CHAPTER 1

INTRODUCTION

Machining is the term related to a number of manufacturing processes that are used to remove unwanted material from the workpiece, usually in form of chips. The conventional machining processes(turning, boring ,milling, broaching, shaping, slotting, etc.) usually results in very high machining cost, and decrease in strength of the workpiece, etc. therefore a need of machining process which give adequate material removal rate as well as minimum damage to the workpiece properties. In addition to this complexity of the work surface, machining of intricate shapes and size led to the development of advanced machining processes(non-conventional or non-traditional machining process).

Abrasive Jet Machining. Laser Beam Machining, Electro-Discharge Machining, Electron Beam Machining, Ultrasonic Machining, etc. are the different machining processes.

1.1 Non-conventional machining process - Classification

The technological developments over the past 60 years have prompted the creation of new, difficult to machine materials such as metal-matrix composites, monolithic and composite ceramics, aluminides and high performance polymers. The difficulty in machining these and other new materials results from their high hardness and brittleness, high refractoriness, poor thermal properties, chemical reactivity with the cutting tool and inhomogeneous microstructures. Thus the only effective way to machine such materials is by non-traditional methods.[4]Non-traditional machining process are subdivided according to the type of energy being harnessed. The sub categories are mechanical, electrical, thermal and chemical.

1.1.1 Mechanical methods:

Mechanical non-traditional process harnessdirect mechanical action to remove material mechanical processes are usually applied to workpiece material that are difficult to machine by traditional techniques because of material hardness, toughness or brittleness. Ceramics, composites or organic materials are particularly good candidates for mechanical machining because most of them are not electrically conductive and because they are damaged by burning, charring or cracking when thermal processes are applied.

- Abrasive Jet Machining(AJM)
- Abrasive Flow Machining(AFM)
- Water Jet Machining(WJM)
- Abrasive Water Jet Machining(AWJM)
- Ultrasonic Machining(USM)

1.1.2 Electrical methods:

The electrical non-traditional processes are limited in application to electrically conductive workpiece materials. These processes are selected because of the ability of the electrical processes to produce complex shapes in a single pass of the tool and to process parts without tool wear.

- Electrochemical Machining(ECM)
- Electrochemical Grinding(ECG)
- Electrochemical Discharge Grinding(ECG)
- Electrostream Drilling(ES)

Thermal methods: mainly because of the rapid increase in the sales of wire electrical discharge machining and laser equipment, thermal process become the fastest growing segment in the nontraditional market. Thermal processes are generally unaffected by the physical properties of the materials being processed and therefore often applied to extremely hard or low-machinability workpiece materials. Since the mechanism of material removal is thermal workpiece that will be used for critical application may require the removal of thermally affected zones.

- Electrical Discharge Machining(ECM)
- Electrical Discharge Wire Cutting(EDWC)
- Electrical Discharge Grinding(EDM)
- Electrical Beam Machining(EBM)
- Laser Beam Machining(LBM)

1.1.3 Chemical Methods:

High-volume, high production manufacturing is often performed by chemical non-traditional processes. Chemical machining has gained wide acceptance for the economical manufacture of high volume products such as springs, electrical motor laminations and television picture tube masks. Because material is removed by means of chemical action there is no forces acting on the workpiece. This enables parts to be machined without concern for distortion or damage.

- Chemical Milling(CM)
- Photochemical Machining(PCM)

1.2 Need for Non-Traditional Machining

For a long time conventional machining meet the requirement of the industries over the decades. But new improved work materials of higher strengthas well as innovative geometric design and intricate shapes of the products and components were putting lot of pressure on capabilities of conventional machining processes to manufacture the components with desired tolerances skillfully and economically. This led to the development Non-Traditional Machining processes in the industry as an economic alternative as well as the efficientone tothe conventional machining. With development in the Non-Traditional Machining processes, presently theseprocesses are often the first choice for machining processesfor certain technical requirements. The following examples are provided where Non-Traditional Machining processesare preferred over the conventional machining process:

• Intricate shaped blind hole – e.g. square hole of 15 mmx15 mm with a depth of 30 mm.

• Difficult to machine material – e.g. same example as above in Inconel, Ti-alloys or carbides.

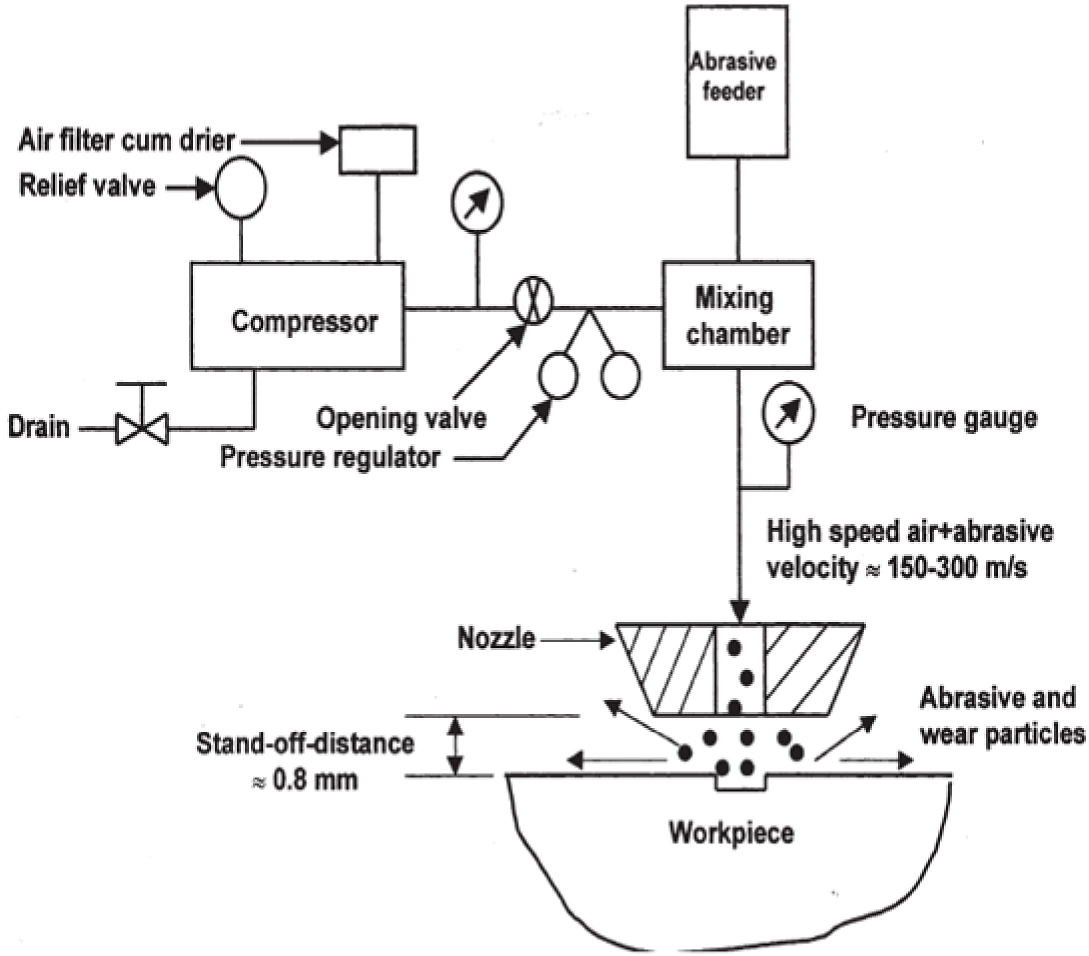
• Low Stress Grinding – Electrochemical Grinding is preferred as compared to conventional grinding.

• Deep hole with small hole diameter – e.g. φ 1.5 mm hole with l/d = 20

• Machining of composites.

1.3 What is Abrasive Jet Machining…?

The basic scheme of Abrasive Jet Machining (AJM) is shown in figure:1, it is a process of material removal through the action of a focussed jet of fluid along with abrasive particles. The high pressure compressed air coming out of compressor is directed to the mixing chamber via opening valve and pressure regulator. The mixing chamber is having another opening at the top for the abrasive particles from the abrasive feeder to flow inside the chamber.



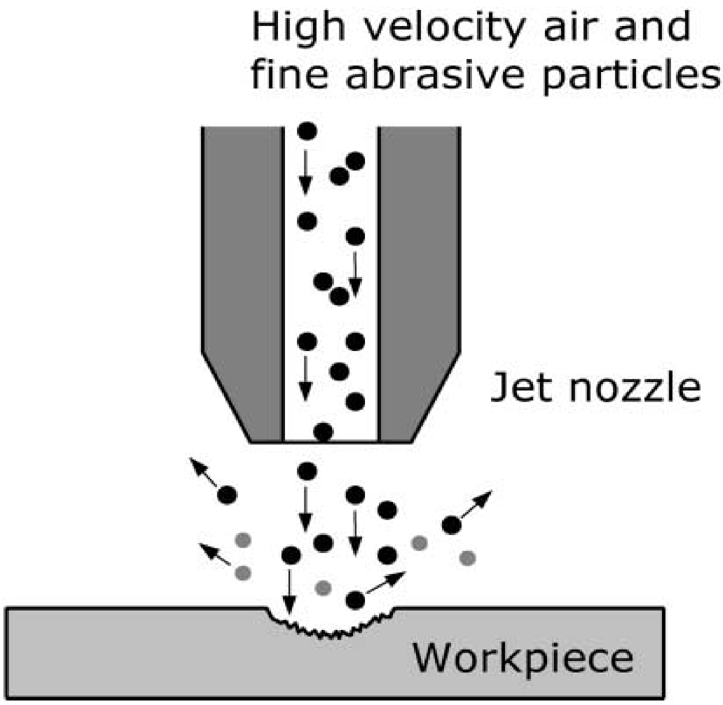
[16]*Figure:1 Basic Scheme of Abrasive Jet Machine*

Thus, in mixing chamber the compressed air mixed with the abrasive particles in correct proportion and the air-abrasive mixture is then allowed to pass through the nozzle which is fitted at a distance above the workpiece. This distance of the nozzle tip from the workpiece is known as Stand-Off Distance (SOD) or Nozzle Tip Distance (NTD). This distance can be varied according to the machining required on the workpiece. Now the high velocity jet coming out of the nozzle when impinge on the workpiece it removes the material from the workpiece through erosion.

Abrasive Jet Machining is used especially for machining ceramics, super alloys, glass and refractory material. It is one of the non-polluting methods used for machining hard materials with precise dimensions having intricate shapes. It has got an important advantage that it cannot be reactive with any of the workpiece materialsand it is versatile to machine the workpiece of any hardness. Another advantage of abrasive jet machining is that no tool changes are required, andminimum fixtures are required to hold the workpiece. It can be used to machine any parts with any type of intricacies of sharp corners.

The heat generated in this process is very less so material being machined do not experience any hardening of surface. And, since the cutting forces are directed in downward direction it can be used to machine materials with very small wall thickness. The thickness of part to be machined or the depth of cut in Abrasive Jet Machining is a function of speed and the best machining is obtained when the thickness is less than 1 inches.

In the AJM process, a high velocity jet of abrasive particles and carrier gas(compressed air) coming out of the nozzle impinges on the target surface and erodes it (as shown in figure:2). The AJM process is featured by relatively low consumption of power and small capital cost. This process is suitable for hard and brittle metals, semiconductors, and non-metallic materials like glass, ceramics, etc. It is especially useful for machining the workpiece plate with thin sections but not suitable for the parts having sharp corners.



[11]***Figure:2 Material removal in abrasive jet machining (AJM)***

1.4 MECHANICS OF ABRASIVE JET MACHINING :

The mechanics involved in the Abrasive Jet Machining process is described below:

- The fine abrasive particles (grit size > 200μm) are accelerated in a gas stream (commonly compressed air is used at a pressure few times of atmospheric pressure).
- The abrasive particles are directed from the nozzle tip towards the focus of machining (less than 1mm from the tip of nozzle).As the particles impact the surface, they fracture off other particles causing removal of material.
- As the abrasive particle impacts the surface of the workpiece with high velocity, the impact causes a small fracture on its surface, and the carrier gas stream (air) carries

both the abrasive particles and the fractured (wear) particles away from the surface, thus causing the material removal process.

Theoretically the material removal rate can be calculated as,

[2]Material Removal Rate (Q) is,

$$Q = \chi Z d^3 v^{\frac{3}{2}} \left(\frac{\rho}{12 H_w} \right)^{\frac{3}{4}}$$

Z = # of abrasive particles impacting per unit time

d = mean diameter of abrasive grains

v = velocity of abrasive grains

ρ = density of abrasive grains

H_w = the hardness of the workpiece - the flow stress

χ = a constant

Material in abrasive jet machining process is removed due to erosive action caused by impingement of a high velocity abrasive jet (containing abrasive particle and compressed air) on the surface of the workpiece material. Different mechanisms of material removal, for both ductile and brittle materials, have been suggested by various investigators. In the case of ductile materials, material is removed by plastic deformation and cutting wear, or plastic strain and deformation wear. In the case of brittle materials, it may take place due to indentation rupture, elastic–plastic deformation, critical plastic strain theory, radial cracking and propagation or surface energy criterion.

1.5 PROCESS PARAMETERS:

Process performance of Abrasive Jet Machining can be evaluated in terms of MRR, geometry and finish of workpiece, and nozzle wear rate.

The important process parameters of AJM are :

- The Abrasive (composition, strength, size and mass flow rate)
- The carrier gas (composition, pressure and velocity)
- The Nozzle (geometry, material, inclination to the workpiece)
- Jet velocity
- Nozzle pressure
- Stand-off-distance (SOD) or nozzle-tip-distance (NTD).

1.5.1 The Abrasives :

Commonly used abrasives in AJM are alumina and silicon carbide. Larger grains are used to get higher material removal rate (MRR), as larger grain size erode larger material from the workpiece as compared to smaller grain sizeand smaller grains causes lower material removal rate and also they are used for fine surface finish but at the same time smaller grain size causes more nozzle choking as compared to the grains of larger size. A larger number of abrasive particles in a given volume of carrier gas gives higher MRR but an optimum value of the amount of abrasives exists beyond which it may result in nozzle choking. The reuse of the abrasive powder is not recommended as it has got some disadvantages. The disadvantages related to reuse of the abrasive particles are

(i) cutting capacity of abrasive particles decreases after the first application and

(ii) contamination clogs(chokes) the small orifice of the nozzle.

When the mass fraction of the abrasives in the jet increases, the material removal rate initially increases, it reaches a maximum value and then drops as shown in figure. When the mass flow rate of the abrasive increases, the material removal rate also increases as shown in figure: 3.

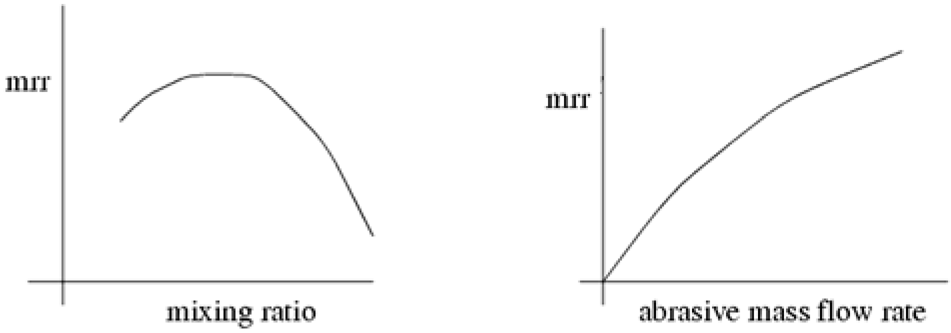


Figure :3 Graph between mrr v/s mixing ratio and mrr v/s mass flow rate

1.5.2The carrier gas:

Abrasive Jet Machine normally operates at a pressure of 0.2 N/mm^2 to 1.0 N/mm^2. The composition of the carrier gas affects the material removal rate indirectly due to the dependence of the velocity–pressure relationship on it. Commonly used gases are compressed air, nitrogen, and carbon-dioxide. Air is mostly preferred due to universal availability and its non-toxic nature.

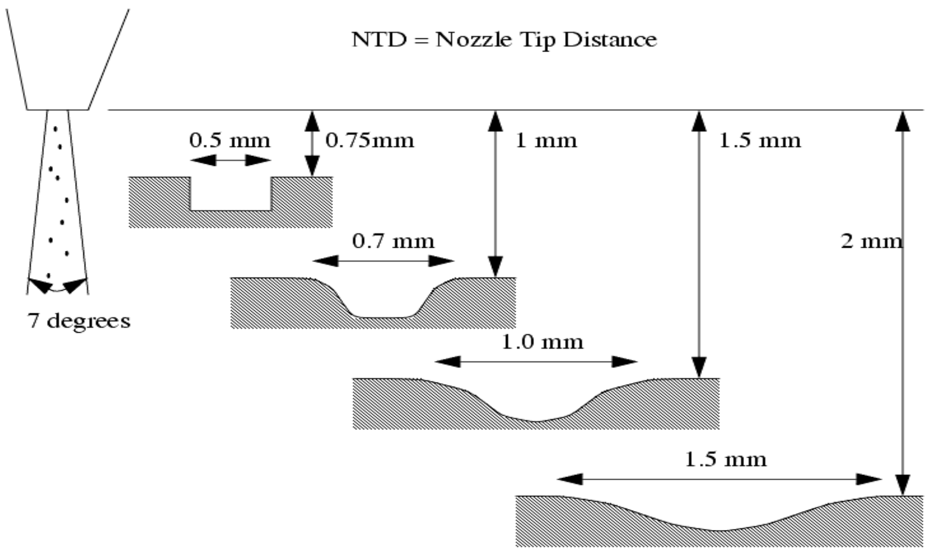
1.5.3 The nozzle:

The nozzle in abrasive jet machine is used fordirecting the mixture containing air and abrasive particles on the workpiece with high velocity. As the nozzle experiences direct contact with the abrasive particles, it wears gradually as the machining progesses as the abrasives are of harder material. To prevent nozzle from frequent wear, nozzle should be made of a harder material. The commonly used materials for nozzle assembly are tungsten carbide (WC) andsynthetic sapphires of diameters 0.2–2 mm. To limit the jet flaring (gradual widening at the end), nozzles may have rectangular orifices ranging from 0.1 × 0.5 mm to 0.18 × 3 mm. The shape and size of the nozzle affect the material removal rate by affecting jet velocity, while nozzle wear influences machining accuracy. Jet velocity depends on nozzle design, pressure, abrasive particle size, and their concentration.

In AJM processes, the abrasive jet must impinge the work surface with a certain minimum (or critical) velocity required for the material removal which is dependent on the type of abrasive and work material. Nozzle pressure affects the material removal rate.

1.5.4 Stand-off distance(SOD):

The distance of the workpiece from the nozzle tip is termed as Stand-off distance (SOD) or Nozzle Tip Distance (NTD). It plays an important role in abrasive jet machining. Stand-off distance (SOD) not only affects the material removal rate but also it affects the shape and size of the cavity produced. As SOD increases, inaccuracy in shape produced increases and jet velocity also increase (as shown in figure: 4) this results in higher MRR but beyond a certain limit jet velocity starts decreasing due to atmospheric drag as shown in the figure below.



[5]***Figure : 4 Effect of NTD on machining surface***

Thus an optimum value of Stand-Off Distance existsbelow which material removal rate keeps on increasing as the SOD increases and at that optimum value there is maximum material removal rate and shape accuracy as shown in figure.5

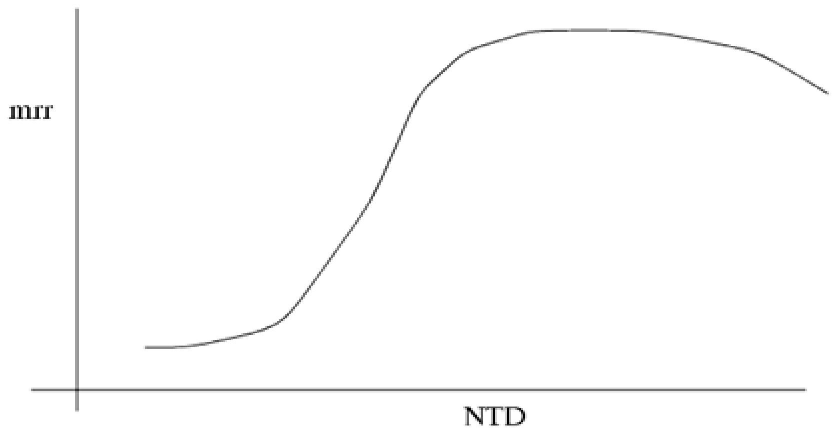


Figure : 5   Graph showing effect of NTD on material removal rate

1.6 ADVANTAGES AND LIMITATIONS OF AJM :

1.6.1 Advantages of AJM include the following:

- There is almost no heat generation:

  In AJM there is almost no heat generation so there will be no hardening of the material being machined, and absence of generation of poisonous fumes, wrapping or recasting of the material. Thus heat-sensitive materials such as glass and ceramics can be machined without affecting their physical properties and crystalline structure. Because of this reason Aerospace industries use Abrasive Jet Machining most of the time.

- Extremely fast setup and programming

In AJM there is no requirement of tool change so there is no need for program tool change and multiple tools. Even the setup and clean up time also reduces. For most of the time, programming generally involves contouring of the parts to be machined and if it is available on disk the half part is done.

- There is no requirement of start hole

  In AJM no start holes are required as in Wire EDM. Start holes are only required to impossible to pierce materials.

- Very little fixturing needed for most parts

  In AJM most of the flat materials are machined by positioning them on the worktable and applying some weight on them so there is almost no fixturing required. Tiny parts generally requires tabs or other fixtures. Thus fixturing in AJM is typically not a big deal.

- Produce holes and intricate shapes in any material

  The AJM is capable of producing holes and intricate shapes of very thin dimensions which are difficult to produce by any other process in hard and brittle materials.

- No multiple tools required

  Since there is only one tool that is nozzle, there is no need to qualify multiple tools or tool change programming. This also reduces the setup and clean up time allowing more parts to be machined in lesser time.

- Some more benefits of AJM are listed below

  - Safe to operate.
  - Characterized by low capital investment and low power consumption.
  - Clean cutting process without producing gases or oil.
  - Used to cut fragile materials of thin walls.
  - No heat generation and no heat affected zones
  - Fast set-up
  - Leaves a satin smooth finish, thus eliminates secondary operations.
  - Can be used to clean surfaces, especially in areas that are inaccessible by ordinary methods.
  - The produced surfaces after cleaning by AJM are characterized by their high wear resistance.
  - No mechanical stresses generated.
  - Cuts virtually any shape.
  - Cuts wide range of thickness to reasonable tolerances upto 50mm.
  - Cuts virtually any material- pre hardened steel, mild steel, titanium, Inconel.
  - Makes its own start hole.

1.6.2 Limitations of AJM include the following:

- Not recommended for soft materials:The application of AJM is restricted to hard and brittle materials that is AJM applications are best suited for hard and brittle materials. It is not recommended for machining soft and malleable materials though it can machine soft materials also.

- Abrasives cannot be reused: Once the abrasives are used for machining, they cannot be reused because they lose their sharpness that is their sharp cutting edges become blunt and hence they lose their cutting ability.Also the contaminated abrasive may clog the small nozzle orifice.

- Nozzle clogging: Nozzle clogging may occurs in AJM if the fine grains having a diameter <10 μm are used. Thus, the use of very fine abrasive particles may results in clogging of the nozzle.

- Tapering in deep holes:If deep holes are to required be produced using AJM, then it may result in tapering of the holes. Thus deep holes are produced by significant taper.

- Sometimes, machined parts have to undergo an additional operation of cleaning to get rid of grains sticking to the surface.

- Excessive nozzle wear causes additional machining cost.

- The process tends to pollute the environment when abrasive particles mix with air.

- High noise levels.

- AJM can be hazardous because of the rebounding of the abrasives.

- AJM can cause Silicosis when silicon carbide abrasive is used. Silicosis is a chronic lung disease caused by breathing tiny dust of silica dust. This silica dust can cause fluid build-up and scar tissue in the lungs that cuts down the ability to breathe.

CHAPTER 2

LITERATURE REVIEW

The literature survey of abrasive jet machining reveals that the abrasive jet machining process starts a few decades ago. Since then there has been a considerable number of detailed experiments and theoretical studies conducted on this process. From the studies carried out on this process,most of the studies emphasis on the hydrodynamic characteristics of abrasive jet, hence justify the influence of all operational variables on the process effectiveness including abrasive type, size and concentration, nozzle inclination with respect to the workpiece. Few of the papers found new problems concerning the carrier gas topologies, type of the nozzle, its shape and size, jet velocity and pressure, nozzle tip distance (NTD) or stand-off distance (SOD). These papers shows the overall process parameters of the abrasive jet machining in terms of material removal rate, geometrical tolerances and surface finish of the workpiece and also the nozzle wear rate. Finally, there are various significant papers which focus on either leading process mechanisms in machining of ductile and brittle materials or on the development of systematic experimental-statistic approaches and artificial neural network to predict the relationship between the values of the operational variables and machining rate and the accuracy of surface finish.

P.K Ray, Dr. A K Paul – [1987]

This paper states that in machining operation, the output parameter is achieved by controlling different input parameters. This research paper on abrasive jet machining(AJM)discusse the study of various input parameters such as pressure, mixing ratio, stand of distance, etc. of on the material removal rate. The experiment carried out with vortex type mixing chamber. The study was restricted to abrasive jet drilling only.

R. Balasubramaniam, J. Krishnan and N. Ramakrishnan-[1997]

This paper studied the Abrasive Jet Machining process for deburring. During the recent years the deburring applications became popularly carried out using abrasive jet machining and since the influence of process parameters on deburring application were not known, the experiment on AJMwas conducted to identify the effect of various parameters of AJM like jet height and angle of impingement etc. on deburring process. In this studystainless steel specimen was used and the experimental design based on taguchi orthogonal array was used to study the effect of major cutting parameters on AJM. A profile protector was used to measure the edge quality and also the visual inspection was conducted to analyze the surface damage of the specimen. The results thereafter, were analyzed by the ANOVA method and thus it was found that the burr removal was affected by the parameters jet height and angle of impingement.

R. Balasubramaniam, J. Krishnan and N. Ramakrishnan-[1998]

Studied the generation of an edge radius in abrasive jet external deburring. The significant advantage of external deburring using AJM is that the edge radius can be easily generated at the deburred edges. This experiment was performed on plaster-of-paris specimen to study the effects of various input parameters like abrasive grit size, mixing ratio, standoff distance and thickness of the workpiece and the response(output parameter) was studied using full factorial design. The variation in the diameters at the entry and exit side of the specimen werealso investigated. Thus it shows that the edge radius generated was affected by stand of distance and the variation in the diameter was affected by the nozzle diameter. The results of the edge radius generation were applied to AISI 304 stainless steelburr specimens and verified.

M.wakuda, Y.Yamauchi, S.Kanzaki-[2002]

Abrasive Jet Machining was performed on ceramic materials and the effect of workpiece properties on machinability in AJM was studied. Since the workpiece was ceramics, a specialized form of shot blasting was used using fine grained abrasives for the micro-machining. The establishedmodels of solid particle erosion were compared to the machinability during the AJM process in which the material removal is assumed to originate in the ideal crack formation system. It was even clarified that the erosion models are not significantly applicable to AJM results because the relative hardness of the abrasive against the target material which is not taken into the account in the models, is a critical factor in the micro-machining process. It follows that there was no strength degradation occurs for AJM surfaces and evidence that radial cracks do not propagate downwards due to partial impacts.

Manabu Wakuda, Yukihiko Yamauchi, Shuzo Kanzaki - [2003]

It is the study of material response to particle impact during abrasive jet machining of alumina ceramics. In this experiment a specialized form of shot blasting used as a micro-machining method for hard, brittle materials such as structural ceramics is employed. This paper studies the material response of alumina ceramics to the abrasive particle impact in the AJM process. Three types of commercial abrasives were used on alumina samples and found that the material response to particle impact depends drastically on the abrasives used. Aluminum oxide (WA) which is the softer abrasive leads to roughening the alumina surface but did not cause any engraving due to lack of abrasive hardness against that of the work piece. Silicon carbide (GC) abrasive produced relatively smooth surface because of its ductile behavior at elevated temperatures (caused by impacts of abrasives). When synthetic diamond (SD) abrasiveis employed, it causes large scale fragmentation and thus results in roughness of the impacted.

Dong-Sam Park, Nyeong-Woo Cho, Honghee Lee And Won-Seung Cho - [2004]

Studied and investigated micro-grooving of glass by using micro-abrasive jet machining micro (AJM). The process removes hard and brittle materials as effectively as the sand blasting, thus AJM has been applied for rough working such as deburring and rough finishing. For micro-machining processes, AJM becomes the useful technique as the need for machining of ceramics, semiconductors,electronic devices keeps on increasing. This journal describes the performance of micro AJM in the micro-grooving of glass. The diameter of the hole-type andwidth of the Line type groove are 80 micro meter. The experiments showed good performance of the micro-grooving of glass and as a result of the experiments the size of the groove increased about 2-4 micro meters was foamed the results showed good performance in the micro-grooving of glass. Thus, as a result of fine-tuning of the masking process and compensation for film wear, micro-AJM could be effectively applied to the micro machining of semiconductor, LCDs, and other electronic devices.

Lei Zhang, TsunematoKuriyagawa, YuyaYasutomi and Ji Zhao - [2004]

Investigated micro abrasive intermittent jet machine. It provides the theory that in machining of small holes by using conventional micro abrasive jet machining, the colliding abrasive accumulate in the bottom of the hole, thus preventing the direct impact of successive abrasive particles onto the work piece resulting in the decrease of machining efficiency as the machining progresses. This paper investigated a new method of micro abrasive jet machining known as micro abrasive intermittent jet machining. (MAIJM). In this machining for a period of time no abrasive is injected into the gas stream from the nozzle. Thus allows a continuous flow of gas without abrasive for a little period of time resulting in the blowing away any abrasive particle which is accommodate (clogged) inside the hole. Further empirical models are developed to measure the effect of MAIJM process parameters on the machining with the help of design of experiments with Taguchi orthogonal array method and by multi-variable line regression.

M. Achtsnick, P. F. Geelhoed, A. M. Hoogstrate, B. Karpusehewski-[2005]

In this paper modeling and evaluation of the micro abrasive blasting is done. Material removal process in micro abrasive blasting (MAB) is based on the erosion mask-protected brittle substrate by an abrasive laden air jet. For the utilization of MAB in various industrial applications, the blasting process has to become more efficient and better predictable. Therefore, in this paper micro abrasive blasting is analyzed by means of a set of models containing different sub models for the particle jet, the erosion mechanism of a single particle sub models for the machining results. In this study a one dimensional and isotropic flow model was for calculating the particle exit velocity of each individual particle in the air flow for two different type of nozzles, first was a converging cylindrical and other was a newly developed line shaped Laval-type. The size of particle and its position inside the air jet are based on probability distribution functions. The result is a nozzle characteristic energy intensity distribution of the beam particle. Thereafter, a classical indentation fracture mechanism is used to model the interaction between incoming particles and the substrate surface. After this modeling, the simulation shows that Laval-type nozzle is able to increase the particle velocity with more than 30% compare to the conversing nozzle and the blasting profile is more uniform with the relatively flat bottom.Particle velocities are experimentally verified with the help of particle image velocimetry (PIV) and the surface roughness and shape measurement of the blasting profile shows that the model presented can accurately predict the blasting performance of both nozzles types.

Henk Wensink, J. W. Berenschot, Henri V. jasen & Miko C. Elwenspoek-[2006]

Studied and investigated about high resolutions powder blast micro machining. It is technique in which a particle jet is directed towards the workpiece for mechanical material removal. This technique is used generally for brittle materials like glass, silion and ceramics, etc. and is very fast, cheap and accurate technique for directional etching. The feature size of this experiment was decreased by introducing a new mask material, Electroplated Copper. Thus, blasting with 9 pm particles (as compared with 30 pm particles) results in a higher slope of the channel sidewall. Furthermore, the measurement shows that the blast lag is increased by using smaller particles. Powder blasting is a directional etch technique for a wide range of materials such as glass, silicon, ceramics, etc. This technique fits very well between the common micro machining technique due to its lithographic masking, compatibility and process similarities. Electro plated copper(new mask for powder blasting) combines a high resistant mask material with the high resolution of lithography, thus makes it possible to obtain smaller feature sizes. After the experiment it was observed that blast lag is decreased by using 9 pm as compared to 30 pm particle mainly due to the steeper sidewalls createdwith these particles.

Deng Jianxin, Wu Fengfang & Zhao Jinlong–[2007]

Studied gradient ceramic nozzle wear mechanism by using abrasive jet machining. Nozzle is the most critical part in AJM equipments and wears gradually being in direct contact with the abrasives.Ceramics are mostly used as nozzle manufacturing material because of its high wear resistant property. In this paper, a (W,Ti) C/Sic gradient ceramic composite was developed to be used as nozzle material. The erosion wear behavior of the (W, Ti) C/Sic gradient nozzle was investigated and compared with that of a conventional ceramic nozzle. It was found that gradient ceramic nozzle exhibited an apparent increase in erosion wear resistance over the conventional ceramic nozzle. It was found that the mechanism responsible was the great reduction of the tensile stresses at the entry region of the nozzle as compared with the conventional nozzle. After the experiment conclusion was drawn that the gradient structure in ceramic nozzle was effective because it provides the improvement in erosion wear resistance of conventional ceramic nozzles in abrasive air jet machining.

Yung-Hsun shin, Yung-Kangshen, Vi-Lin, Keny-Liango, Rang-Hong Hong & Sung-Chin Hsu - (2008)

Study of micro fluidic chip fabrications by micro-powder blasting. It uses high speed gas flow which mixed the micro particle and gas to impact the brittle substrate by the specialize nozzle. Various diameters of $Al_2 0_3$ eroding particle with a novel masking technique used to fabricate the pattern channel in soda glass with a width down to 50 micro meter and depth down to 90 micro meter. There are two polymers consisted in the masking technology. First one is the brittle epoxy resin SU8 for its photo sensitivity. Second one is the elastic and thermal curable poly (dimethyl siloxane) PDMS for its erosion resistance. Different types of processing parameter such as gas pressure, nozzle/substrate distance, particle size, impact angle and erosion time are used in this experiment to find the optimal process by single parameter method. The outcome result shows that when the gas pressure increases the micro channel becomes deeper. When the nozzle distance increases, the micro channel decreases in depth. The surface roughness of micro channel of micro fluidic chip is about 5 to 6 micro meters.

M.A. Azmira, A.K. Ahsan- (2009)

Studied the surface roughness (Ra) and kerf taper ratio (T_R) characteristics of an abrasive water jet machined surfacesof glass/epoxy composite laminate. To determine the effect of machining parameters on Ra and T_R, Taguchi's design of experiments and analysis of variancewere employed. There are numerous associated parameters and factors of AWJM process that can influence the surface quality of the AWJmachinedsurfaces. Design of experiments using Taguchi`s orthogonal array is employed to reduce the number of experiments to a more practical and affordable size. The effect and optimization of control and noise factors in terms of surface roughness were investigated using taguchi methods and ANNOVA. The conclusions drawn for effective machining of glass/epoxy composite follows: 1.) Hydraulic pressure andtype of abrasive materials were considered as the most significant control factor in influencing Ra and T_R,respectively. 2.) Due to hardness of aluminium oxide type of abrasive materials, it performs better than garnet in terms of both machiningcharacteristics. 3.) Decreasing the standoff distance and traverse rate may improve both criteria of machining performance but cuttingorientation does not influence the machining performance inboth cases. 4.) Increasing the kinetic energy of abrasive water jet machining (AWJM) process may produce a betterquality of cuts.

D. A. Axinte, D. S. Srinivasu, J. Billingham, M. Cooper- (2010)

This paper deals with the modelling of abrasive waterjet footprints aimed at controlled freeform surfaces. It reports a geometrical model of the jet footprint (kerf) in maskless controlled-depth milling applications. By taking limiting conditions (i.e. high jet feed speeds) on the proposed geometrical model, shallow kerf profiles aregenerated that enable the calibration/identification of the specificetching rate of the workpiece materials to be identified. Thereafter, the full geometry of the jet footprint can be obtained for any (technologically required) jet feed speed by employing numericalmethods to solve the nonlinear differential equation which theproposed model is based on.The results revealed that only at low values of jet feed speeds (high jet dwell times) the predicted kerf profile wasdeeper (by 30 mm) than the real ones and the gradient of thekerf was found to be very similar. Thus,it revealed the need tointroduce into the model a linear correction on the stand-offdistance of the nozzle to the real target surface that develops aseroded kerf profile. Such addition to the geometrical model enabled accurate (errors < 5%) prediction of the jet footprint over awide range of jet feed speed values. Thus, the proposed geometrical kerf model which was initially developed for normal jet impingement angle, findsits use in developing innovative jet paths capable to generatecomplex geometry surfaces.

T. Matsumura, T. Muramatsu, S. Fueki- (2011)

Studied abrasive water jet machining for the machining of micro grooves and fluid polishing of micro channels with CFD analysis of the glass. The paper discusses control of abrasive flow using the stagnation in the abrasive water jet processes for machining andpolishing of micro grooves. The stagnation area under the jetnozzle is evaluated using computational fluid dynamics andassociated with the surface finishing. The effect of the stagnationarea is verified in the machining tests. For a crack-free surface, the process has been controlled to allow the abrasive particles to flow horizontally andcollide onto the surface at small impingement angles.In machining of the micro groove, the machining area has been controlled by the V-shaped masks on the surface. The results show that the stagnation area can be controlled by the taper angle of the V-shaped masks. Furthermore, when thetaper angle is small, the stagnation areabecome small andthe abrasive particles collide onto the surface at large impingement angles results in brittle fracture at the surface. Thetaper angle should be large to flow abrasive particles horizontally.In polishing of the micro groove, the sidewall of the grooves promotes development of the stagnation area and controls the flowdirection along the grooves. When the abrasive slurry is supplied to a flat surface, brittle fracture isinduced by collision of the particles at large impingement angles due to a small stagnation area.

Jiuan-Hung Kea, Feng-CheTsaia, Jung-Chou Hungb, Biing-HwaYanc- (2012)

This paper presents a novel hybrid method that self-made magnetic abrasive with elasticity was utilized to investigate machiningcharacteristics in abrasive jet machining. The magnetic abrasive jet machining has been applied to perform the internal polishing of circular tubes. This study shows that a self-made magnetic abrasive with elasticity was adopted toachieve restrained jet, high material removal rate andobtain better surface roughness via slip-scratch effect inprocess.According to the results drawn from taguchi method and the experimental results, flexible magnetic abrasive isadopted in abrasive jet machining not only restrains the abrasive jet direction to enhance more uniform main processing area andmaterial removal rate but also has slip-scratch effect to obtain better surface roughness than traditional machining.

Ming Chu Kong, Devadula Srinivasu, Dragos Axinte, Wayne Voice c, Jamie McGourlay, Bernard Hon- (2013)

This research paper deals with the use of multi-mode (through cutting, countersinking, milling) through abrasive jet machining of NiTi by investigating the influence of various process parameters on geometrical accuracy by taken into account the secondary temperature and mechanical induced transformations in the workpiece material. NiTi-based shape memory alloys (SMAs) are used as function materials as for various medical and MEMS applications due to their key properties such as shape memory effect, superelasticity, fatigue/corrosion resistance, biocompatibility. AWJ machining of NiTi SMAs could become 'sensitive' to the variations in heat/stress exerted since thetransformation temperature can be at low temperatures. This research gives a unified view of the surface quality expected inmulti-mode (i.e. through cutting, countersinking, milling) and the critical analysis of quality of surfaces of NiTi SMAs with AJM cutting is done to meetthe demands of high-value industrial applications (e.g. aerospace). After conducting the experiment, the paper reveals that surfaces of controlled quality can be generated by multimode AWJ of NiTi shape memory alloys. There was no white layer, deformed structure and no cracks found in the workpiece. Thus the real complex parts can be generated in NiTi SMAs by multimode AJM machining for high value added industries.

R. Haj Mohammad Jafar, J. K. Spelt, M. Papini- (2013)

In this paper a numerical model was developed to simulate the brittle erosion process leading to the creation of unmasked channels as a function of particle size, velocity, dose, impact angle and target material properties. The model investigated the actual machining conditions such as particle size, velocity and spatial distributions across the air abrasive jet and assumed two brittle damage mechanisms: (1) crater removal due to the initiation and growth of lateral cracks beneath the impact site, and (2) edge chipping due to the propagation of cracks that extend parallel to the impact direction. Comparisons with experimental data showed that the model can predict the average roughness of the centreline of channels machined on borosilicate glass with 9% average error over different particle kinetic energies. The numerical model predicted the glass erosion rate with an average error of 29% for a broad range of AJM process conditions. The results shows that the main erosion mechanism in the AJM of borosilicate glass was chip removal by lateral cracking. Edge chipping normally occurred when the impact angle was small and a particle impact occurred on an eroded surface near the apex of a peak, resulting in the removal of a relatively small portion of the peak.

CHAPTER 3

EXPERIMENTAL SET-UP

3.1 Problems in the Previous Model:

There were many problems in the abrasive jet machining set-up present in the lab. In this model the mixing chamber was placed horizontally and thus does not allow the proper mixing of the abrasive particles with the compressed air as the abrasive feeder is just above it in vertical direction, some of the abrasives settle down at the bottom of the mixing chamber due to gravity. Also the compressed air inlet was at other end of the mixing chamber along the direction of flow and doesn't allow the proper vortex motion needed in the mixing chamber for the proper mixing of the abrasives with the compressed air.

Fig.6 Previous Set-up of Abrasive Jet Machine Metal forming lab Department Of Mechanical Engg. DTU

There was no provision for controlling the mass flow rate as there was no control valve between the mixing chamber and the nozzle outlet. Also at high pressure there was leakage from different joints so readings at high pressure coudn`t be taken. Thus the machine was fabricated for better machining.

Fig.7 Limitations of Previous Set-up of Abrasive Jet Machine.

3.2 Improvement in the previous model of AJM (Fabrication part):

- Firstly the mixing chamber is fabricated to positioned in vertical directional from its earlier horizontal position.
- For allowing the vortex motion of compressed air in the mixing chamber, the compressed air inlet is relocated in transverse direction of the chamber. Vortex motion can only be provided when the incoming compressed air inlet is in transverse direction for allowing the air to swirl in the chamber, thus results in proper mixing of the abrasives with the air.
- The pressure regulator and pressure gauges are replaced by the new ones for preventing the leakage in the flow process.

- Now the abrasive feeder is relocated just above the mixing chamber with a valve in between to control the flow of abrasive particles.
- After the mixing chamber a valve is provided to control the mass flow rate of the mixture coming out of the mixing chamber.
- The nozzle is replaced with a stainless steel nozzle having outlet diameter of 2mm.(stainless steel converging nozzle is welded on a cast iron opening to fit the geometry).

3.3 Experimental Procedure:

Fig. 8 Abrasive Jet Machine (improved), Metal forming lab Department Of Mechanical Engg. DTU

Table no. 1 Abrasive jet machining characteristics

Mechanics of metal removal	Brittle fracture by impinging abrasive grains at high velocity
Carrier gas	Compressed air
Abrasives	Silicon Carbide (SiC)
Pressure	2-8kg/cm^2
Nozzle	Stainless Steel
Workpiece material	Toughened glass
Material Dimension	(70x30x5) mm

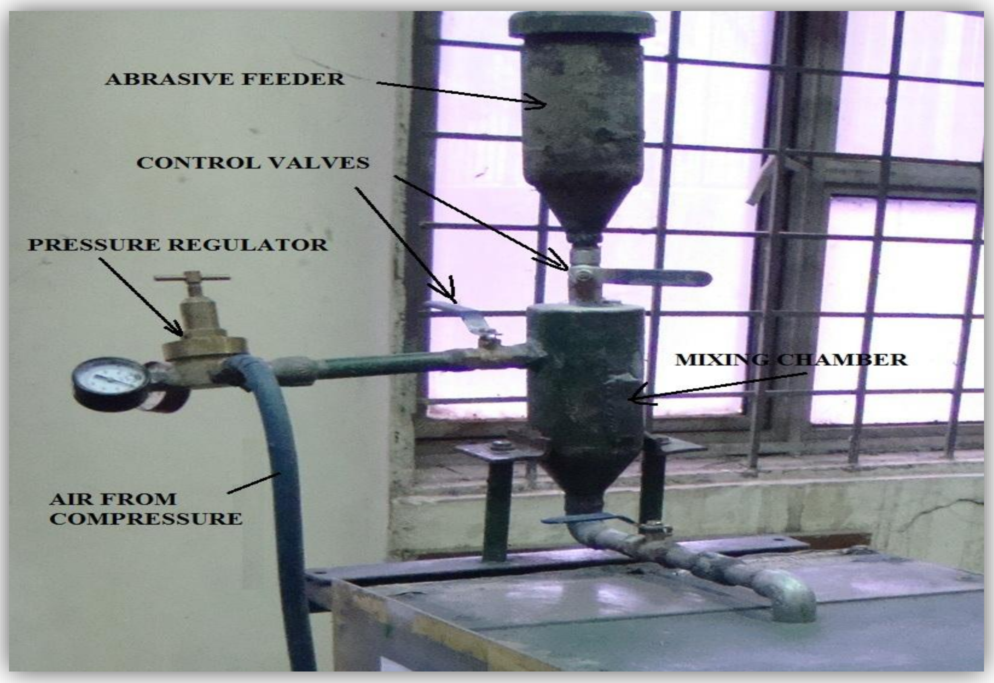


Fig:9 Different components of Abrasive Jet Machine Set-up

Experiment was performed on abrasive jet machining set-up using silicon carbide abrasives and tempered glass(toughened glass)is used as the work material to study the material removal rate (MRR). The different parameters used to study the material removal rate are pressure, angle of inclination (of workpiece with the nozzle) and the abrasive mesh size.The parameters and levels were selected primarily based on the literature review of some of the studies. The design of experiment table was used for different combinations of the process parameters for the readings to be taken.

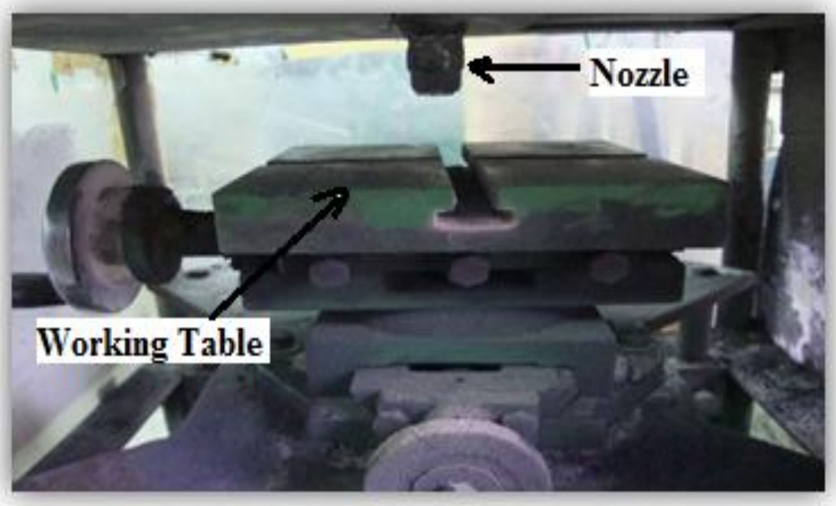


Fig.10 The working table and Nozzle of Abrasive Jet Machine, Metal forming lab Department Of Mechanical Engg. DTU

The tempered glass workpiece of size 7cm x 3cm with a thickness of 5mm is used for machining. Initial weight of the workpiece and weight after machining is measured by using digital balance for calculating the MRR. Time of machining was 4 seconds. Thus MRR is calculated using the formula:

$$MRR = \frac{\text{(intial weight- final weight)}}{\text{machining time}}$$

Based on taguchi`s method DoE with three factors (three levels), a L_9 orthogonal arrays table with 9 rows (corresponding to the number of experiments) was selected for experimentation.

For each experimental run, the machining parameters were set to the pre-defined levels according to the orthogonal array. Rectangular test specimen of dimension 7cmx3cm with thickness of 5mm were used on which experiments were carried out.

Table: 2 Machining parameters and their respective levels

NO.	SYMBOLS	MACHINING PARAMETERS	LEVELS			UNITS
			1	2	3	
1	A	Pressure	2	5	8	Kg/Cm^2
2	B	Angle	40	20	0	Degree
3	C	Grit size	1000	60	200	Mesh

3.4 Specification of compressor used in AJM:

Fig.11 Air compressor, Metal forming lab Department Of Mechanical Engg. DTU

Table no. 3 Specifications of Air Compressor

Manufacturer	INGERSOLL- RAND (INDIA) LTD.
Model	2475
Type	2-Stage, 2-Cylinders, Single Acting
Speed	1100 Rpm (Max.)
Discharge Pr. Rating	200psi (14 Kg/Cm^2)
Piston Displacement	22cfm At Max. Rpm

AIR TREATMENT SYSTEM:

Manufacturer	TRIDENT PNEUMATICS PVT. LTD.
Model	Dry Spell- 20
Type	Heatless Dessicant Dryer
Qty. Of Dessicant In Dryer	4.8 Kg
Nominal Flow	20 Clin
Dew Point	-40^0 C
Maximum Working Pressure	16 Kg/Cm^2
Drying Time	20mins. 30 Sec
Regeneration Time	1 Min 30 Seconds
Pressurization Time	30sec.
Electricals	230 V, 1ph, 50 Hz
Prefilter Condensate Discharge	Every 4 Min For 4 Secs.

MOTOR:

Manufacturer	CROMPTON GREAVES LTD.
Type	3 Ph Induction
Kw (Hp)	3.7 (6)
Speed	1430 Rpm
Current	7.4 Amp

CHAPTER 4

DATA COLLECTION AND DATA ANALYSIS

4.1 Concept of Design of Experiment (DOE):

Design of experiments (DOE) is a structured and organised method used for determining the relationship between different factors affecting a process and the output of that process. Sir Ronald A. Fisher, the renowned mathematician and geneticist firs developed this method in the1920s and 1930.Design of experiment (DOE) is used to understand the impact of specific changes to the inputs of the process, and then to maximize, minimize or normalize the outcome by manipulating the input. It investigates a number of input factors with relatively small number of tests.

Design of experiment is usually used when it is not clear what impact a specific set of inputs may have either individually or in combination on process output. To accomplish DOE, the level of factors are varied in a strategic manner with the help of DOE table and the results are analysed to determine the influential factors and preferred levels. And also to increase or decrease of the different levels which will potentially lead to further improvement.

The DOE process is divided into three main phases, in which all experimental approaches are included. These three phases are.

1. The Planning Phase
2. The Conducting Phase
3. The analyzing phase

In planning phase, the factors and levels are selected and, therefore it is the most important stage of experimentation. Also the correct selection factor and levels is non-statistical in nature and more dependent upon product or process expertise.

In the second phase known as the conducting phase, the test results are actually collected. If experiments are well planned and conducted, the analysis is much easier and more likely to give positive information about factors and levels.

The third phase is the analysis phase, in which the positive or negative information concerning the selected factors and levels is generated based on the previous two phases. This phase is statistical in nature.

The major steps to complete an effective designed experiment are listed in the following 12 steps. The planning phase includes steps 1 through 9, the conducting step 10, and the analysis phase include steps 11 and 12.

1. State the problem(s) or areas (s) pf concern
2. State the objective (s) of the experiment
3. State the quality characteristic(s) and measurement system(s)
4. Select the factors that may influence the selected quality characteristics.
5. Identify control and noise factors.
6. Select levels of factor
7. Select the appropriate orthogonal array (OA) or Ors.
8. Select interactions that may influence the selected quality characteristics.
9. Assign factors to OA(s) and locate interactions.
10. Conduct tests described by trials in OAs.

11. Analyse and interpret results of the experimental trials.

12. Conduct confirmation experiment.

4.2 Taguchi Orthogonal Arrays:

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The Taguchi method was developed by Dr. Genichi Taguchi of Japan who maintained that variation. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources.

4.3 Experimental Readings:

Degree of Freedom (DOF) = number of levels -1

For each factor, DOF equal to:

For (A); DOF = 3 – 1 = 2

For (B); DOF = 3 – 1 = 2

For (C); DOF = 3 – 1 = 2

In this research nine experiments were conducted at different parameters. For this Taguchi L9 orthogonal array was used, which has nine rows corresponding to the number of tests, with three columns at three levels. L9 Orthogonal Array has eight DOF, in which 6 were assigned to three factors (each one 2 DOF) and 2 DOF was assigned to the error.

<u>Table no.4 Design Of Experiments Table:</u>

Experiment. No.	PRESSURE (Kg/Cm^2)	ANGLE (Degree)	GRIT SIZE (mesh)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Experiment No.1

Pressure (kg/cm^2) = 2

Angle (degree = 40^o

Abrasive(mesh size) = 1000

Initial weight (gram) = 25.3562

Final weight (gram) = 25.3386

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0044

Figure:12 Workpiece for Experiment no. 1

Experiment No. 2

Pressure (kg/cm^2) = 2

Angle (degree = 20^o

Abrasive(mesh size) = 600

Initial weight (gram) = 25.4458

Final weight (gram) = 25.4226

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0058

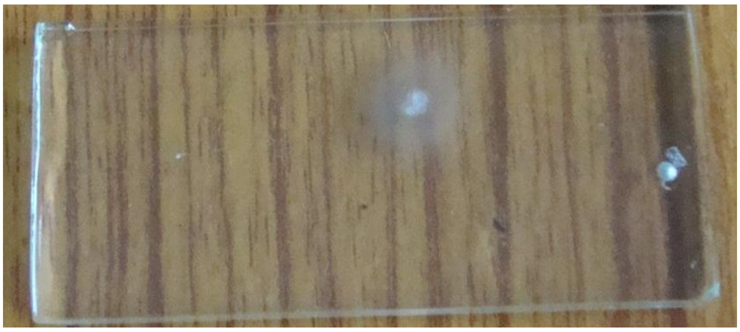


Figure:13 Workpiece for Experiment no. 2

Experiment No. 3

Pressure (kg/cm^2) = 2

Angle (degree = 0^o

Abrasive(mesh size) = 200

Initial weight (gram) = 25.2044

Final weight (gram) = 25.1664

Time of machining (sec.) = 4

MRR(g/sec.) = .0095

Figure: 14 Workpiece for Experiment no. 3

Experiment No. 4

Pressure (kg/cm^2) = 5

Angle (degree = 40^o

Abrasive(mesh size) = 600

Initial weight (gram) = 25.5624

Final weight (gram) = 25.5236

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0097

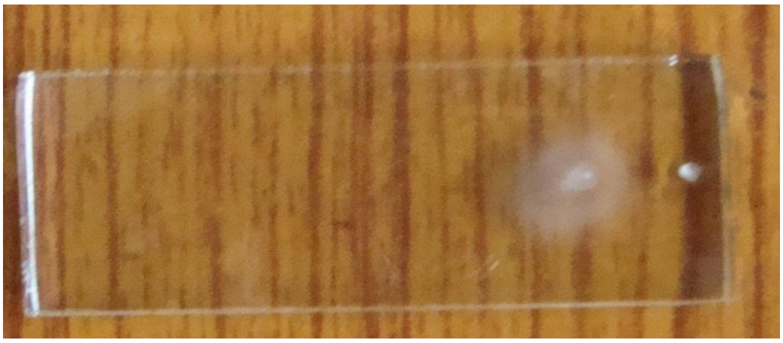


Figure:15 Workpiece for Experiment no. 4

Experiment No. 5

Pressure (kg/cm^2) = 5

Angle (degree = 20^o

Abrasive(mesh size) = 200

Initial weight (gram) = 25.7699

Final weight (gram) = 25.7267

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0108

Figure: 16Workpiece for Experiment no. 5

Experiment No. 6

Pressure (kg/cm^2) = 5

Angle (degree = 0^o

Abrasive(mesh size) = 1000

Initial weight (gram) = 25.517

Final weight (gram) = 25.4754

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0104

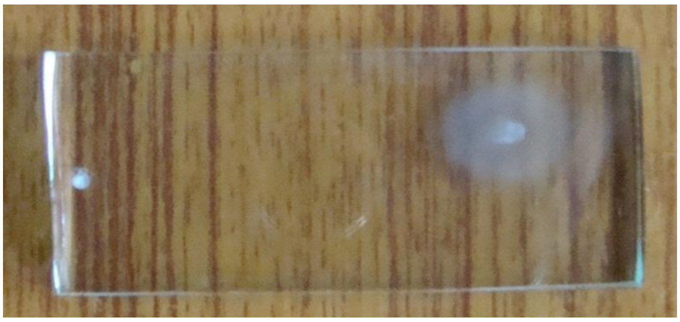


Figure:17 Workpiece for Experiment no. 6

Experiment No. 7

Pressure (kg/cm^2) = 8

Angle (degree = 40^o

Abrasive(mesh size) = 200

Initial weight (gram) = 25.3082

Final weight (gram) = 25.2602

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0120

Figure: 18 Workpiece for Experiment no. 7

Experiment No. 8

Pressure (kg/cm^2) = 8

Angle (degree = 20^o

Abrasive(mesh size) = 1000

Initial weight (gram) = 25.5896

Final weight (gram) = 25.5432

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0116

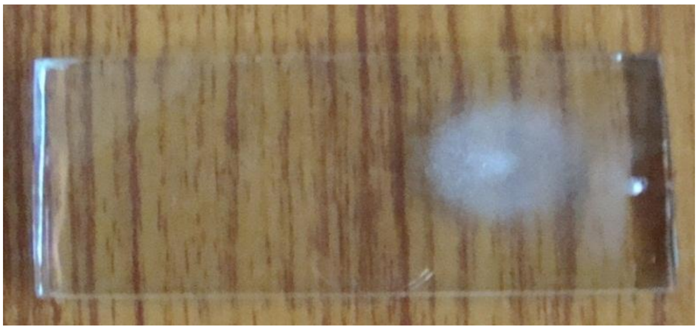


Figure: 19 Workpiece for Experiment no. 8

Experiment No. 9

Pressure (kg/cm^2) = 8

Angle (degree = 0^o

Abrasive(mesh size) = 600

Initial weight (gram) = 25.4836

Final weight (gram) = 25.4284

Time of machining (sec.) = 4

MRR(g/sec.) = 0.0138

Figure:20 Workpiece for Experiment no. 9

Taguchi Orthogonal Array Design for L9 (3**3) with number of factors 3 and 9 runs

<u>Table no. 5 Table for MRR of Taguchi L9 OA</u>

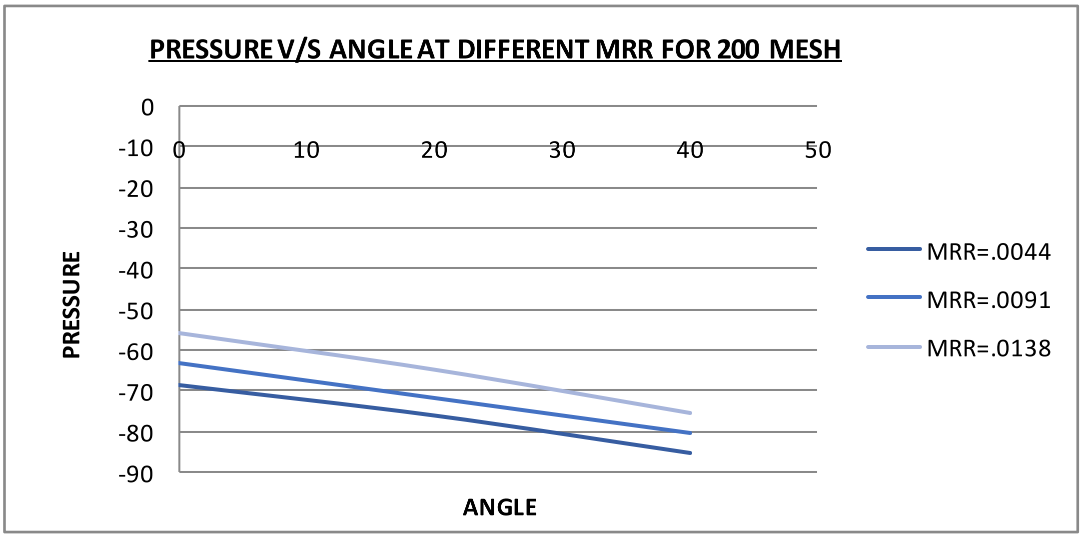
EXPERIMENT No.	PRESSURE (Kg/Cm^2)	ANGLE (Degree)	GRIT SIZE (Mesh)	MRR (gm/sec.)
1	1	1	1	0.0044
2	1	2	2	0.0058
3	1	3	3	0.0095
4	2	1	2	0.0097
5	2	2	3	0.0108
6	2	3	1	0.0104
7	3	1	3	0.0120
8	3	2	1	0.0116
9	3	3	2	0.0138

4.4 Data Analysis:

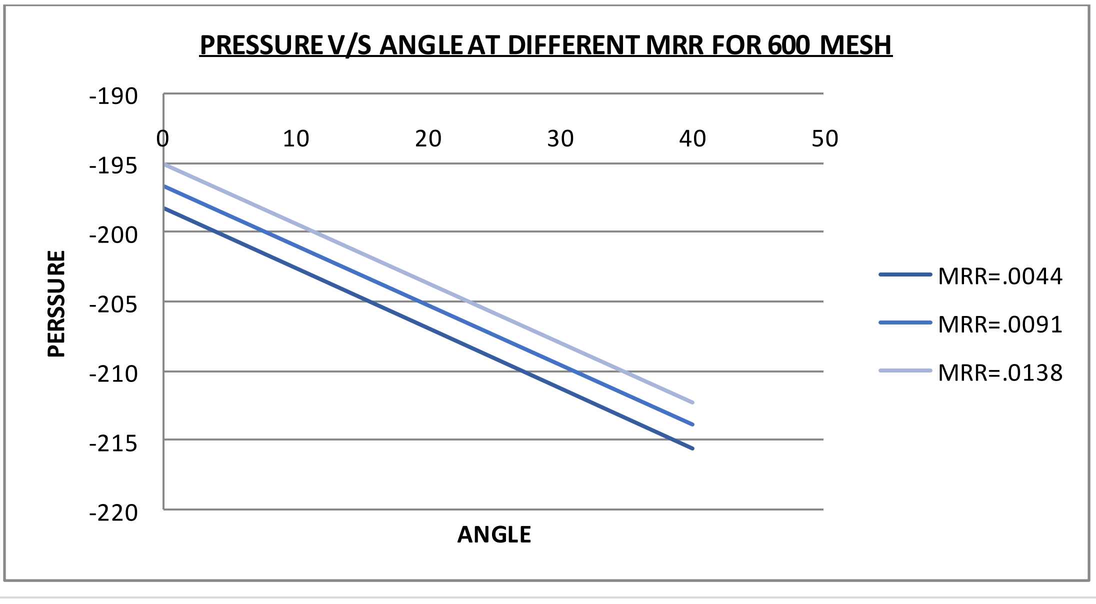
For the analysis of data different graphs are plotted from the regression equation-

MRR = - 0.00062 + 0.00295 Pressure + 0.00127 Angle + 0.000983 Grit Size

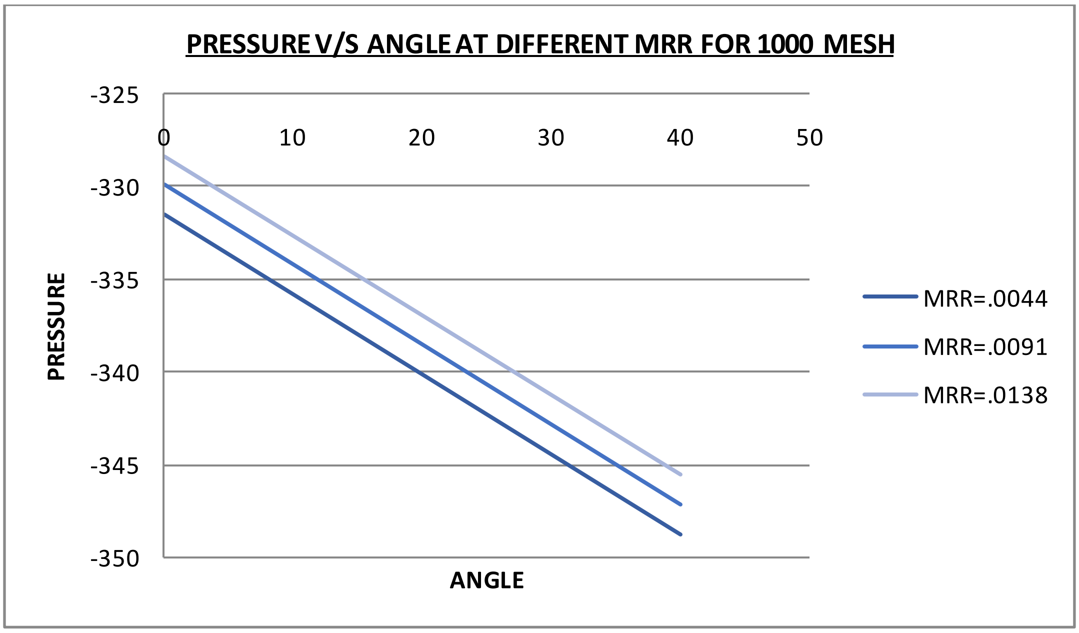
varying the parameters keeping one parameter constant at a time and at different values of MRR. The different graphs are shown below.



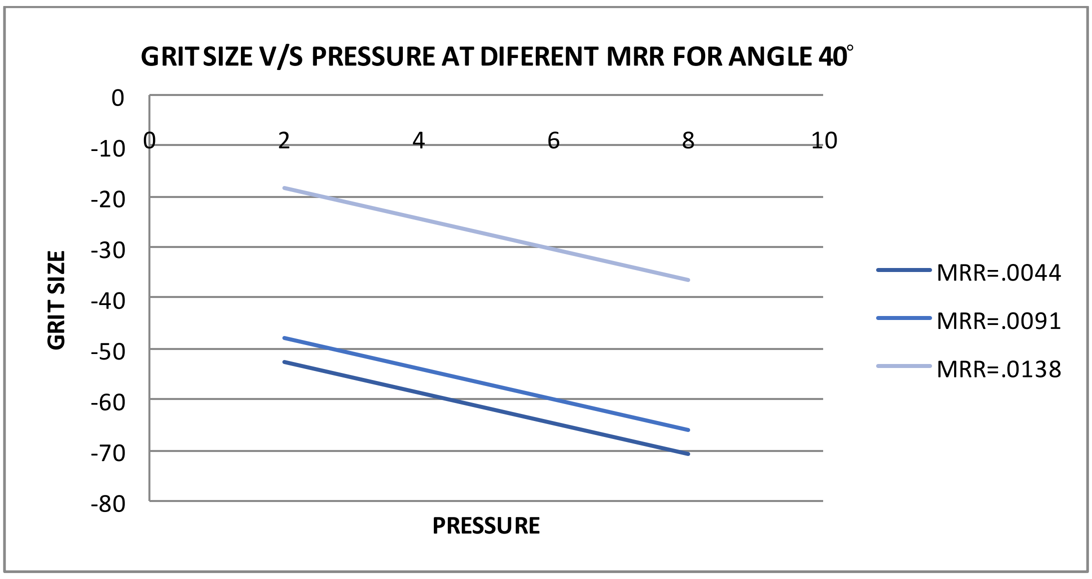
From the regression equation graph has been plotted between pressure and angle at different MRR for Grit size 200 mesh. Thus, pressure has been calculated at different angles for different MRR individually for 200 mesh. From the graph it is seen that as the angle increases from 0 degrees to 40 degrees, pressure decreases for different MRR and pressure is higher for higher MRR.



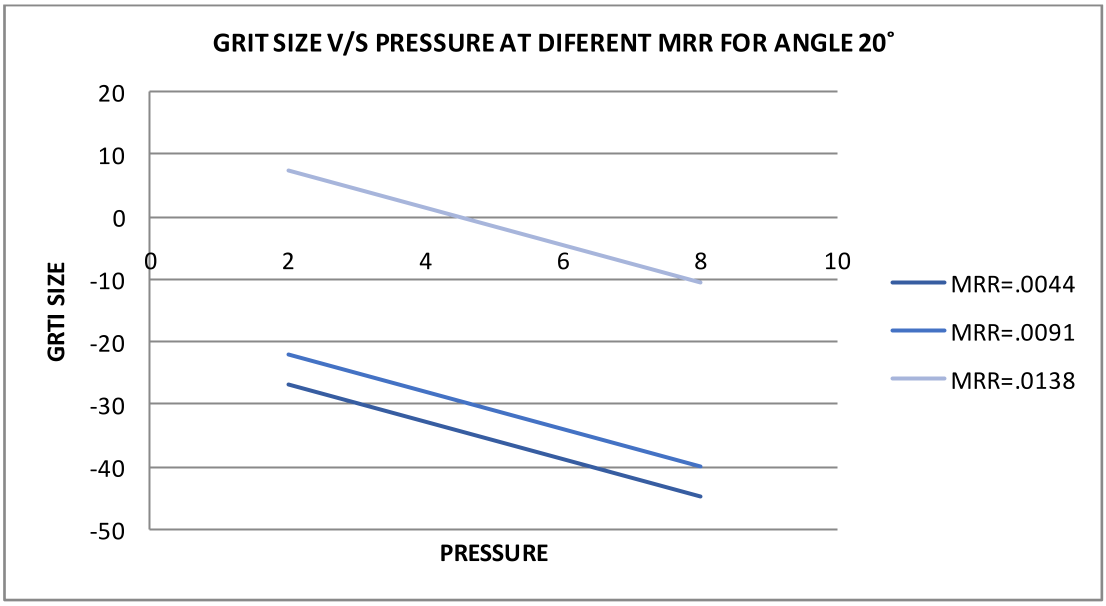
Graph has been plotted between pressure and angle at different MRR for Grit size 600 mesh and pressure has been calculated at different angles for different MRR individually for 600 mesh. From the graph it is seen that the pressure decreases with the increase in angle but for the 600 mesh size the decrease in pressure is more gradual.



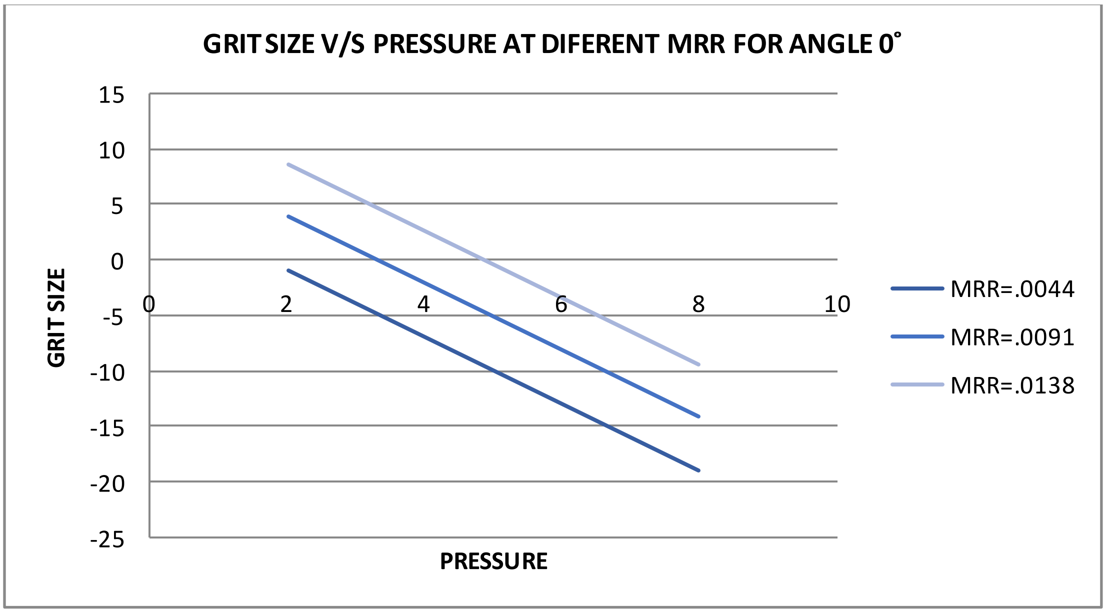
When the graph is plotted between pressure and angle at different MRR for grit size 1000 mesh and pressure is calculated at different angles for different MRR individually, the pressure decrease is even more gradual with the increase in angle for 1000 mesh size as compared to 600 mesh size.



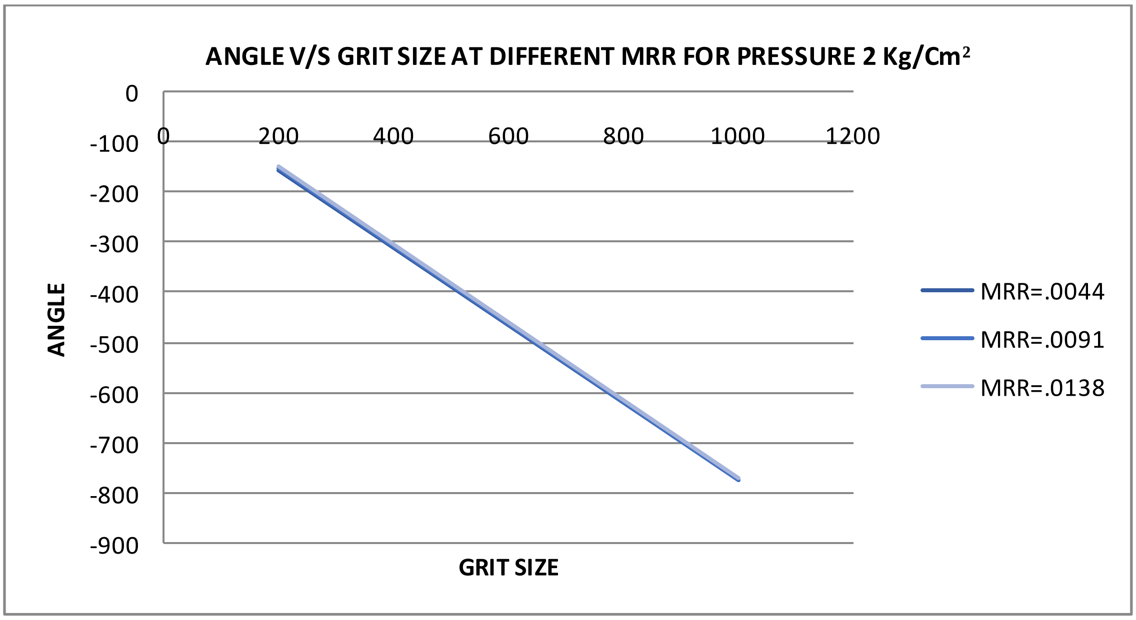
With the help of regression equation when the graph is plotted between grit size and pressure at different MRR individually for angle 40°, it is seen that the grit size decreases with the increase in pressure for a particular MRR. Also the grit size is higher for higher MRR.



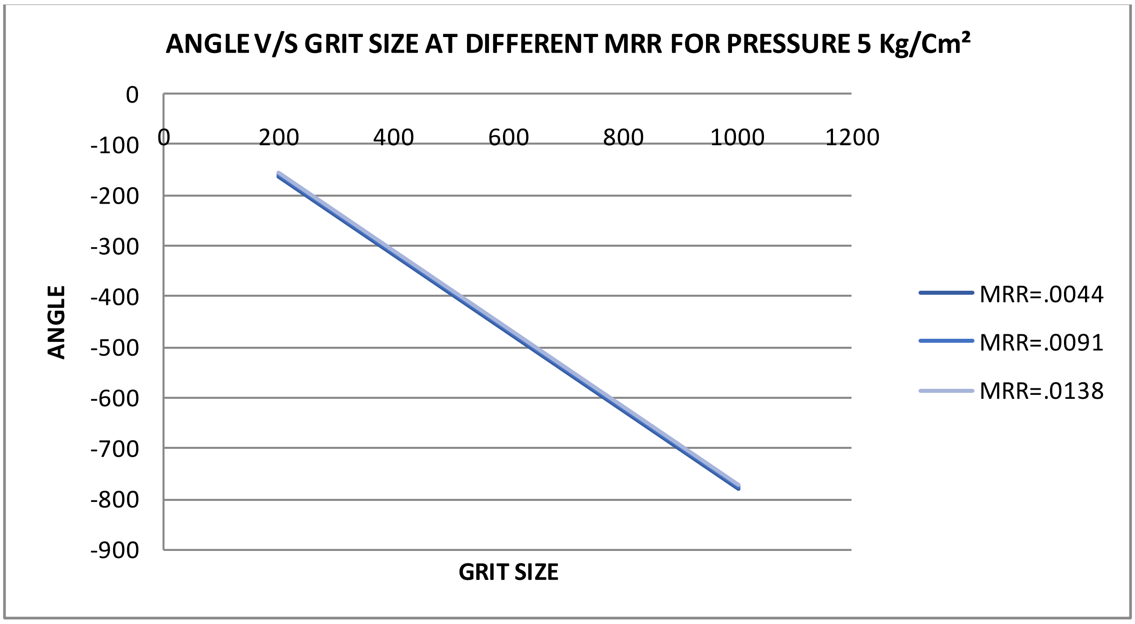
For angle 20° the grit size v/s pressure graph shows similar trend and thus the grit size decreases for the increasing values of pressure. And also the grit size is higher for higher MRR.



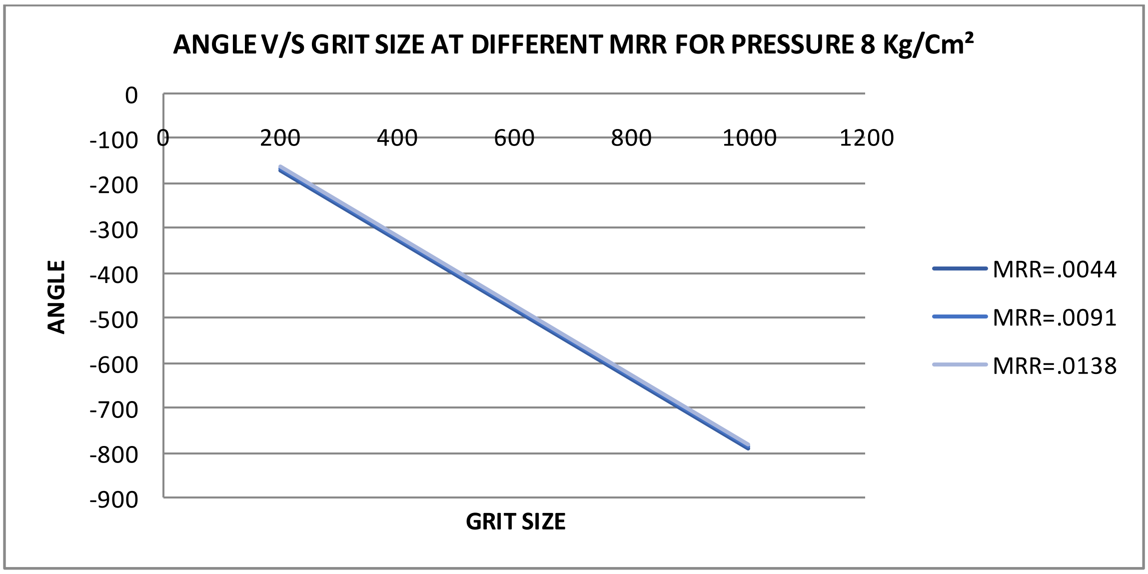
When the graph is plotted between grit size and pressure for angle 0˚ the grit size decreases for the increase in pressure value and the decrease is more gradual for 0˚ angle. And also the grit size is higher for higher value of MRR.



When the graph is plotted between angle and grit size for pressure value of 2 Kg/Cm² at different MRR value individually, the trend shows almost equal results for all MRRs that is the angle decreases for the increase in grit size.



When the graph is plotted between angle and grit size for pressure value of 4 Kg/Cm² at different MRR value individually, the trend shows almost equal results for all MRRs that is the angle decreases for the increase in grit size.



When the graph is plotted between angle and grit size for pressure value of 8 Kg/Cm² at different MRR value individually, the trend shows almost equal results for all MRRs that is the angle decreases for the increase in grit size. Thus it can be stated that the variation of angle at different grit size does not depends upon the MRR.

CHAPTER 5

RESULTS AND DISCUSSIONS:

The study has discussed an application of the Taguchi method for investigating the effects of process parameters on the metal removal rate value in the abrasive jet machining of tempered glass. In the AJM process, the parameters were selected taking into consideration of manufacturer and industrial requirements. From the experimental results, data in the AJM process are analyzed using the conceptual signal-to-noise (S/N) ratio approach, regression analysis, analysis of variance (ANOVA), and Taguchi`s optimization method as discussed below.

5.1 Analysis of the S/N Ratio

Taguchi method stresses the importance of studying the response variation using the signal–to–noise (S/N) ratio, resulting in minimization of quality characteristic variation due to uncontrollable parameter. The metal removal rate was considered as the quality characteristic with the concept of "the larger-the-better". The S/N ratio used for this type response is given by:

The S/N ratio for the larger-the-better is: -10*log (mean square deviation)

$$\frac{S}{N} = -10*\log_{10}\left(\frac{1}{n}\Sigma\frac{1}{y2}\right)\ldots\ldots(1)$$

Where n is the number of measurements in a trial/row, in this case, n=1 and y is the measured value in a run. The S/N ratio values are calculated by taking into consideration Eqn. 1. The

MRR values measured from the experiments and their corresponding S/N ratio values are listed in Table 6.

Table no.6Taguchi Analysis: Response Table for Signal to Noise Ratios Larger is better

LEVEL	PRESSURE	ANGLE	MESH SIZE
1	-44.10	-41.94	-41.83
2	-39.75	-40.92	-40.73
3	-38.11	-39.10	-39.40
DELTA	5.99	2.83	2.44
RANK	1	2	3

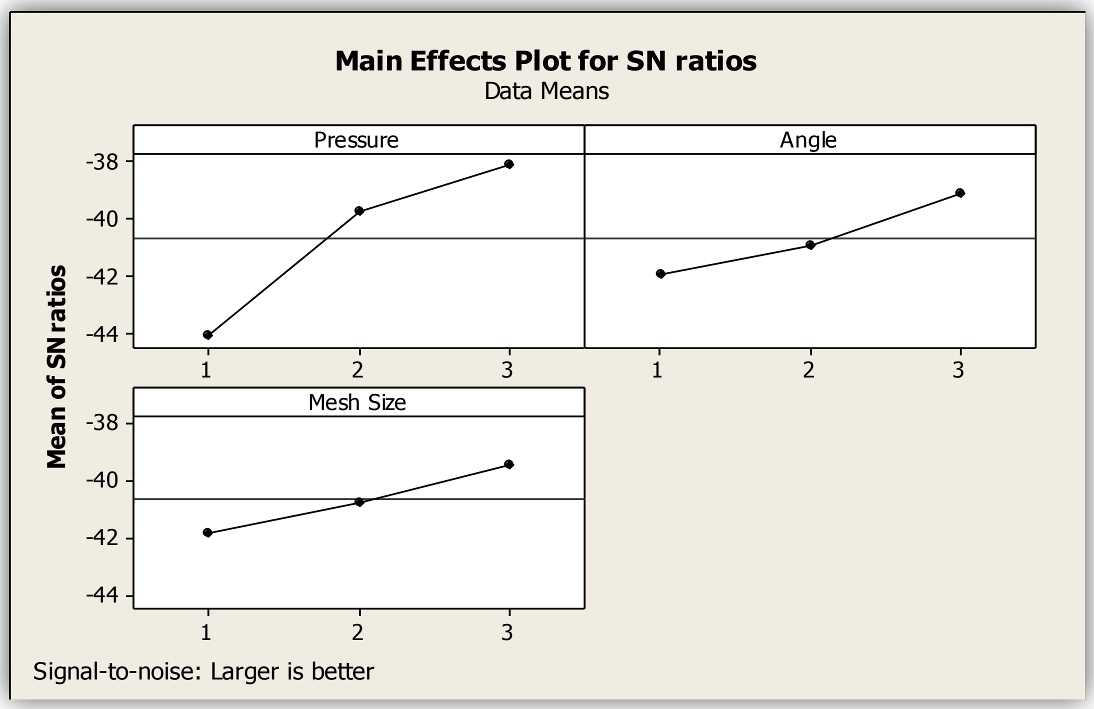


Figure:21 Graph showing S-N Ratio, Larger is better.

Regardless of the category of the performance characteristics, a greater S/N value corresponds to a better performance. Therefore, the optimal level of the machining parameters is the level with the greatest S/N value. Based on the analysis of the S/N ratio, the optimal machining performance for the metal removal rate was obtained at 8 Kg/Cm^2 pressure (level 3), 0^oangle (level 3) and 200 mesh grit size (level 3). Fig. 5 shows the effect of the process parameters on the metal removal rate values.

The effect of process parameters on the metal removal rate values was shown in Fig. . The MRR increases with increase in pressure, and decrease in angle and abrasive grit size (mesh). With the increase in pressure, the kinetic energy of the abrasive particles increases and thus abrasives will impinge on the work surface with high velocity results in higher MRR. With the decrease in angle between the workpiece and nozzle, the abrasive mixture impinge on the workpiece more directly without deflecting with a larger force, thus results in greater removal rate. And as the abrasive mesh size decreases, abrasive particle size increases, thus removes more metal as compared to the particle of smaller size

5.2 Analysis of Variance (ANOVA) :

ANOVA is a statistically based, objective decision making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. First, the total sum of squared deviations SST from the total mean S/N ratio nm can be calculated:

$$SS_T = \sum_{i=1}^{n}(n_i - n_m)^2$$

where n is the number of experiments in the orthogonal array and n_i is the mean S/N ratio for the i_{th} experiment. The percentage contribution P can be calculated as:

$$P = \frac{SS_D}{SS_T}$$

Where SSd is the sum of the squared deviations. The ANOVA results are illustrated in Table 6.Statistically, there is a tool called an F test, named after Fisher, to see which design parameters have a significant effect on the quality characteristic. In the analysis, the F-ratio is a ratio of the mean square error to the residual error, and is traditionally used to determine the significance of a factor.

Table: 7 ANOVA results for metal removal rate

Source of variation	Degree of Freedom (DF)	Sum of squares (S)	Variance (V)	F-ratio (F)	P-value (P)	Percentage contribution
Model	6	6.951E-005	1.159E-005	19.60	0.0103	-
A- Pressure	2	5.344E-005	2.672E-005	45.20	0.0043	76.82 %
B- Angle	2	1.027E-005	5.134E-006	8.69	0.0274	14.74 %
C- Grit Size	2	5.802E-006	2.901E-006	4.91	0.0418	8.28 %
Residual	2	1.182E-006	5.911E-007	-	-	0.16 %
Cor Total	8	7.070E-005				100.00 %

The P-value reports the significance level (suitable and unsuitable) in Table .Percent (%) is defined as the significance rate of the process parameters on the metal removal rate. The percent numbers depict that the pressure, angle and abrasive grit size have significant effects on the metal removal rate. It can observed from Table 6 that the pressure (A), angle (B) and

abrasive grit size (C) affect the metal removal rate by 76.82%, 14.74% and 8.28% in the abrasive jet machining of tempered glass, respectively. A confirmation of the experimental design was necessary in order to verify the optimum cutting conditions.

5.3 Regression Analysis:

The pressure, angle and the grit size were considered in the development of the mathematical models for calculating the material removal rate. The correlation between the factors (pressure, angle and grit size) and the material removal rate on the tempered glass were obtained by multiple linear regressions.

The standard commercial statistical software package MINITAB was used to derive the models of the form:

The regression equation is

MRR = - 0.00062 + 0.00295 Pressure + 0.00127 Angle + 0.000983 Grit Size.

R^2 value is 95.1% that is greater than 90. R^2 gives the percent of variance due to betweengroup variation. In multiple linear regression analysis, R^2 is the regression coefficient (R^2>0.90) for the models,which indicate that the fit of the experimental data issatisfactory.

$$R^2 = \frac{SS[Between]}{SS[Total]} = \frac{SSG}{SST}$$

Table no. 8Regression Analysis: MRR versus Pressure, Angle, Grit Size

Predictor	Coef	SE Coef	T	P	VIF
Constant	-0.0000622	0.001136	-0.55	0.607	---
Pressure	0.0029500	0.0003190	9.25	0.000	1.000
Angle	0.0012667	0.0003190	3.97	0.011	1.000
Grit Size	0.0009833	0.0003190	3.08	0.027	1.000

S = 0.000781309   R-Sq = 95.7%   R-Sq(adj) = 93.1%

5.4 CONFIRMATION TEST

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi's design approach. The optimal conditions are set for the significant factors (the insignificant factors are set at economic levels) and a selected number of experiments are run under specified cutting conditions. The average of the results from the confirmation experiment is compared with the predicted average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results. In this study, a confirmation experiment was conducted by utilizing the levels of the optimal process parameters. (A3B3C3) for metal removal rate value in the abrasive jet machining of tempered glass obtained as 0.0155 g/sec.

CHAPTER- 6

CONCLUSIONS

On the basis of experimental results, analysis of variance (ANOVA) and the effect of machining parameters on metal removal rate, the conclusions can be drawn for effective machining of tempered glass by AJM process as follows :

- Statistically designed experiments based on Taguchi methods were performed using L9 orthogonal arrays to analyze the metal removal rate as response variable. Conceptual S/N ratio and ANOVA approaches for data analysis drew similar conclusions.
- Statistical results (at a 95% confidence level) show that the pressure (A), angle (B), and abrasive grit size (C) affects the metal removal rate by 76.82%, 14.74% and 8.28% in the abrasive jet machining of tempered glass, respectively.
- The maximum metal removal rate is calculated as 0.0155 g/sec. by Taguchi`s optimization method.
- In this study, the analysis of the confirmation experiment for metal removal rate has shown that Taguchi parameter design can successfully verify the optimum cutting parameters (A3B3C3), which are pressure = 8 Kg/Cm^2 (A3), angle = 0 degree (B3) and abrasive grit size = 200 mesh (C3).
- As the angle increases, the pressure decreases for the same grit size at different MRR values
- As the pressure increases, the grit size decreases for the same angle at different MRR vlaues

- Angle decreases for the increase in grit size for the same pressure value at different MRR values.
- Metal removal rate increases with increase in pressure and decrease in angle and abrasivegrit size in abrasive jet machining of tempered glass.

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