutting parameters on cutting performance of granite, Key Eng. Mater. 304 (2006) 560–564,

[36] Naresh Babu M, Muthukrishnan N. Investigation on surface roughness in abrasivewater-jet machining by the response surface method. Mater Manuf Processes29(11–12) (2014) 1422–1428,

[37] Azmir MA, Ahsan AK, Rahmah A, Noor MM, Aziz AA. Regional conference onengineering mathematics, mechanics, manufacturing and architectureOptimization of abrasive water jet machining process parameters using orthogonalarray with grey relational analysis. 2007. p. 21–30.

[38] Srinivas S, Babu NR. Role of garnet and silicon carbide abrasives in abrasive waterjetcutting of aluminum-silicon carbide particulate metal matrix composites. IntJ Appl Res Mech 2011;1:109–22.

[39] Selvan MC, Raju NM. Analysis of surface roughness in abrasive waterjet cutting ofcast iron. Int J Sci Environ Technol 1(3) (2012) 174–82,

[40] Iqbal A, Dar NU, Hussain G. Optimization of abrasive water jet cutting of ductilematerials. J Wuhan Univ Technol-Mater Sci Ed 26(1) (2011) 88–92,

[41] Pal VK, Choudhury SK. Surface characterization and machining of blind pockets onTi6Al4V by abrasive water jet machining. Procedia Mater. Sci.5 (2014) 1584–92,

[42] Shipway PH, Fowler G, Pashby IR. Characteristics of the surface of a titanium alloyfollowing milling with abrasive waterjets. Wear 258(1–4) (2005)123–32,

[43] Powell M. American WJTA Conference and Expo, Optimization of UHP WaterjetCutting Heads the Orifice. 2007. p. 19–21,

[44] Jegaraj JJ, Babu NR. A strategy for efficient and quality cutting of materials withabrasive waterjets considering the variation in orifice and focusing nozzle diameter.Int J. Mach. Tools Manuf.45(12-13) (2005) 1443–50,

[45]Gudimetla P, Wang J, Wong W, Kerf formation analysis in the abrasive waterjetcutting of industrial ceramics, J Mater Process Technol 128 (1-3) (2002) 123–129

[46] Karakurt I, Aydin G, Aydiner K. Analysis of the kerf angle of the granite machinedby abrasive waterjet. Indian J. Eng. Mater. Sci. 18 (2011) 435–42,

[47] Fowler G, Pashby IR, Shipway PH. The effect of particle hardness and shape whenabrasive water jet milling titanium alloy Ti6Al4V, Wear 266(7-8) (2009) 613–20,

[48]Zohoor M, Nourian SH. Development of an algorithm for optimum control process to compensate the nozzle wear effect in cutting the hard and tough material using abrasive water jet cutting process, Int. J. Adv. Manuf. Technol 61 (9-12) (2012) 1019–28.

[49] Boud F, Loo LF, Kinnell PK, The impact of plain waterjet machining on the surface integrity of aluminium 7475, Procedia CIRP 13 (2014)382–386,

[50]Jiuan-Hung Ke , Feng-Che Tsai, Jung-Chou Hung, Biing-Hwa Yan, Characteristics Study of Flexible Magnetic Abrasive in Abrasive Jet Machining,Procedia CIRP 1 (2012) 679-680, https://doi.org/10.1016/j.procir.2012.05.025

[51] Putz M, Dix M, Morczinek F, Dittrich M. Suspension technology for abrasive waterjet (AWJ) cutting of ceramics. Procedia CIRP 2018;77:367–70.