Experimental analysis of piercing in titanium alloy using abrasive waterjet machine*

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Piercing,
Titanium Alloy.

ABSTRACT

Abrasive Water Jet Machining (AWJM) is one of the fastest growing non- traditional machining processes, which uses highly pressurized water mixed with abrasive particles and is capable of cutting even difficult-to-cut materials. It is used in the manufacturing of components with intricate shapes and profiles. Here the experimentation is conducted on abrasive water jet (AWJ) machining of the most commonly used titanium alloy, Ti-6Al-4V. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties The machining operations, i.e. drilling (or piercing), were conducted. For the experiments, the influences of water pressure and drilling time, mesh size and abrasive flow rate were investigated.

The experiments are carried out based on Response Surface Methodology (RSM) designed using Box-Behnken method for four parameters into three levels. Using response surface graphs the significant AWJM machining parameters and their levels are identified to achieve depth of cut, hole diameter and kerf width.

1. Introduction

1.1. Abrasive water jet machining

Abrasive water jet machining (AWJM) is one of the non-traditional machining processes used to machine difficult-to-machine materials. It employs a highly pressurized water jet along with abrasives and air. The momentum of high pressurized water is transferred to the abrasive particles and impinges on the work piece causing erosion. Industrial machining in the late 60's R. Franz of University of Michigan, examine the cutting of wood with high velocity jets. The first industrial application manufactured by McCartney Manufacturing Company and installed in Alto Boxboard in 1972. The invention of the abrasive water jet in 1980 and in 1983 the first commercial system with abrasive entrainment in the jet became available. The added abrasives increased the range of materials, which can be cut with a Watergate drastically. This technology is most widely used compare to other non-conventional technology because of its distinct advantages. It is used for cutting a wide variety of materials ranging from soft to hard materials. This technique is especially suitable for very soft, brittle and fibrous materials. This technology is less sensitive to material properties as it does not cause chatter.

The schematic view of AWJM nozzle head is shown below in Figure 1.1. AWJM system consists of high pressure water, abrasive port, mixing chamber, primary nozzle (orifice) and secondary nozzle (focusing tube), etc., AWJM is found to be superior to other machining techniques due to nearly zero thermal effects on the work piece,

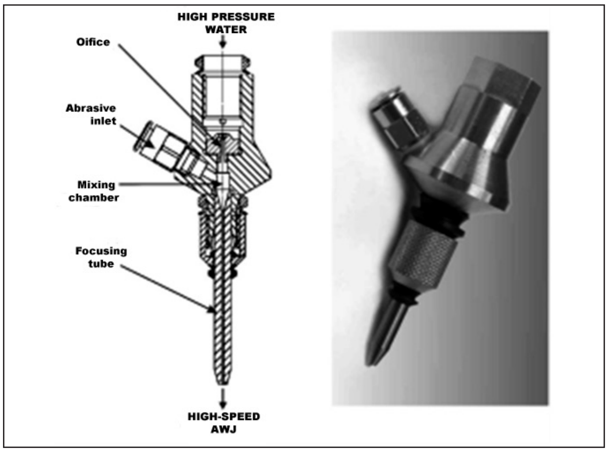

Fig. 1.1. Schematic views of AWJM nozzle head.

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simple fixturing, production of complex contoured parts, maintenance of material integrity, maximum material use as the geometry is nested, minimization of material waste as very small kerfs are produced, negligible sensitivity to material properties, etc.

The process parameters of AWJM greatly influence its machining performance. It is widely classified into four types namely (1) abrasive parameters: abrasive mass flow rate, abrasive size distribution, abrasive particle shape, diameter and hardness, etc., (2) cutting parameters: stand- off distance, impact angle, number of passes, traverse rate etc., (3) mixing chamber and acceleration parameters: focusing nozzle length, focusing nozzle inside diameter, etc. and (4) hydraulic parameters: water flow rate, pump pressure, orifice diameter, etc. Each of these parameters has been investigated by several researchers using experimental trials and their optimum values have been found. These values become indispensable when one advances towards condition monitoring. For any process to be completely automated and monitored, an in depth understanding of the interaction between the machine, work piece and tool is required. Hence, condition monitoring of AWJM is of primary importance for full automation. Condition monitoring is the continuous/periodic verification of few or all parameters of the system. It is usual to make sure that all system components are performing in close agreement to the optimum level or as a fault detection system. A comprehensive review on major research activity carried out so far by several researchers on condition monitoring of AWJM is also discussed here.

1.2. Classification of AWJM

AWJM is mainly classified into

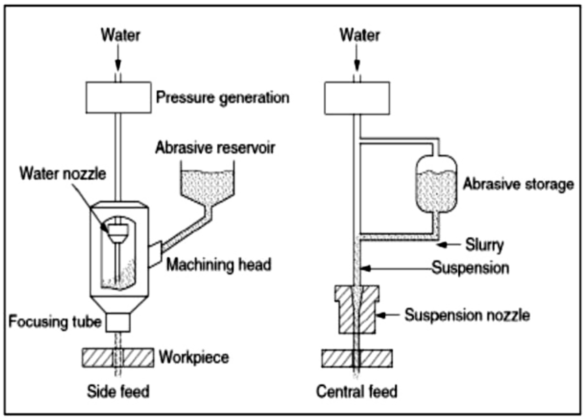


Fig. 1.2. Injection and suspension type of AWJM cutting heads

- Injection type AWJM (air, water and abrasives) and
- Suspension type AWJM phases (water and abrasives)

Figure 1.2 shows about the comparison view of injection and suspension type of AWJM cutting heads used commonly in Abrasive waterjet machine.

1.3. Important components of AWJM

A typical abrasive jet machining centre and their components are shown in Figure 1.3 follows;

1.3.1. Abrasive delivery system

A simple fixed abrasive flow rate is all that's needed for smooth, accurate cutting. Modern abrasive feed systems are eliminating the trouble-prone vibratory feeders and solids metering valves of earlier systems and using a simple fixed-diameter orifice to meter the abrasive flow from the bottom of a small feed hopper located immediately adjacent to the nozzle on the Y-axis carriage. An orifice metering system is extremely reliable and extremely repeatable. Once the flow of abrasive through the orifice is measured during machine set-up, the value can be entered into the control computer program and no adjustment or fine-tuning of abrasive flow will ever be needed. The small abrasive hopper located on the Y-axis carriage typically holds about a 45-minute supply of abrasive and can be refilled with a hand scoop while cutting is underway.

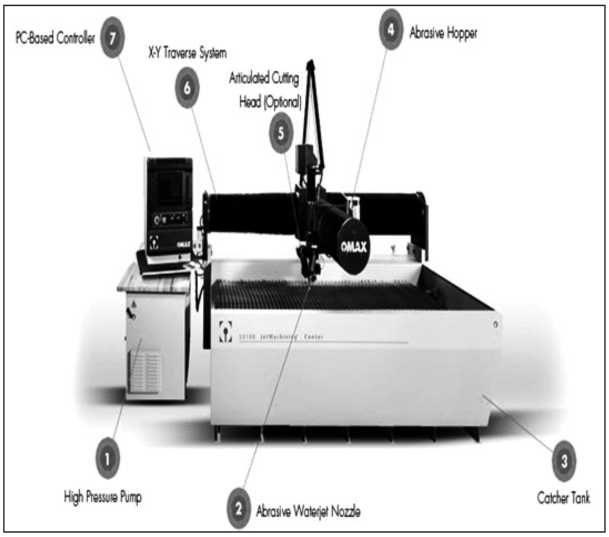


Fig. 1.3. Photograph of OMAX 2626 abrasive water jet machining centre

1.3.2. Control system

The control algorithm that computes exactly, how the feed rate should vary for a given geometry in a given material to make a precise part. The algorithm actually determines desired variations in the feed rate every 0.0005" (0.012 mm) along the tool path to provide an extremely smooth feed rate profile and a very accurate part. Using G-Code to convert this desired feed rate profile into actual control instructions for the servo motors would require a tremendous amount of programming and controller memory. Instead, the power and memory of the modern PC can be used to compute and store the entire tool path and feed rate profile and then directly drive the servomotors that control the X-Y motion. These results in a more precise part that is considerably easier to create if G-code programming were used.

1.3.4. Pump

Early ultra-high pressure cutting systems used hydraulic intensifier pumps exclusively. At the time, the intensifier pump was the only pump capable of reliably creating pressures high enough for water jet machining. An engine or electric motor drives a hydraulic pump which pumps hydraulic fluid at pressures from 1,000 to 4,000 psi (6,900 to 27,600 kPa) into the intensifier cylinder. The hydraulic fluid then pushes on a large piston to generate a high force on a small diameter plunger. This plunger pressurizes water to a level that is proportional to the relative cross-sectional areas of the large piston and the small plunger.

Nowadays AWJM uses crankshaft pumps. Crankshaft pumps are inherently more efficient than intensifier pumps because they do not require a power-robbing hydraulic system. In addition, crankshaft pumps with three or more cylinders can be designed to provide a very uniform pressure output without needing to use an attenuator system. Crankshaft pumps were not generally used in ultra-high pressure applications until fairly recently. This was because the typical crankshaft pump operated at more strokes per minute than an intensifier pump and caused unacceptably short life of seals and check valves. Improvements in seal designs and materials, combined with the wide availability and reduced cost of ceramic valve components, made it possible to operate a crankshaft pump in the 40,000 to 50,000 psi (280,000 to 345,000 kPa) range with excellent reliability.

1.3.5. Nozzle

All abrasive jet systems use the same basic two-stage nozzle as shown in the Figure 1.4. First, water passes through a small-diameter jewel orifice to form a narrow jet. The water jet then passes through a small chamber where a venturi effect creates a slight vacuum that pulls abrasive material and air into this area through a feed tube. The abrasive particles are accelerated by the moving stream of water and together they pass into a long, hollow cylindrical ceramic mixing tube. The resulting mix of abrasive and water exits the mixing tube as a coherent stream and cuts the material. It's critical that the jewel orifice and the mixing tube be precisely aligned to ensure that the water jet passes directly down the centre of the mixing tube. Otherwise the quality of the abrasive jet will be diffused, the quality of the cuts it produces will be poor, and the life of the mixing tube will be short. The mixing tube is where the abrasive mixes with the high-pressure water. The mixing tube should be replaced when tolerances drop below acceptable levels. (Ref. Fig 1.4)

For maximum accuracy, replace the mixing tube more frequently. The size of the kerf and cutting performance are the best indicators of mixing tube wear. The schematic view of the mixing tube is shown in the figure 1.5.

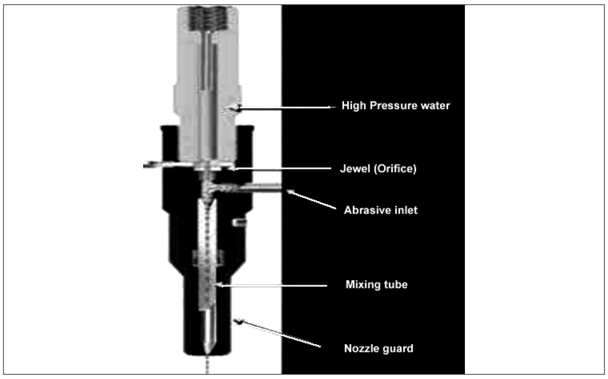


Fig. 1.4. Typical abrasive water jet nozzle

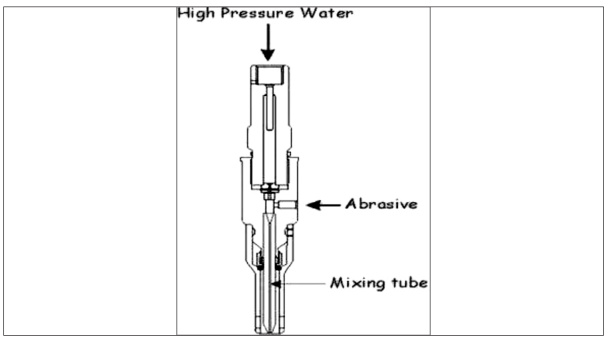


Fig. 1.5. Schematic view of mixing tube

1.3.6. Motion system

In order to make precision parts, an abrasive jet system must have a precision X-Y table and motion control system. Tables fall into three general categories:

- Floor-mounted gantry systems with separate cutting tables
- Integrated table/gantry systems
- Floor-mounted cantilever systems with separate cutting tables.

1.4. Advantages of Awjm

- Extremely versatile process
- No Heat Affected Zones
- No mechanical stresses
- Thin material cutting
- Little or no burr
- Unlike machining or grinding, water jet cutting does not produce any dust or particles that are harmful if inhaled.
- Pollution free process
- Any material can be machined.

1.5. Applications of AWJM

- Paint removal
- Cleaning
- Cutting soft materials
- Cutting frozen meat
- Textile, leather industry
- Mass Immunization
- Surgery
- Cutting
- Pocket milling
- Drilling
- Turning
- Nuclear plant dismantling.

1.6. The need for abrasive water jet machining

The working principles of AWJM are briefly presented here. A stream of small abrasive particles usually garnet is introduced in the high velocity water jet in such manner that water jet's momentum is partly transferred to the abrasive particles. The main role of water is primarily to accelerate the large quantities of abrasive particles to a high jet velocity. The jet is directed towards the target materials to perform machining the process parameters of AWJM are broadly classified into four categories namely (i) hydraulic parameter: pump pressure, orifice diameter, water flow rate, etc. (ii) mixing chamber

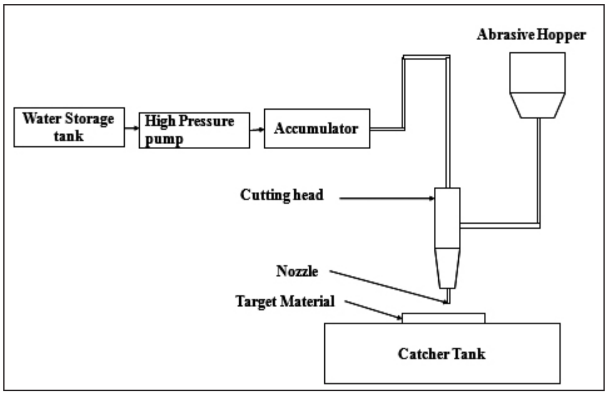


Fig. 1.6. The schematic diagram of the AWJM.

and acceleration parameters: focus nozzle diameter and focus nozzle length, etc. (iii) cutting parameters: traverse rate, number of passes, standoff distance, impact angle, etc. (iv) abrasive parameters: abrasive flow rate, abrasive particles diameter, abrasive size distribution, abrasive particle shape, abrasive particle hardness, etc. Various operations that can be performed in the AWJM are straight cut, contour cutting, drilling, milling, turning, cleaning, paint removal, nuclear plant dismantling, etc.

The schematic diagram of the AWJM is shown in the figure 1.6. Abrasive water jet (AWJ) machining is a technology in evident growth since its first industrial application in 1983. The flexibility of the process brought a rapid spread in various fields, beyond the process of cutting all types of materials. The milling process using AWJ was first considered and mentioned by Hashish in 1987.

The low cost of the process along with the productivity, the flexibility.

The advantages of AWJ over other unconventional machining operations are evident from the amount of research that is going on in the field. AWJ uses very high pressure water and the high pressure jet is passed through an orifice to convert pressure energy in to kinetic energy. The high velocity particle is mixed with abrasive material. The tube inside which mixing occurs is called mixing tube. Inside mixing tube momentum transfer takes place causing abrasive particle to gain momentum. The abrasive water mixture exits through nozzle of small diameter, because of reduction of diameter again velocity and momentum of abrasive water mixture increases. This high velocity mixture is made to impinge on the work piece. The material removal thus takes place due to abrasive action of high velocity abrasive particle. It's practical to use it to cut any kind of material. In AWJ cutting, there is no heat generated. This is especially useful for cutting tool steel and other metals where excessive heat may change the properties of the material. AWJ cutting does not leave a burr or a rough edge, and eliminates other machining operations such as finish sanding and grinding. It can be easily automated for production use.

2. Literature Survey

2.1. Abrasive water jet machining

Azmir and Ashan (1998) had done a practical for surface roughness and kerf taper ratio of glass/epoxy composite laminate machined by AWJM. They considered six process parameters of different level and use Taguchi method and ANOVA (analysis of variance) for optimization. Parameter used are abrasive types (two-level), hydraulic pressure (three-level), standoff distance (three-level), abrasive flow rate (three-level), traverse rate (three-level), cutting orientation (three-level). Kerf taper ratio is the ratio of top kerf width to bottom kerf width. Types of abrasives and traverse rate are insignificant for surface roughness while hydraulic pressure is most significant for that. Standoff distance, cutting orientation and abrasive mass flow rate is equally significant for surface roughness. For kerf taper ratio hydraulic pressure, abrasive mass flow rate and cutting orientation are insignificant. Types of abrasives are most significant for kerf taper ratio while Standoff distance and traverse rate are almost equally significant for that. By increasing the kinetic energy of AWJM process better quality of cut produce.

Jegaraj and Babu (2004) had worked on strategy for efficient and quality cutting of materials with abrasive water jets considering the variation in orifice and focusing nozzle diameter in cutting 6063-T6 aluminium alloy. They found the effect of orifice size and focusing nozzle diameter on depth of cut, material removal rate, cutting efficiency, Kerf geometry and surface roughness. The ratio of 3:1 between focusing nozzle diameter to orifice size was suggested as the best suited combination out of several combinations of focusing nozzle to orifice size in order to achieve the maximum depth of cut in cutting they suggest the ratio of 5:1 and beyond cause ineffective entrainment of abrasives in cutting head. It is noticed that with an increase in hydraulic pressure for different combinations of orifice and focusing nozzle size the depth of cut increased. The material removed increased with an increase in the size of focusing nozzle up to 1.2 mm diameter but with further increase it is reduced. The abrasive flow rate is found to be less significant on kerf width. This study suggests maintaining the orifice size and focusing nozzle size within certain limits say 0.25–0.3 mm and 1.2 mm, respectively, for maintaining less taper on kerf. Any increase in the size of orifice and focusing nozzle is not much affects the surface quality but larger size of orifice produces a better surface finish on cut surface.

Jurisevic et al (2003) made an attempt to establish an optimal stand-off distance for AWJM of aluminium alloy using sound sensor. They have observed that the stand-off distance has predominant influence on the work piece quality. Experiments are carried out on two work pieces having thickness of 6.1 mm and 50 mm with traverse rate of 6.5 mm/s and 0.5 mm/s respectively. Experiments are performed with different values of stand-off distance from 0.5 mm to 10 mm. The data recorded are sampled at a rate of 48 kHz. They have observed that the RMS values and Amplitude Cumulative Sum (ACS) values are found to be increasing with the increase in the stand-off distance. They have observed that the RMS and ACS values are found to be lower while machining 6.1 mm work piece compared to that of 50 mm work piece.

Wang and Wong (1996) had done study of abrasive water jet cutting of metallic coated sheet steels based on a statistically designed experiment. They discussed relationships between kerf characteristics and process parameters. They produce empirical models for kerf geometry and quality for the prediction and optimization of AWJ cutting performance. They perform three-level four-factor full factorial designed experiment. Process parameters used are water jet pressure, traverse speed, abrasive flow rate and standoff distance. The top and bottom kerf widths increase as the water pressure increase. The top and bottom kerf widths increase as the standoff distance increase but the rate of increase for the bottom kerf width is smaller. The traverse speed produces a negative effect on both the top and bottom kerf widths but the kerf taper increase as the traverse speed increase. The surface roughness decreases with an increase in the abrasive flow rate. They show the burr height steadily decreases with a decrease in the traverse speed.

A. A. Khan and M. M. Hague (1999) analysed the performance of different abrasive materials during abrasive water jet machining of glass. They make comparative analysis of the performance of garnet, aluminium oxide and silicon carbide abrasive in abrasive water-jet machining of glass. Their hardness of the abrasives was 1350, 2100 and 2500 knoops, respectively. Hardness is an important character of the abrasives that affect the cut geometry. The depth of penetration of the jet increases with the increase in hardness of the abrasives. They compare the effect of different of abrasive on taper of cut by varying cutting parameter standoff distance, work feed rate, pressure. It is found that the garnet abrasives produced the largest taper of cut followed by aluminium oxide and silicon carbide abrasives. For all kinds of abrasives, the taper of cut increases with SOD. For all the types of abrasives used taper of cut decreases with increase in jet pressure. Taper of cut is smaller for silicon carbide abrasives followed by aluminium oxide and garnet.

P K Ray and Paul (1995) had investigated that the MRR increases with increase of air pressure, grain size and with increase in nozzle diameter. MRR increases with increase in standoff distance (SOD) at a particular pressure. They found after work that initially MRR increases and then it is almost constant for small range and after that MRR decreased as SOD increases. They introduced a material removal factor (MRF). MRF is a non-dimensional parameter and it gives the weight of material removed per gram of abrasive particles. MRF decreases with increase in pressure that means the quantity of material removed per gram of abrasives at a lower pressure is higher than the quantity of material removed per gram of abrasives at a higher pressure. This is happened because at higher air pressure more number of abrasive particles is carried through the nozzle. So more number of inter particle collisions and hence more loss of energy.

2.2. Machining of hardened materials

Huai zhong Li 1 & Jun Wang(2015) had investigated and analysed a study on abrasive waterjet (AWJ) machining of the most commonly used titanium alloy, Ti-6Al-4V for drilling (piercing) and slotting, were conducted. For the drilling experiments, the influences of water pressure and drilling time were investigated. It was found that both the hole depth and diameter increased as drilling time increased but in a decreasing rate. An increase in the water pressure increased both the hole depth and the hole diameter. For the slot cutting, the influence of water pressure and the traverse speed were investigated. A slower traverse speed resulted in a deeper depth of cut. The kerf showed a taper shape with a wider entry on top, and the width decreased as jet cut into the material. At the bottom of the kerf, a pocket was generated. The variation of the depth of cut became insignificant when the traverse speed was increased.

Biermanna, Mark Wolf, Robert Abmutha (2012) has worked onan improvement in the efficiency of the cutting process requires high tool performance. For the tool performance the microscopic cutting edge shape is very important. By preparing the cutting edge the tool performance can be improved due to the reduction of the cutting edge chipping and the creation of a defined stable edge rounding. In this study, the influence of a cutting edge preparation on the deep hole drilling process is investigated. The aim is to increase the feed rate by a specific cutting edge design.

M Ramul, P Posinasetti and M. Hashish (2005) has analysed the deep hole drilling in hard-to-cut materials. However in AWJ drilling of blind holes, the backflow of the impacting jet and the standoff distance influences the shape of the hole drilled. This shape of the hole can be critical in applications where exact hole dimensions are required. The AWJ process parameters like pressure, flow rates etc also affect the dimensions of the hole as well as the time required drilling. The drilling time can be critical in applications where machining times are constraints. These effects and issues can be investigated through the mathematical modeling of the AWJ drilling process. Thus for a better understanding of the AWJ drilling process, a need exists to understand the models published so far to describe this process. This paper attempted to review briefly all the published models and critically evaluate them to highlight the advantages and the limitations of the existing models. Representative experimental data has been utilized as the common platform for evaluating all the models including the recently developed conical cavity model.

Hamatani and Ramulu (1990)[8] investigated slot cutting and piercing of MMC (Al 6061+30% of SiC) and CMC (TiB_2+20% of SiC). Experiments were carried out with garnet abrasive of different mesh size namely #80, #100, and #150. In the case of slot cutting, the abrasive flow rate, abrasive mesh size and traverse rate are varied. They have observed that increase in the abrasive particle size leads to increase in the kerf taper in both the MMC and CMC. Similarly, it is also observed that increased traverse rate leads to increase in the kerf taper. They have also observed that the increase in the traverse rate and abrasive particle size leads to increase in the R_a. The R_a values achieved with mesh size of #80 is found to be twice than that of achieved with abrasive of mesh size of #150. Increase in the abrasive flow rate results in the decreased R_a values. They also found that higher depth of cut is achieved with mesh #80 abrasives and lower depth of cut is observed with mesh #120 abrasives. Higher depth of cut is also achieved with multi-pass cutting SEM image indicates that during slot cutting the damage zone on the machined surface is found to be 500 µm. In the case of piercing, abrasive flow rate and standoff distance are varied while abrasive mesh size of #80 is maintained constant. They have observed that increase in the standoff distance results in the increased kerf taper. Linear behavior is found with MMC, while non-linear behavior is observed in CMC.

3. Experimental Details

In This Chapter, Various Equipments, Tools And Instruments Used In The Work Are Discussed Below.

3.1. AWJM Machine

The experiments are carried out in OMAX 2626 JET MACHINING CENTRE with AWJT setup, which is available in the Department of Manufacturing Engineering, Anna University, Chennai (Figure 3.1, 3.2, 3.3).

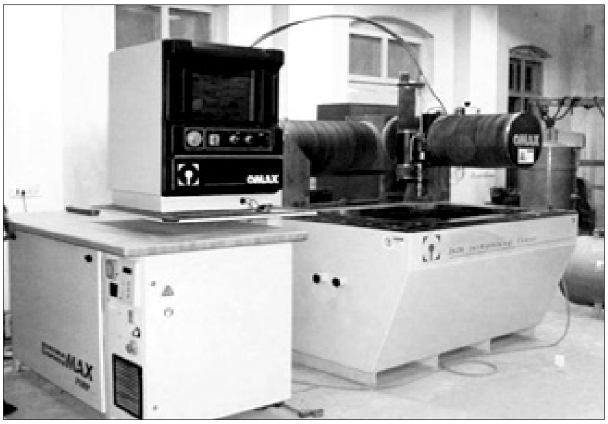


Fig. 3.1. Photograph of AWJ machine used in the project work (Side view).

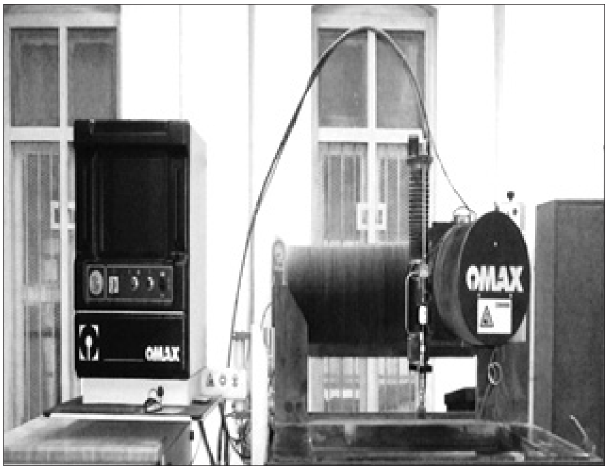


Fig. 3.2. Photograph of AWJ machine PC based controller for nozzle movement of the jet (Front view).

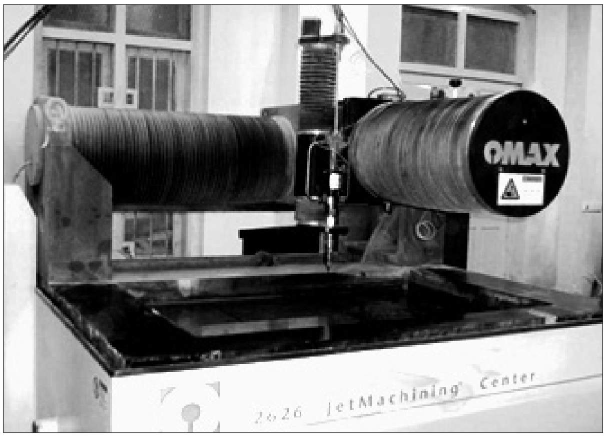


Fig. 3.3. Photograph of AWJ machine (closer view).

3.2. Material selection

- The material selected for this experimental analysis is Titanium alloy – Grade 5.
- Size of the material for machining is 110 x 30 x 30 mm
- Grade 5, also known as Ti6Al4V, Ti-6Al-4V or Ti 6-4, is the most commonly used alloy.
- It has a chemical composition of 6% aluminum, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, and the remainder titanium.
- It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties (excluding thermal conductivity, which is about 60% lower in Grade 5 Ti than in CP Ti).
- Among its many advantages, it is heat treatable.
- This grade is an excellent combination of strength, corrosion resistance, weld and fabricability.

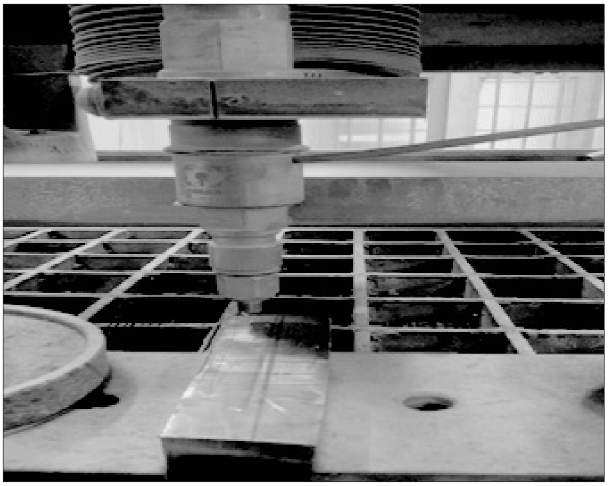


Fig. 3.4. Photograph of a work piece.

3.3. Major applications

- Blades
- Discs
- Rings
- Airframes
- Fasteners
- Components
- Vessels
- Cases
- Hubs
- Forgings
- Biomedical implants.

3.4. Experimental set – up

The following figure 3.4 explains about the experimental set up which carried out during the piercing process in AWJM.

Before the experimental set up is carried out for machining, the detailed study is made from the literature surveys about the piercing process in AWJM.

3.5. Piercing process

Drilling is one of the most common machining processes, accounting for most of the material removed by all metal cutting processes. It involves creating holes of right circular cylindrical shape, traditionally by employing rigid twist drills. In deep-hole applications, removal of the chips and cooling of the cutting front are significant issues involved with traditional drilling operations. However, the AWJ drilling or piercing process involves impacting the target material with an abrasive-laden water jet, directed normal to the target surface, to penetrate the material by erosion. The process is continuous and clean; leaving no heat affected zones or residual stresses. Since both the eroded material and any generated heat can leave the cavity with the out-flowing slurry, the issues of chip removal and cutting front cooling are avoided. The process of penetrating a material with a stationary AWJ can be broadly classified into three categories: piercing, trepanning, and drilling.

Piercing involves creating a hole through the entire thickness of the target material. Because the hole passes all the way through, the shape of the drilled cavity and the back-flow of the abrasive jet are not of much concern. Trepanning involves enlarging previously cut holes; thus, cavity shape and back-flow are again of less importance. The AWJ drilling process, however, involves creating blind holes, whose depth and internal shape may be difficult to control accurately. One problem is determining the time necessary to drill a hole down to a particular depth. Also, due to the nature of the abrasive jet and the mechanics of the erosion process, the jet may not necessarily produce straight-walled or non-tapered holes like traditional drills. Hole taper may not be acceptable in applications where accurate dimensions are required. Non-tapered through-holes are possible in piercing applications, but generally require keeping the jet on for some time beyond that required for simple piercing. To mathematically express the shape of the drilled cavity is quite complex, owing to the nature of the numerous machining parameters involved and the complex interactions among them. So there is a need for accurate models of the AWJ drilling process, which can be used to determine optimal ranges for process parameters under any arbitrary set of conditions.

3.6. Piercing process input parameters

The piercing process is carried out by the following input parameters;

- Water Pressure
- Drilling time
- Abrasive types
- Abrasive mesh size
- Abrasive flow rate
- Stand-off distance

These input parameters are statistically obtained from Box benhkan method, Design of expert software – RSM [Response surface methodology]

3.7. Response surface methodology (RSM)

RSM is a collection of statistical and mathematical methods that are useful for the modelling and analysing engineering problems. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters. RSM also quantifies the relationship between the controllable input parameters and the obtained response surfaces.

Response Surface Methodology (RSM) is the collection of experimental strategies, mathematical methods and statistical inferences that enable an experimenter to make efficient empirical exploration of the system of interest. RSM can be defined as a statistical method that uses quantitative data from appropriate experiments to determine and simultaneously solve multi-variable equations. The work which initially generated interest in the package of techniques was a paper by (Box and Wilson, 1951). Iqbal and Khan (2010) have been involved in developing prediction models using this renowned response surface methodology for their machining studies.

3.8. Rsm can be used in the following ways

- To determine the factor levels that will simultaneously satisfy a set of desired specifications.
- To determine the optimum combination of factors that yields a desired response and describes the response near the optimum.
- To determine how a specific response is affected by changes in the level of the factors over the specified levels of interest.
- To achieve a quantitative understanding of the system behaviour over the region tested
- To predict product properties throughout the region, even for a factor combinations not actually run.
- To find the conditions necessary.

3.9. Box- behnken design

In this study, the box-behnken experimental design was chosen for finding out optimized piercing output parameters and regression equations which gives the relationship between the response functions hole diameter and hole depth.

Box-Behnken design is rotatable second-order designs based on three-level fractional factorial designs. The special arrangement of the Box-Behnken design levels allows the number of design points to increase at the same rate as the number of polynomial coefficients. The geometry of a Box-Behnken design is shown in Figure 3.5.

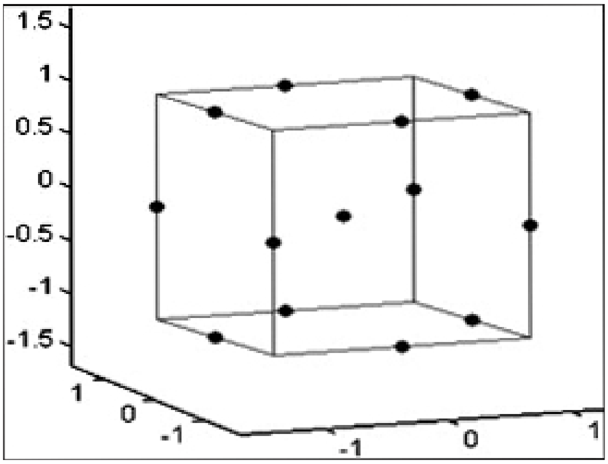


Fig. 3.5. Box-Behnken design.

Table 3.1.
AWJM Input parameters.

S.No	Description	Low	Medium	High
1	Water Jet Pressure (MPa)	125	200	275
2	Abrasive Flow rate (g/min)	240	340	440
3	Abrasive mesh size (#)	80	100	120
4	Time (s)	10	20	30

Reason for the selection of Box-Behnken design over central composite design is for fewer no. of input factors (here four) lesser no. of experiments is required than central composite design (Aslan 2007).

3.10. Level – input parameter-using RSM

The table 3.1 shows the input parameters which are considered during machining process.

The allotted AWJ machining parameters in the RSM table and experimental results are shown in the Table 3.2.

3.11. Machining process

The above figure 3.6 shows the drawing of the workpiece to be machined for the piercing

Table 3.2.
The allotted AWJ machining parameters.

S.No	Mesh size (#)	Abrasive flow rate (g/min)	Waterjet pressure (Mpa)	Time (sec)
1	80	240	200	20
2	120	240	200	20
3	80	440	200	20
4	120	440	200	20
5	100	340	125	10
6	100	340	275	10
7	100	340	125	30
8	100	340	275	30
9	80	340	200	10
10	120	340	200	10
11	80	340	200	30
12	120	340	200	30
13	100	240	125	20
14	100	440	125	20
15	100	240	275	20
16	100	440	275	20
17	80	340	125	20
18	120	340	125	20
19	80	340	275	20
20	120	340	275	20
21	100	240	200	10
22	100	440	200	10
23	100	240	200	30
24	100	440	200	30
25	100	340	200	20
26	100	340	200	20
27	100	340	200	20
28	100	340	200	20
29	100	340	200	20

process. The below figure 3.7 shows the piercing process from left to right during machining.

The figure 3.8 shows the material after the machining process. The 29 pierced holes can be seen clearly in the Fig. 3.8.

3.12. Measurement of hole diameter

The pierced hole diameter for 29 holes of the material are measured using Video measuring

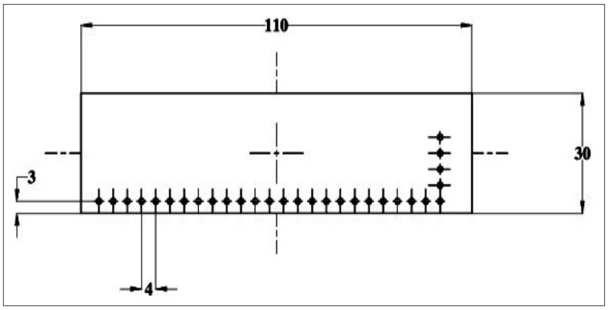


Fig. 3.6. Drawing of the work piece AUTOCAD 2013 [All dimensions are in 'mm'].

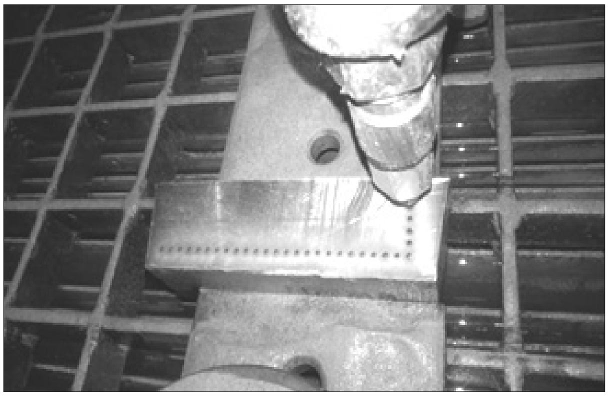


Fig. 3.7. Piercing operations during machining process.

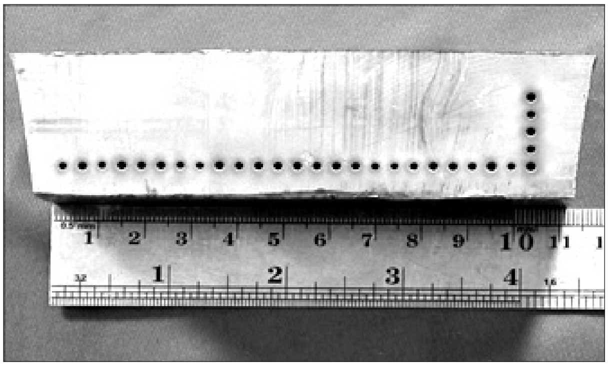


Fig. 3.8. Material after machining process. [With scale].

device. The figure 3.9 shows the workpiece on the table of the video measuring device.

The figure 3.10 shows the measurement of a sample hole diameter in the video measuring device.

The figure 3.11 shows the sample hole diameter measured in the video measuring device. The hole diameter shown below are the sample holes pierced with #80, #100, #120 mesh sizes.

3.13. Measurement of hole depth and kerf width

The pierced hole diameter is measured using video measuring device. Some parameters of the hole diameters are measured using SEM

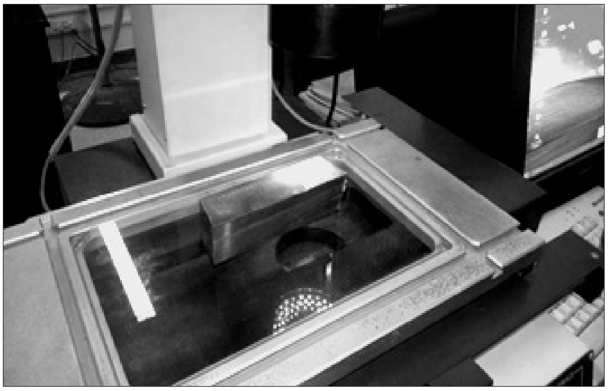


Fig. 3.9. Work piece on the table of video measuring device.

Fig. 3.10. Measurement of a sample hole diameter.

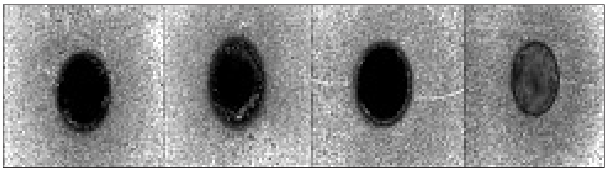


Fig. 3.11. Image of sample hole diameter measured.

according to the mesh sizes with respect to larger and smaller hole diameters. Hence to find out the hole depth, the workpiece is cross sectioned using CNC Wire cut Micro – EDM machine. The below figure 3.12 shows a clear view of the workpiece after the machining process in EDM machine which it made a traverse crossectional cut along the center axis of the 29 pierced holes. This picture illustrates a clear idea to investigate hole depth and kerf width.

The figure 3.13 shows a clear view of hole depth and the impact of the penetration occurred due to the abrasive particles collide on the workpiece during machining process.

These hole depths are measured using video measuring device and to make a complete analyze on the hole depth, higher resolution images are taken corresponding to the hole diameters.

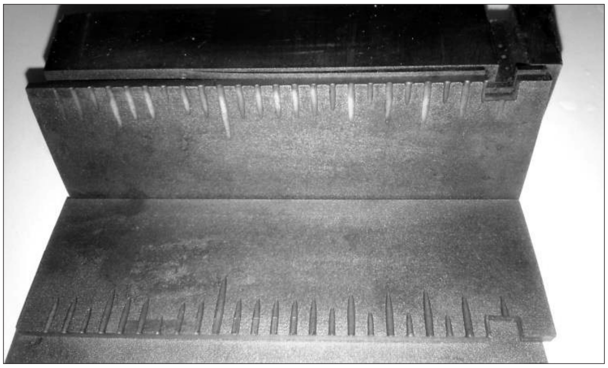


Fig. 3.12. Image of crossectional view of the work piece made towards the centre of hole diameter.

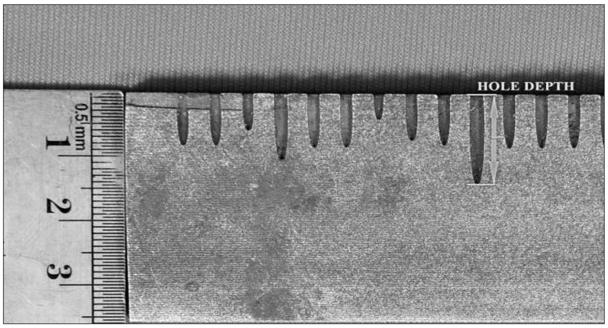


Fig. 3.13. Various hole depths captured for measuring.

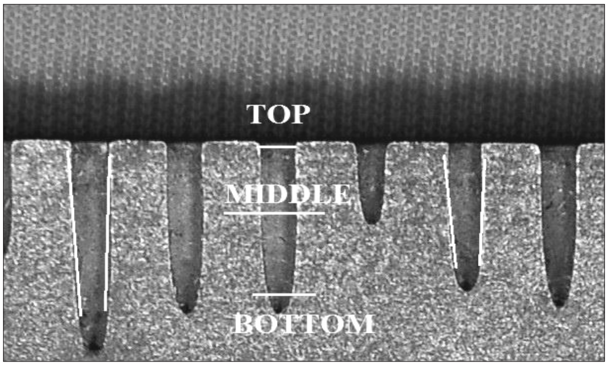


Fig. 3.14. Various kerf width captured for measuring.

The dimensions of kerf width are noted corresponding to the hole diameter and hole depth. The figure 3.14 shows a clear view of kerf width occurred and how it is measured.

These kerf widths are measured using video measuring device and to make a complete analyze on the kerf width, higher resolution images are taken corresponding to the hole diameters.

The output parameters of 29 hole diameters are measured using video measuring machine and the measured larger holes, smaller holes, rough finish in hole diameters and smooth finish in hole diameters are clearly analyzed using SEM images. These images shown in Fig. 3.15, 3.16

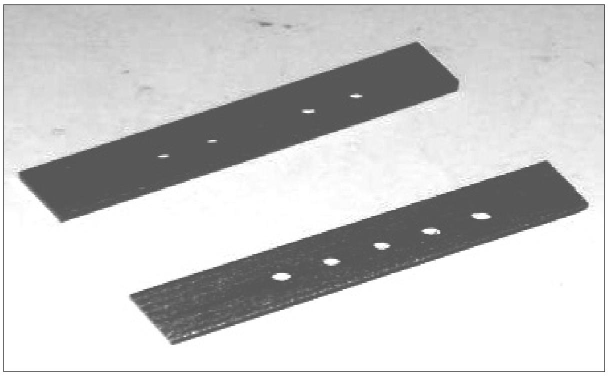


Fig. 3.15. Specimen for SEM analysis.

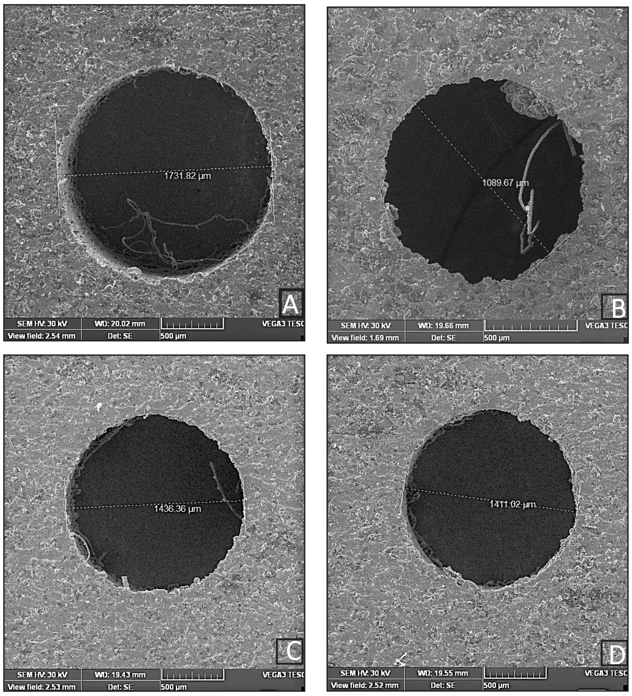


Fig. 3.16. SEM image: A,B,C,D.

The figure 3.15 shows the specimen splited from the workpiece for the SEM analysis.

The figure 3.16 shows the SEM image samples of larger hole diameter, smaller hole diameter, Rough finish occurrence in hole diameter and smooth finish occurred in hole diameter.

The figure 3.16 – (A) clearly shows the hole diameter is larger with burrs filled in it. This occurrence is mainly due to the larger abrasive grain size #80 with decrease in time.

The figure 3.16 – (B) clearly shows the hole diameter is larger with burrs filled in it. This occurrence is mainly due to the larger abrasive grain size #80 with increase in time.

The figure 3.16 – (C) clearly shows the hole diameter is larger with rough finish filled inside it. This occurrence is mainly due to the medium abrasive grain size #100 with decrease in time

The figure 3.16 – (D) clearly shows the hole diameter is larger with smooth finish filled inside in it. This occurrence is mainly due to the smaller abrasive grain size #120 with increase in time.

The obtained and measured values are entered in the table 3.3 for hole diameter, hole depth and kerf width.

The table 3.3, shows; the values are segregated based on mesh sizes # 80, 100, 120.

4. Results and Discussions

4.1. Response surface of output parameters for various combinations

a) Mesh size Vs Abrasive flow rate)
b) Mesh size Vs Water jet pressure
c) Mesh size Vs Drilling time
d) Abrasive flow rate Vs Water jet pressure
e) Drilling time Vs Abrasive flow rate
f) Drilling time Vs Water jet pressure

4.2. Analysis of hole diameter (Ref. Fig. 4.1)

Fig. 4.1 shows the response surface graphs that are resulted in higher hole diameter with various combinations of AWJM process parameters and their levels in the titanium alloy- grade 5.

Fig. 4a, shows that the higher diameter is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). among these combinations, it is observed that by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min) while, the waterjet pressure is held at high level (275 mpa) and the drilling time is held at high level (30 s) leads to higher diameter. The hole diameter value achievable with the above combinations is found to be around 1.65 mm (Fig. 4a).

Fig. 4b, shows that the higher diameter is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). among these combinations, it is observed that by varying the abrasive mesh size

Table 3.3.
Measured output parameters.

S. No	Mesh Size (#)	Abrasive Flow Rate (G/Min)	Waterjet Pressure (Mpa)	Time (Sec)	Hole DIAMETER (mm)	Hole Depth (mm)	Kerf Width (mm)		
							Top	Middle	Bottom
1	80	240	200	20	1.514	7.910	1.514	1.437	0.478
2	80	440	200	20	1.519	7.968	1.519	1.470	0.427
3	80	340	200	10	1.649	5.674	1.649	1.358	0.529
4	80	340	200	30	1.440	10.359	1.440	1.707	0.544
5	80	340	125	20	1.686	8.230	1.686	1.589	0.558
6	80	340	275	20	1.596	8.246	1.596	1.591	0.486
7	100	340	125	10	1.594	3.982	1.594	1.212	0.521
8	100	340	275	10	1.307	7.115	1.307	1.515	0.568
9	100	340	125	30	1.467	7.826	1.467	1.570	0.546
10	100	340	275	30	1.657	13.910	1.657	1.890	0.509
11	100	340	200	20	1.524	8.266	1.524	1.593	0.523
12	100	340	200	20	1.581	8.246	1.581	1.577	0.587
13	100	340	200	20	1.583	8.179	1.583	1.582	0..446
14	100	340	200	20	1.575	8.089	1.575	1.559	0.589
15	100	340	200	20	1.577	8.252	1.577	1.577	0.484
16	100	240	125	20	1.581	6.406	1.581	1.405	0.533
17	100	240	275	20	1.453	9.338	1.453	1.681	0.588
18	100	240	200	10	1.549	5.394	1.549	1.338	0.527
19	100	240	200	30	1.364	9.510	1.364	1.654	0.604
20	100	440	125	20	1.577	5.380	1.577	1.320	0.526
21	100	440	275	20	1.530	10.892	1.530	1.316	0.496
22	100	440	200	10	1.681	5.118	1.681	1.500	1.610
23	100	440	200	30	1.419	9.650	1.419	1.327	0.283
24	120	340	200	10	1.769	5.080	1.769	1.501	1.320
25	120	340	200	30	1.404	8.550	1.404	1.365	0.320
26	120	340	275	20	1.684	10.123	1.684	1.550	0.245
27	120	340	125	20	1.605	9.560	1.605	1.590	0.520
28	120	240	200	20	1.534	8.545	1.534	1.420	0.603
29	120	440	200	20	1.488	10.101	1.488	1.400	0.488

(#80–120) and abrasive flow rate (240–440 g/min) while, the abrasive flow rate is held at high level (440 g/min) and the drilling time is held at low level (10 s) leads to higher diameter. The hole diameter value achievable with the above combinations is found to be around 1.65 mm (fig. 4b).

Fig. 4c, shows that the higher diameter is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). among these combinations, it is observed that by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min) while, the abrasive flow rate is held at high level (440 g/min) and the water pressure is held at higher level (275 Mpa) leads to higher diameter. The hole diameter value achievable with the above combinations is found to be around 1.65 mm (Fig. 4c).

Fig. 4d, shows that the higher diameter is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). among these combinations, it is observed that by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min) while, the abrasive mesh size is held at low level and the drilling time is held at lower level (10s) leads to higher diameter. The hole diameter value achievable with the above combinations is found to be around 1.65 mm (Fig. 4d).

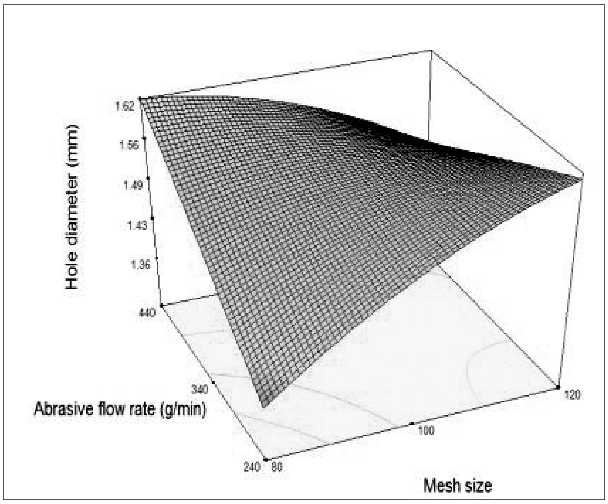
Fig. 4e, shows that the higher diameter is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). among these combinations, it is observed that by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min) while, the abrasive mesh size is held at low level and the water pressure is held at higher level (275 Mpa) leads to higher diameter. The hole diameter value achievable with the above combinations is found to be around 1.65 mm (Fig. 4e).

Fig. 4f, shows that the higher diameter is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). Among these combinations, it is observed that by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min) while, the abrasive mesh size is held at low level and the abrasive flow rate is held at higher level leads to higher diameter. The hole diameter value achievable with the above combinations is found to be around 1.65 mm (fig. 4f). From fig. 4.1, it is generally found that low abrasive mesh size (# 80) is the most influencing factor for higher hole diameter in the material studied in this work. Mesh size (#80) abrasive is bigger than that of the other mesh size of abrasives used in this work. this is due to the fact that bigger sizes ofabrasives posses higher energy, which leads to higher hole diameter. In the case of abrasive flow rate, higher abrasive flow rate leads to higher hole diameter. This is due to the fact that an increase in abrasive flow rate results in increased number of abrasive particles impinging on the target material, which leads to higher hole diameter. In the case of waterjet pressure, high waterjet pressure increases higher hole diameter. This is due to fact of higher waterjet pressure, increases the kinetic energy of the jet and leads to higher hole diameter. In the case of drilling time, it is found that a low drilling time, results in higher hole diameter. This is due to the fact that during lower drilling time, more number of abrasive particles will impact and participate in material removal process and hence results of higher hole diameter. The table 4.1 explains about the analysis of variance. (Ref. Tab. 4.1).

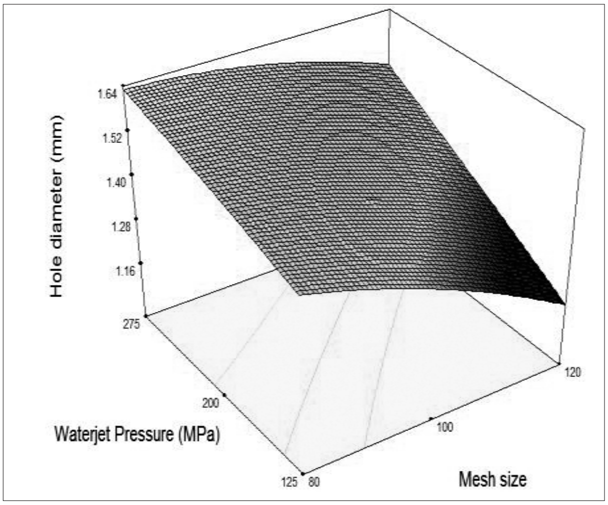
4.3. Analysis of holedepth

Similarly the response surface output parameters for hole depth is also taken and noted from design of expert software as the same procedure followed in hole diameter. The sample response surface output parameter for hole depth is shown in the figure 4.2.

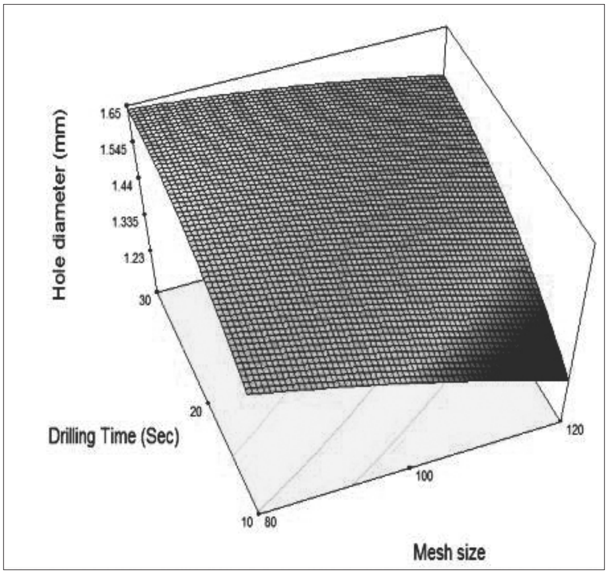
Figure 4.2, shows that the higher hole depth is achieved by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min), while waterjet pressure and drilling time are maintained at any one levels (low, medium and high). among these combinations, it is observed that by varying the abrasive mesh size (#80–120) and abrasive flow rate (240–440 g/min) while, the waterjet pressure is held at high level (275 mpa) and the drilling time is held at high level (30 s) leads to higher hole depth. The holedepth value achievable with the above combinations is found to be around 14.10 mm.



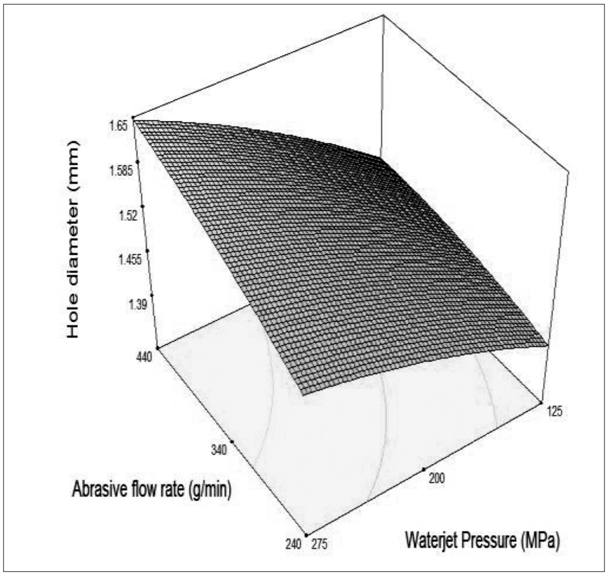
a) Mesh size Vs Abrasive flow rate



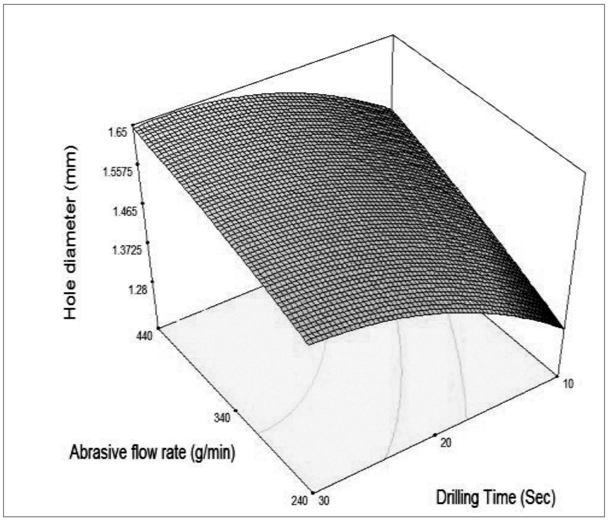
b) Mesh size Vs Water jet pressure



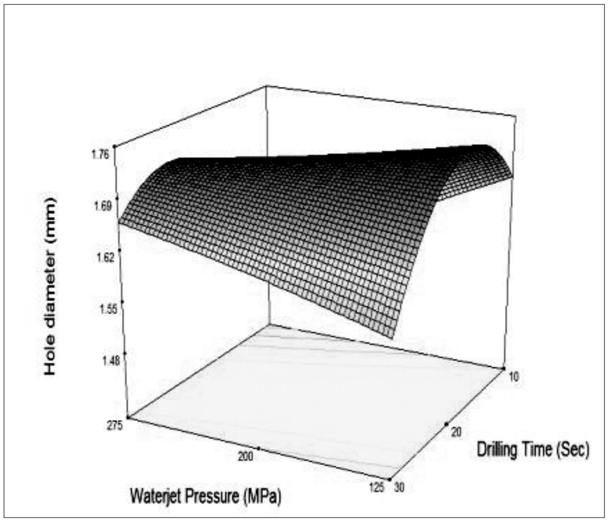
c) Mesh size Vs Drilling time



d) Abrasive flow rate Vs Water jet pressure



e) Drilling time Vs Abrasive flow rate



f) Drilling time Vs Water jet pressure

Fig. 4.1. Response surfaces of output parameters for various combinations.

Table 4.1.
Anova Table For Hole Diameter.

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	
Model	0.262994	14	0.018785	1.45042	0.002	significant
A- water pressure	0.049408	1	0.049408	3.814836	0.0011	
B-AFR	0.011347	1	0.011347	0.876087	0.3651	
C-mesh size	0.000574	1	0.000574	0.044325	0.001	significant
D-Time	0.0076	1	0.0076	0.586825	0.002	significant
AB	0.0402	1	0.0402	3.103876	0.0999	
AC	0.00714	1	0.00714	0.551301	0.4701	
AD	0.000784	1	0.000784	0.060533	0.8092	
BC	0.00164	1	0.00164	0.126644	0.001	significant
BD	0.001482	1	0.001482	0.114445	0.7402	
CD	0.019182	1	0.019182	1.481069	0.2437	
A^2	0.019735	1	0.019735	1.523728	0.2374	
B^2	0.003274	1	0.003274	0.252791	0.6229	
C^2	0.000181	1	0.000181	0.01398	0.9076	
D^2	0.097192	1	0.097192	7.504247	0.0160	
Residual	0.181323	14	0.012952			
Lack of Fit	0.178848	10	0.017885	28.90232	0.0027	Significant
Pure Error	0.002475	4	0.000619			
Cor Total	0.444317	28				

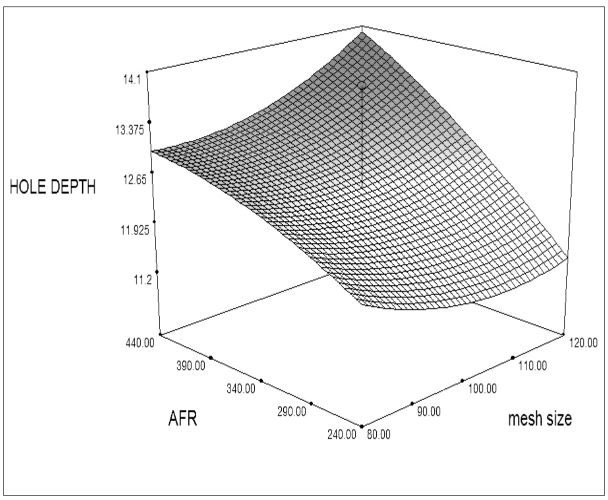


Fig. 4.2. Response surfaces of parameter for hole depth

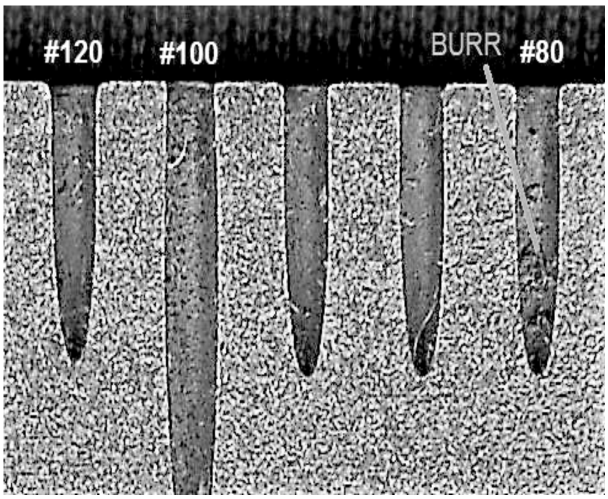


Fig. 4.3. Analysis of kerf width.

Table 4.2.
Analysis of variance table or hole depth. [Partial sum of squares-Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Probe > F	
Model	*103.20*	14	*7.37*	5.23	*0.0019*	**significant**
A-A	*1.07*	1	*1.07*	0.76	*0.3975*	
B-B	*0.34*	1	*0.34*	0.24	*0.6310*	
C-C	*27.72*	1	*27.72*	19.67	*0.0006*	
D-D	*62.79*	1	*62.79*	44.54	*<0.0001*	
AB	*0.57*	1	*0.57*	0.40	*0.5351*	
AC	*0.076*	1	*0.076*	0.054	*0.8202*	
AD	*0.37*	1	*0.37*	0.26	*0.6183*	
BC	*1.68*	1	*1.68*	1.19	*0.2938*	
BD	*0.044*	1	*0.044*	0.031	*0.8621*	
CD	*2.19*	1	*2.19*	1.55	*0.2330*	
A2	*0.67*	1	*0.67*	0.48	*0.5012*	
B2	*0.25*	1	*0.25*	0.17	*0.6831*	
C2	*1.07*	1	*1.07*	0.76	*0.3989*	
D2	*3.18*	1	*3.18*	2.26	*0.1551*	
Residual	*19.74*	14	*1.41*			
Lack of Fit	*19.71*	10	*1.97*	339.86	*<0.0001*	**significant**
Pure Error	*0.023*	4	*5.801E-003*			
Cor Total	*122.94*	28				

The table 4.2 shows about the analysis of variance table for hole depth. (Ref. Table. 5.2)

4.4. Analysis of kerf width

The kerf width is analyzed based on the mesh sizes through higher resolution images. The figure 4.3 shows a clear view of kerf width based on the comparison of mesh sizes. (Ref. Fig. 4.3)

From the above figure 4.3, it clearly shows that the mesh size plays a major role in the increasing or decreasing of kerf width. The larger grain size #80 makes a greater kerf width with rough finish and even with the burrs as shown in figure. The smaller grain size #120 makes a smaller kerf width with smooth finish when compared to #80 and #100.

5. Conclusion

- An experimental study on AWJ machining of Ti-6Al-4V has been made. AWJ drilling have been considered in the study and from the hole piercing experiments, the influences of mesh size, Abrasive flow rate, Waterjet pressure and drilling time were investigated.
- The experiments were conducted using RSM with Box-Behnken design. The signification AWJM process parameters and their levels are identified for achieving maximum and minimum hole diameter, deeper and smaller hole depth and wider and smaller kerf width.
- From the hole piercing experiments, it was found that both the hole depth and diameter increased as drilling time increased but in a decreasing rate.
- An increase in the water pressure increased both the hole depth and the hole diameter.
- The kerf showed a taper shape with a wide entry on top, and the width decreased as jet cut in to the material. At the bottom of kerf, a pocket was generated.

6. References

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