CHAPTER - 1

INTRODUCTION

Modern machining methods are also named asNon Traditionalmachining methods. These methods form a group of processes which removes excess material by various techniques involving mechanical, thermal, electrical chemical energy or combination of these energies. There is no cutting of metal with the help of metallic tool having sharp cutting edge. The major reasons of development and popularity of modern machining methods are listed below.

- Need of machine newly developed metals and non-metals having some special properties like high strength, high hardness and high toughness. A material possing the above mentioned properties are difficult to be machined by the Conventional machining methods.

- Sometimes it is required to produce complex part geometries that cannot be produced by following conventional machining techniques. Non Traditional machining methods also provide very good quality of surface finish which may also be an encouragement to these methods. There can be a very long list of non-conventional machining methods. These methods can be classified as the basis of their base principle of working.

1.1 Classification Of Non Traditional Machining Processes :

The classification of Non Traditional Machining processes is carried out depending on the nature of energy used for material removal. The broad classification is given as follows:

1.1.1 Mechanical Processes

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

1.1.2 Electrochemical Processes

- Electrochemical Machining (ECM)
- Electro Chemical Grinding (ECG)
- Electro Jet Drilling (EJD)

1.1.3 Electro-Thermal Processes

- Electro-discharge machining (EDM)
- Electron Beam Machining (EBM)

1.1.4 Chemical Processes

- Chemical Milling (CHM)
- Photochemical Milling (PCM)

1.2 Principle Working of Energy

The principle of working is the base of type of energy used to remove the material. Classification along with the principle of working is described below.

1.2.1 Mechanical Energy

Mechanical energy is used for removing material from work piece. In this process, cutting tool with sharp edge is not used but material is removed by the abrasive action of high velocity of stream of hard, tiny abrasive particles. The particles are kept vibrating with very high velocity and ultra-high frequency to remove the material.

1.2.2 Electrical Energy

In this category of non-traditional machining electrical energy is used in the form of electrochemical energy or electro-heat energy to erode the material or to melt and vapourized it respectively. Electrochemical machining, electroplating or electro discharge machining are the examples work on this principle.

1.2.3 Thermal Energy

According to this principle heat is generated by electrical energy. The generated thermal energy is focused to a very small portion of workpiece. This heat is utilized in melting and evaporating of metal. The example based on this principle is electric discharge machining.

1.2.4 Chemical Energy

According to this principle of working chemicals are used to erode material from the workpiece. Selection of a chemical depends upon the workpiece material. Example of this type of machining is electrochemical machining. The dame principle can also be applied in reversed way in the process of electrochemical plating.

1.3 Need for Non Traditional Machining

Conventional machining sufficed the requirement of the industries over the decades. But new exotic work materials as well as innovative geometric design of products and components were putting lot of pressure on capabilities of conventional machining processes to manufacture the components with desired tolerances economically. This led to the development and establishment of NTM processes in the industry as efficient and economic alternatives to conventional ones. With development in the NTM processes, currently there are often the first choice and not an alternative to conventional processes for certain technical requirements. The following examples are provided where NTM processes are 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.

1.4 Abrasive Jet Machining

In abrasive jet machining, a focused stream of abrasive particles, carried by high pressure air or gas is made to impinge on the work surface through a nozzle and the work material is made to impinge on the work surface through a nozzle and work material is removed by erosion by high velocity abrasive particles.

In abrasive jet machining abrasive particles are made to impinge on work material at high velocity. Jet of abrasive particles is carried by carried gas or air. The high velocity stream of abrasives is generated by converting pressure energy of carrier gas or air to its kinetic energy and hence high velocity jet. A nozzle directs abrasive Jet in a controlled manner onto work material. The high velocity abrasive particles remove the material by micro cutting action as well as brittle fracture of the work material.

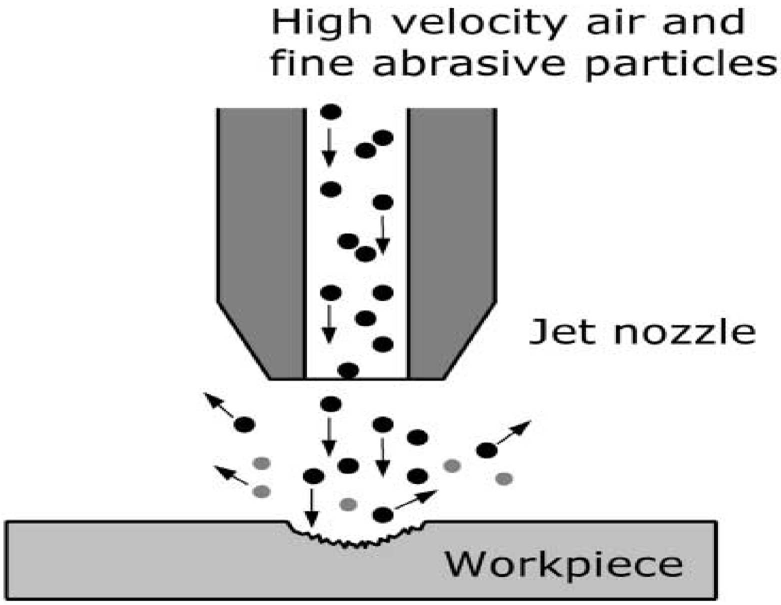

Fig. 1 Principle of the AJM process [7]

This is a process of removal of material by impact erosion through the action of concentrated high velocity stream of grit abrasives entrained in high velocity gas stream. AJM is different from shot or sand blasting, as in AJM, finer abrasive grits are used and parameters can be controlled more effectively providing better control over product quality.

In AJM, generally, the abrasive particles of around 50 microns grit size would impinge on the work material at velocity of 200m/s from a nozzle of ID 0.5mm with a stand off distance of around 2mm. The kinetic energy of the abrasive particles would sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives. System of abrasive jet machining consists of:

- Gas propulsion system
- Abrasive feeder
- Machining Chamber
- AJM Nozzle
- Abrasives

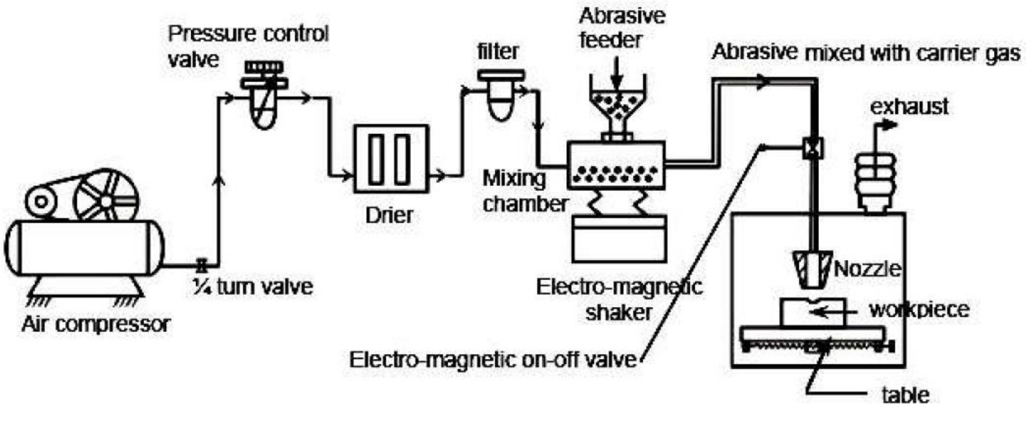

Fig.2 Schematic layout of AJM [25]

1.4.1 Gas Propulsion System

Supplies clean and dry air. Air, Nitrogen and carbon dioxide to propel the abrasive particles. Gas may be supplied either from a compressor or a cylinder. In case of a compressor, air filter cum drier should be used to avoid water or oil contamination of abrasive powder. Gas should be non-toxic, cheap, easily available. It should not excessively spread when discharged from nozzle into atmosphere. The propellant consumption is of order of 0.008 m^3/Min at a nozzle pressure of 5 bar and abrasive flow rate varies from 2 to 4 gm/min for fine machining and 10 to 20 gm/min for cutting operation.

1.4.2 Abrasive Feeder

Required quantity of abrasive particles is supplied by abrasive feeder. The filleted propellant is fed into the mixing chamber where in abrasive particles are fed through a sieve. The sieve is made to vibrate at 50-60 Hz and mixing ratio is controlled by the amplitude of vibration of sieve. The particles are propelled by carrier gas to a mixing chamber. Air abrasive mixture moves further to nozzle. The nozzle imparts high velocity to mixture which is directed at work piece surface.

1.4.3 Machining Chamber

It is well closed so that concentration of abrasive particles around the working chamber does not reach to the harmful limits. Machining chamber is equipped with vacuum dust collector. Special consideration should be given to dust collection system if the toxic materials (like beryllium) are being machined.

1.4.4 AJM Nozzle

AJM nozzle is usually made of tungsten carbide or sapphire (usually life -300 hours for sapphire, 20 to 30 hours for WC) which has resistance to wear. The nozzle is made of either circular or rectangular cross section and head can be head can be straight, or at a right angle. It is so designed that loss of pressure due to the bends, friction etc is minimum possible. With increase in wear of a nozzle, the divergence of jet stream increases resulting in more stray cutting and high inaccuracy.

1.4.5 Abrasive

Aluminum oxide (Al_2O_3) Silicon carbide (Sic) Glass beads, crushed glass and sodium bicarbonate are some of abrasives used in AJM. Selection of abrasives depends on MRR, type of work material, machining accuracy.

Table.1 Selection of Abrasives

Abrasives	Grain Sizes	Application
Aluminum oxide (Al_2O_3)	12,20,50 microns	Good for cleaning, cutting and deburring
Silicon carbide (Sic)	25,40 micron	Used for similar application but for hard material
Glass beads	0.635 to 1.27 mm	Gives matte finish
Dolomite	200 mesh	Etching and polishing
Sodium bicarbonate	27 micros	Cleaning, deburring and cutting of soft material light finishing below 50^oc

1.5 Physics of the AJM Process

- Fine particles (0.025mm) are accelerated in a gas stream
- The particle are directed towards the focus of machining
- As the particles impact the surface , it causes a micro fracture, and gas carries fractured particles away
- Brittle and fragile work better.

The gas stream is then passes to the nozzle through a connecting house. The velocity of the abrasive stream ejected through the nozzle is generally of the order of 330 m/sec.

1.6 Process Parameters of AJM

1.6.1 Abrasives

a) Material- Al_2O_3 Sic Glass beads Crushed glass Sodium bi carbonate
b) Shape –irregular/regular

c) Size-10 to 50 microns

d) Mass flow- 2 to 20 gm/min

1.6.2 Carrier Gas

a) Composition –Air, CO_2, N_2

b) Density- 1.3 kg/m3

c) Velocity -500 to 700 m/s

d) Pressure – 2 to 10 bar

e) Flow rate- 5 to 30 microns

1.6. 3 Abrasive jet

b) Velocity – 100 to 300 m/s

c) Mixing ratio- Volume flow rate of abrasives / Volumes flow rate of gas

d) Stand off distance-SOD- 0.5 to 15 mm.

e) Impingement angle – 60 to 90 deg.

1.6.4 Nozzle

a) Material- WC/Sapphire

b) Diameter – 0.2 to 0.8 mm

c) Life- 300 hours for sapphire , 20 to 30 hours for WC

1.7 Process Capability

1. Material removal rate- 0.015 Cm3/min
2. Narrow slots – 0.12 to 0.25 + 0.12mm
3. Surface finish -0.25 micron to 1.25 micron
4. Sharp radius up to 0.2 mm is possible
5. Steel up to 1.5mm, Glass up to 6.3mm is possible to cut.
6. Machining of thin sectioned hard and brittle materials is possible

1.8 Advantages And Disadvantages of Abrasive Jet Machining:

1.8.1 Advantages:

1. High surface finish can be obtained depending upon the grain sizes
2. It provides cool cutting action, so it can machine delicate and heat sensitive material

3. Process is free from chatter and vibration as there is no contact between the tool and work piece.
4. Capital cost is low and it is easy to operate and maintain AJM.
5. Thin sections of hard brittle materials like germanium, mica, silicon, glass and ceramics can be machined.
6. It has the capability of cutting holes of intricate shape in hard materials.

1.8.2 Disadvantages :

1. Limited capacity due to low MRR, MRR for glass is 40 gm/minute
2. Abrasives may get embedded in the work surface, especially while machining soft material like elastomers or soft plastics.
3. The accuracy of cutting is hampered by tapering of hole due to unavoidable flaring of abrasive jet.
4. Stray cutting is difficult to avoid
5. A dust collection system is a basic requirement to prevent atmospheric pollution and health hazards.
6. Nozzle life is limited (300 hours)
7. Abrasive powders cannot be reused as the sharp edges are worn and smaller particles can clog the nozzle.
8. Short stand off distances when used for cutting, damages the nozzle.

1.9Effect of process parameters on MRR

1.9.1 Effect of abrasive flow rate and grain size on MRR

It is clear from the figure that at a particular pressure MRR increase with increase of abrasive flow rate and is influenced by size of abrasive particles. But after reaching optimum value, MRR decreases with further increase of abrasive flow rate. This is owing to the fact that Mass flow rate of gas decreases with increase of abrasive flow rate and hence mixing ratio increases causing a decrease in material removal rate because of decreasing energy available for erosion.

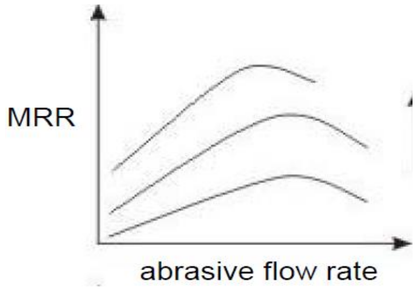

Fig* 3.*Effectof Abrasive flow rate on MRR [26]

1.9.2 Effect of Mixing ratio on MRR

Increased mass flow rate of abrasive will result in a decreased velocity of fluid and will thereby decreases the available energy for erosion and ultimately the MRR. It is convenient to explain to this fact by term MIXING RATIO. Which is defined as

$$\text{Mixing ratio} = \frac{\text{Volume flow rate of carrier gas}}{\text{Volume flow rate of carrier gas}}$$

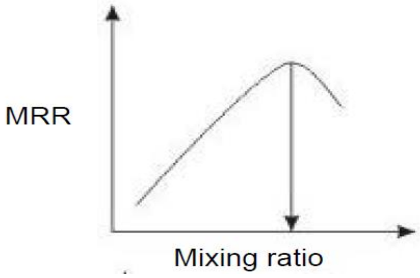

Fig.4 Effect of Mixing ratio on MRR[26]

The effect of mixing ratio on the material removal rate is shown above. The material removal rate can be improved by increasing the abrasive flow rate provided the mixing ratio can be kept constant. The mixing ratio is unchanged only by simultaneous increase of both gas and abrasive flow rate.

1.9.3 Effect of Nozzle pressure on MRR

The abrasive flow rate can be increased by increasing the flow rate of the carrier gas. This is only possible by increasing the internal gas pressure as shown in the figure. As the internal gas pressure increases abrasive mass flow rate increase and thus MRR increases. As a matter of fact, the material removal rate will increase with the increase in gas pressure Kinetic energy of the abrasive particles is responsible for the removal of material by erosion process. The abrasive must impinge on the work surface with minimum velocity for machining glass by SIC particle is found to be around 150m/s.

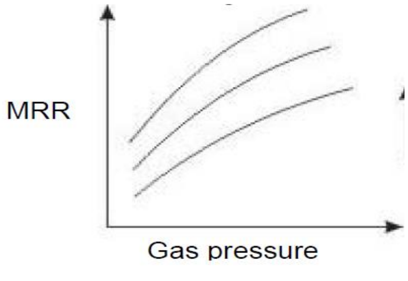

Fig.5Effect of Nozzle pressure on MRR[26]

1.9.4 Effect of Stand off distance on MRR

Stand off distance is defined as the distance between the face of the nozzle and the work surface of the work. SOD has been found to have considerable effect on the work material and accuracy. A large SOD results in flaring of jet which leads to poor accuracy.

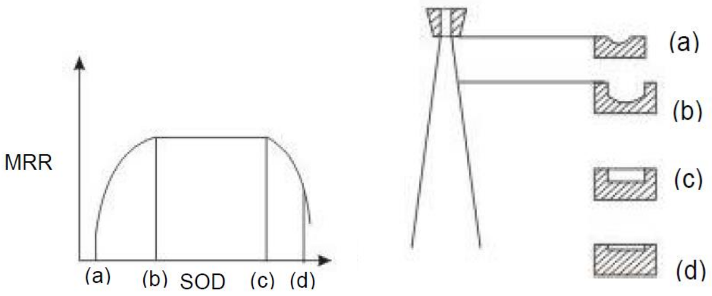

Fig.6 Effect of Stand off distance on MRR[26]

1.10 Applications of AJM:

i. This is used for abrading and frosting glass more economically as compared to etching or grinding

ii. Cleaning of metallic smears on ceramics, oxides on metals, resistive coating etc.

iii. AJM is useful in manufacture of electronic devices , drilling of glass wafers, deburring of plastics, making of nylon and Teflon parts permanent marking on rubber stencils, cutting titanium foils

iv. Deflashing small castings, engraving registration numbers on toughened glass used for car windows

v. Used for cutting thin fragile components like germanium, silicon etc.

vi. Register treaming can be done very easily and micro module fabrication for electrical contact , semiconductor processing can also be done effectively.

vii. Used for drilling , cutting , deburring etching and polishing of hard and brittle materials.

viii. Most suitable for machining brittle and heat sensitive materials like glass, quartz, sapphire , mica , ceramics germanium , silicon and gallium.

ix. It is also good method for deburring small hole like in hypodermic needles and for small milled slots in hard metallic components.

CHAPTER - 2

LITERATURE REVIEW

A considerable number of studies have investigated the general effects of the Stand off distance, Abrasive size, Pressure, Machining Time and others on Material removal rate(MRR). These studies have been briefly discussed for the variations observed experimentally.

2.1 Different AJM Methods:

AJM is classified according to working methods. These methods are depend on the working conditions , parameters and other factors .AJM unit with vortex type mixing chamber and it was restricted to abrasive jet drilling only[1]. Magnetic abrasive jet machining is a new concept in AJM used for in finishing processes for internal surfaces, in this method working fluid mixed with magnetic abrasives, which is jetted into the internal surface of the tube, with magnetic poles being provided on the external surface of the tube. In this study, the new-concept finishing process or the magnetic abrasive jet machining system was developed [2].For studied the Effect of work piece properties on machinability in abrasive jet machining of ceramic materials. Abrasive jet machining (AJM), a specialized form of shot blasting using fine-grained abrasives was used; it is an attractive micro-machining method for ceramic materials. In this paper, the machinability during the AJM process is compared to that given by the established models of solid particle erosion, in which the material removal is assumed to originate in the ideal crack formation system [6]. The specialized form of shot blasting in Abrasive jet machining

(AJM) and is beneficial for hard, brittle materials such as structural ceramics [7]. For investigated Micro-grooving of glass by using micro-abrasive jet machining, Micro abrasive jet machining (AJM) is similar to sand blasting, and effectively removes hard and brittle materials [10].In the machining of small holes by the conventional micro abrasive jet machining, the colliding abrasives accumulate in the bottom of the hole, preventing the direct impact of successive abrasives onto the work piece. As a result, the machining efficiency decreases as the machining progresses. Hence introduces a new method of micro abrasive jet machining, called micro abrasive intermittent jet machining (MAIJM), in which there exists a period of time during which no abrasive is injected into the gas stream from the nozzle so that the continuous flow of gas without abrasives from the nozzle could blow away any abrasives that have accumulated in the hole.[11]. Micro abrasive blasting (MAB) technique in AJM is an important machining technique for the cost effective fabrication of micro devices. The material removal process is based on the erosion of a mask-protected brittle substrate by an abrasive-laden air jet. The two different types of nozzles used, Laval-type nozzle and converging nozzle and predict which nozzle have more efficient blasting process .The simulation shows that the Laval-type nozzle is able to increase the particle velocity with more than 30% compared to the converging nozzle. [12]. High Resolution Powder Blast Micromachining technique in AJM is a technique in which a particle jet is directed towards a target for mechanical material removal. It is a fast, cheap and accurate directional etch technique for brittle materials like glass, silicon and ceramics [13]. Some other methods in which the wax-coated abrasive particles are used and in this method polishing time reduces and achieves an improved surface finish.[14]. Studied Ultrasonic abrasive machining with thermoplastic tooling. Ultrasonic machining generally involves the use of high hardness tooling material such as tungsten carbide or Monel to provide efficient energy transmission to abrasive particles and minimize tool wear. Whereas visco elastic thermoplastic composite material is used as tooling to conduct ultrasonic micromachining operations.[17].

2.2 Abrasive Particles:

Three kinds of commercial abrasive particles aluminum oxide silicon carbide, synthetic diamond. And these abrasive used to study the Material response to particle impact during abrasive jet machining of alumina ceramics. After the experiment it was found that the softest abrasive, aluminum oxide, leads to roughening of the alumina surface but causes no engraving, due to the lack of the abrasive hardness against that of the work piece. The softest abrasive, aluminum oxide (WA), leads to roughening of the alumina surface but causes no engraving, due to the lack of the abrasive hardness against that of the work piece. The impingement by synthetic diamond (SD) abrasive tends to cause large-scale fragmentation, and therefore the impacted surface becomes rough.[7].

2.3 Process Parameters and MRR:

A large number of investigations which have been carried out on AJM explain various input parameters, viz. abrasive grit size, mixing ratio, nozzle diameter, stand-off-distance. Input Parameters--Particle size, Stand off distance, Centre line and peripheral velocities of jet. Output Parameters-MRR, Edge radius, Entry side diameters. Effect of Parameters on the shape of the surface generated and MRR in AJM [5]. The effect of various input parameters on the shape of the abrasive jet machined surface and on abrasive jet deburred edges [3]. The erosion mechanism and experiments have been carried out to determine the effect of various input parameters on material removal rate, penetration rate, and on surface finish. Different material removal mechanism has been proposed by various investigators. It has been studied that due to plastic deformation, material removal mechanism causes crack and spalling of ductile material [19, 20]. For brittle materials, the impingement angle is 90◦ for maximum erosion rate, while it is 20–30◦ for ductile materials. Later, Sheldon and Finnie proposed that the erosion occurs as a result of Hertzian contact stress which causes a crack to grow from a pre-existing flaw in the existing work-material. The stress at which the crack propagation occurs is related to the distribution of sur-face flaws through Weicull statistics, where it is assumed that the risk of rupture is proportional to a function of the stress and the volume of the body. He calculated minimum effective angle of impingement for ductile materials erosion [21,22].Study of effect of Process Parameters (nozzle tip distance, mixing ratio, mass flow rate and so on) of Abrasive jet machining. The results of experiments have been conducted by changing pressure, nozzle tip distance on different thickness of glass plates. The effect of their process parameters on the material removal rate (MRR) were measured and plotted. As the pressure increases material removal rate (MRR) was also increased.

2.4 Applications:

Abrasive jet machining (AJM) has so many applications in industries and some applications are discussed. Magnetic abrasive jet machining is used for internal finishing processes, being a precision internal finishing method using a working fluid mixed with magnetic abrasives, which is jetted into the internal surface of the tube, with magnetic poles being provided on the external surface of the tube. In this study, the new-concept finishing process or the magnetic abrasive jet machining system was developed[2]. In recent years abrasive jet machining has been gaining increasing acceptability for deburring applications. An experimental investigation has been conducted to identify the abrasive jet deburring process parameters and the edge quality of abrasive jet deburred components. [3]. AJM has a attractive feature of external deburring with an abrasive jet is the ability to generate an edge radius at the deburred edges[4]. With the increase of the needs for machining of ceramics, semiconductors, electronic devices and LCD's, micro-AJM has become a useful technique for micro-machining. Micro-AJM could be effectively applied to the micro-machining of semiconductors, electronic devices and LCD [8, 10]. AJM has a wide application in etching AJM is a fast, cheap and accurate directional etch technique for brittle materials like glass, silicon and ceramics [9,13]. AJM has a wide application in machining of small holes [11]. AJM is a fast, cheap and accurate directional etch technique for brittle materials like glass, silicon and ceramics [13] .By using wax-coated abrasive particles in AJM we can reduces the polishing time and achieves an improved surface finish.[14].Abrasive jet polishing on mold steel using SiC coated with Wax. This study investigates the abrasive jet polishing (AJP) of electro-discharge-machined and ground SKD61 mold steel specimens using #2000, #3000 or #8000SiC particles and compound additives comprising either pure water, pure water and water-solvent machining oil, or pure water and water wax[15]

CHAPTER – 3

3.1 Concept of Design of Experiment(DOE):

Design of Experiment (DOE)is a structured, organized method is used to determine the relationship between the different factors (Xs) affecting a process and the output of that process (Y). Sir Ronald A. Fisher, the renowned mathematician and geneticist first developed this method in the1920s and 1930.

Design of experiment (DOE) is 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.

DOE is a scientific approach which allows the researchers to gain knowledge in order to better understand a process and to determine how the impacts (attribute effect the output response).

It is usually used when it is unclear what impact a specific set of inputs may have either individually or collectively on process or product. A designed experiment is the simultaneous evaluation of two or more factors (parameters) for their ability to affect the resultant average or variability of a particular product or process characteristic. To accomplish this in an effective and statically proper fashion, the level of factors are varied in a strategic manner, the results is analyzed to determine the influential factors and preferred levels, and whether increase or decrease of those levels will potentially lead to further improvement. It is important to note that this is an iterative process; the first round of experimentation. The beginning round, often referred to as screenings experiment, is used to find the few important influential factors out of the many possible factors involved with the process or product design. The experiment is typically a small experiment with many factors at two levels. The experiment is typically a small experiment with many factors at two levels. Later rounds of experiments typically involve few factors at more than two levels to determine conditions of further improvement.

- DOE is the most cost effective and efficient method for identifying the key input factors and in understanding the relationship between input factors and response.
- DOE investigate a number of input factors with relatively small number of tests.
- DOE helps to identify important/critical attributes of a process improvement effort, as they can be characteristics to be examined and the desired effect.

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

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

The planning phase is when factors and levels are selected and, there for 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.

The second most important phase is the conducting phase, when the test results are actually collected. If experiments are well planned and conducted, the analysis is actually much easier and more likely to yield positive information about factors and levels.

The analysis phase is when 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 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 or go back to step 4(iterative steps)
9. Assign factors to OA(s) and locate interactions.
10. Conduct tests described by trials in OAs.
11. Analyze and interpret results of the experimental trials.
12. Conduct confirmation experiment.

Problem Identification

Set-up parameters play the most important role to get the desired results. The main objectives of this research are to carry out the experiments by selecting different variables and their levels, applying Taguchi design of experiment and then analyzing the results obtained. Quality characteristics considered is:

- Material Removal Rate

The set-up parameters, which were used to get the expected results, are

- Abrasive grit size
- Stand Off distance
- Pressure

The experiments were conducted according to the Taguchi design of experiment i.e. the number of experiments were done as suggested by the Taguchi design of experiment according to number of factors, their levels and their interactions.

3.2 Taguchi Methods:

Taguchi methods are statistical methods developed by Genichi Taguchi to improve the quality of manufactured goods and, marketing and advertising. Taguchi methods are considered controversial among some traditional Western statisticians but others accept many of his concepts as being useful additions to the body of knowledge.

3.2.1 Objective of Taguchi’s Method

Taguchi’s parameter design can be used to make a process robust against sources of variation and hence improve field performance. If we can design a process that has the robustness to noise factors that largely affects the variance of performance characteristics at a developing stage, it will very possible for the process to have robustness against other noise factors that could not be considered at the development stage. The aim of a parameter design experiment is, then, to identify settings of the design parameters that maximize the chosen performance measure and are insensitive to noise factors.

3.2.2 Orthogonal Array

The goal of a Taguchi's experimental design is to identify optimal settings for all the design parameter, not to build the model fitting of process Taguchi has achieved substantial payoffs just by conducting many main-effect-only-experiments and checking the results by confirmation experiments. If it can be proved that the system could be described well by even only main effects, the optimal condition determined by only main effect analysis can be very efficient and simple method for optimization. Orthogonal array has been used to minimize the number of test runs while keeping the pair-wise balancing property in Taguchi's method for that purpose. These basic principles serve as a screening filter, which allows the examination of the effects of many process variables, identifying those factors, which have a major effect on process characteristics using a single trial with a few reactions. For example, optimization experiment would normally require each variable to be tested independently. Thus, a trial run investigating the effects and interactions of four reaction variables each at three concentration level, would require an experiment with 81 (i.e. 3^4) separate reactions. Using an orthogonal array, however, an estimate of the effect of each variable can be carried out using only nine experiments. Providing that three level are used for each variable tested, the number of experiments required (E) is calculated from the equation E=2k+1, where K is the number of factors to be tested. If the calculated number is not a multiple of three, then the required number of variables to be tested is the next multiple. Hence, as the number of experiments required becomes more marked; e.g. to test 9 factors would require 3^9 = 19683 experiments to analyze fully, whereas using Taguchi's methods this could be reduced to just 21 (2*9+1=19), 19 is not a multiple of three and then next integer divisible by three is 21.

Example of Orthogonal Array for 4 factors and 3 levels

Table. 2 Taguchi L9 OA(Orthogonal Array)

Expt. No.	A	B	C	D	response
1	1	1	1	1	-
2	1	2	2	2	-
3	1	3	3	3	-
4	2	1	2	3	-
5	2	2	3	1	-
6	2	3	1	2	-
7	3	1	3	2	-
8	3	2	1	3	-
9	3	3	2	1	-

Table 2 shows L9 OA (Orthogonal Array). This L9 table can apply for maximum 4 parameters and 3 levels.

3.3 Use of Orthogonal Arrays (OAs) and Signal-to-Noise(S/N) Ratio:

OAs is used to minimize the number of runs (or combinations) needed for the experiment. Many people are of the opinion that the application of OA is TM, but the application of OAs is only a part of TM. S/N ratios are used as a measure of the functionally of the system. S/N ratios capture the magnitude of real effects (signals) after making some adjustment to uncontrollable variation (noise).

CHAPTER – 4

EXPERIMENT PROCEDURE

4.1 Experimental Setup

The experimental setup of AJM consists of the following:

1) Reciprocating air compressor
2) Abrasive chamber
3) Central valves
4) Mixing chamber
5) Nozzle
6) Work piece

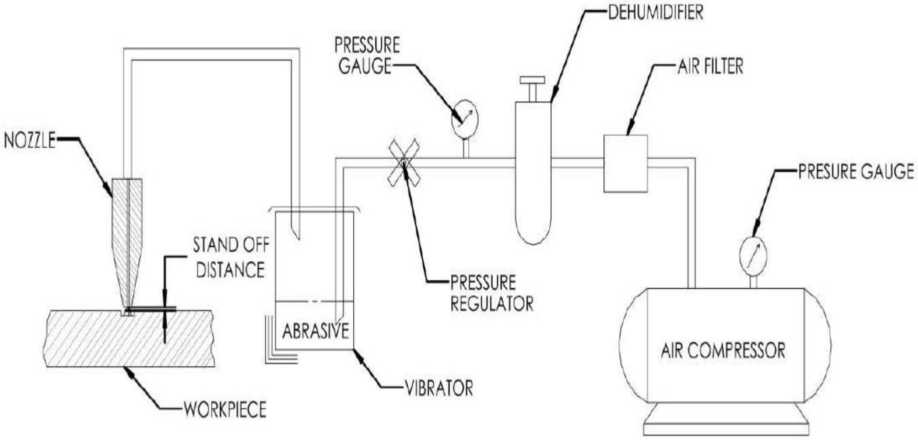

Fig .7 AJM setup [24]

- Reciprocating air compressor is used to supply compressed air to a reservoir on opening the valve the air passes from the reservoir to the mixing chamber.

- Abrasive chamber(Hopper) contains the abrasives and the abrasives mixed with compressed air in mixing chamber.
- When there abrasive particle mixed with compressed air, strikes the work piece removes the material due to impact. Tiny brittle fractures occur and the carrier gas carries away the fractured fragments.

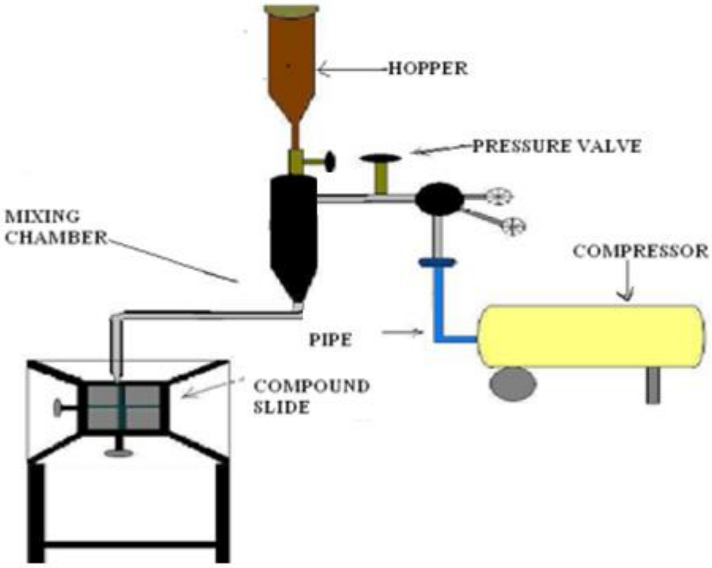

Fig. 8 Basic experimental setup

Table . 3 Abrasive jet machine characteristics

Mechanics of metal removal	Brittle fracture by impinging abrasive grains at high speed
Carrier gas	Compressed Air
Abrasives	Al_2O_3(aluminum oxide)
Pressure	2-8kg/cm^2
Nozzle	stainless steel
Material application	Hard and brittle metals ,alloys, and non-metallic

4.2 Problems of already existing set-up:

The setup had many problems. These problems are

- Improper mixing of compressed air and abrasive
- Arrangement of an abrasive dust collector and
- Too many openings which leads to leakages
- Wastage of abrasives
- In convenient working environment also causes health hazards to the operator
- There was problem in motion to the work table in up and down direction
- It was very difficult work with high pressure due to leakages and vibrations.
- Back pressure.

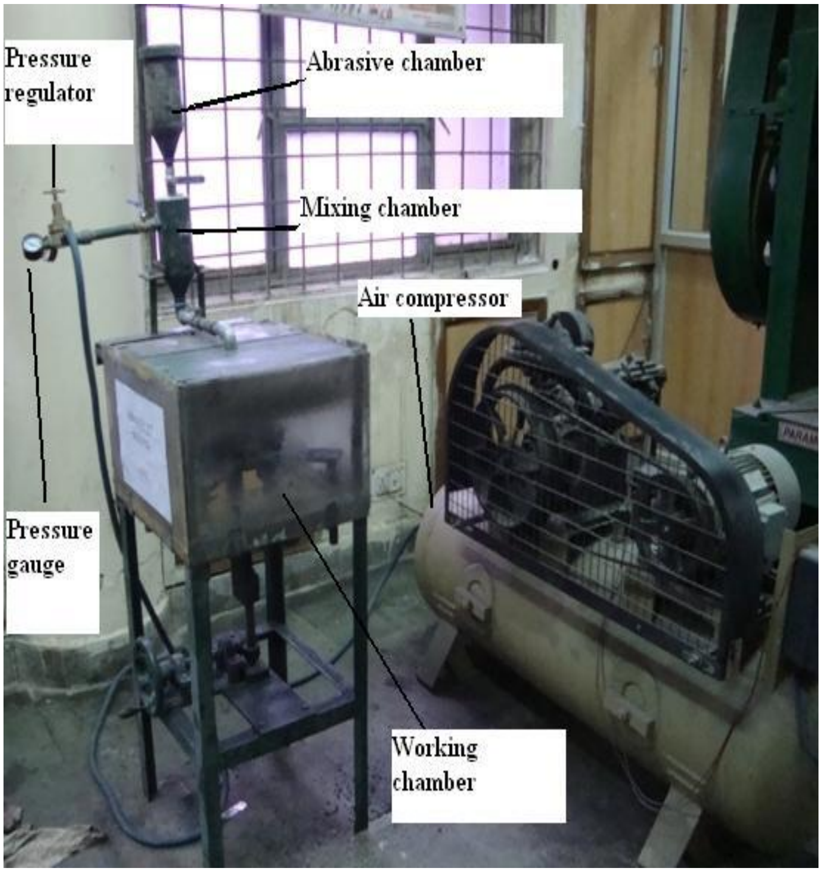

Fig. 9 Abrasive Jet Machine Metal forming lab Department Of Mechanical Engg.DTU

In the setup due to the problems stated as above modification were made so as to improvise the process and remove the problems associated with the machine. The main problem was mixing of compressed air and abrasive, leakages and back pressure.

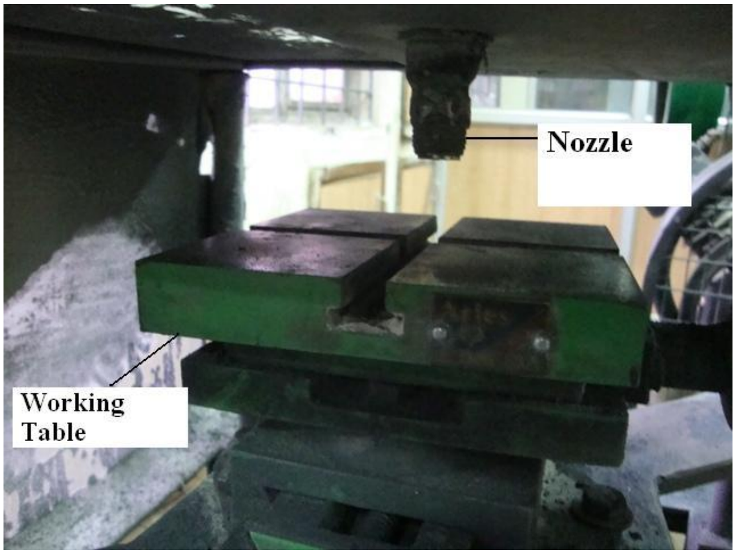

Fig. 10 The working table and Nozzle of Abrasive Jet Machine, Metal forming lab Department Of Mechanical Engg. DTU

4.3 Improvements in the Previous Model of AJM:

- 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.

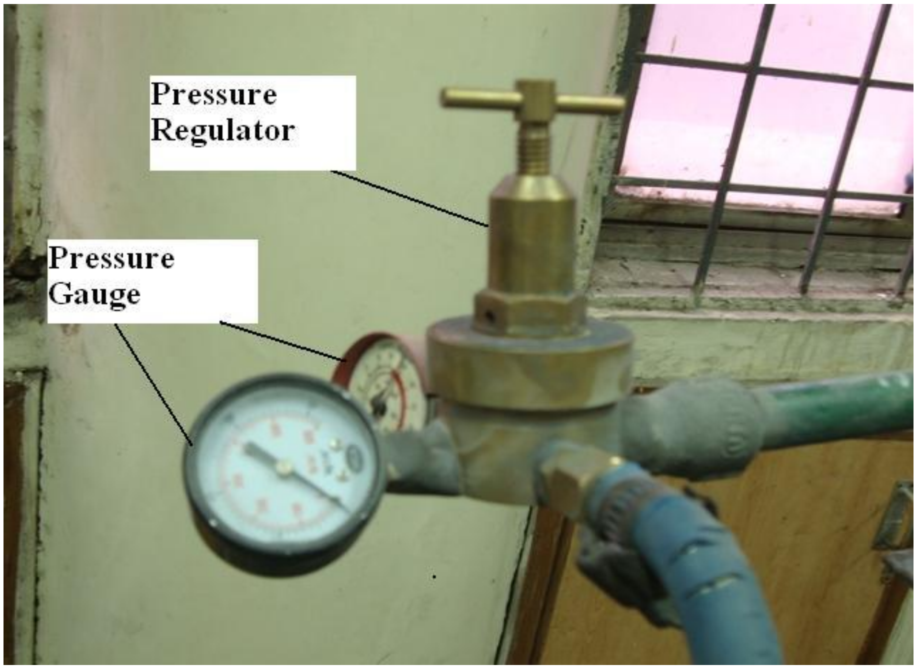

Fig. 11 Pressure Gauge and Pressure Regulatorof Abrasive Jet Machine

- 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).

- The position of abrasive chamber was horizontal so that abrasive get settle down and accumulated inside mixing chamber. There was no proper mixing of abrasive and compressed air. To solve this problem the position of mixing chamber was changed horizontal to vertical. After that we found better mixing between compressed air and abrasive and abrasive did not settled down. We change the nozzle because the nozzle was so much eroded. We provide the proper enclosure so that the abrasive did not come out.

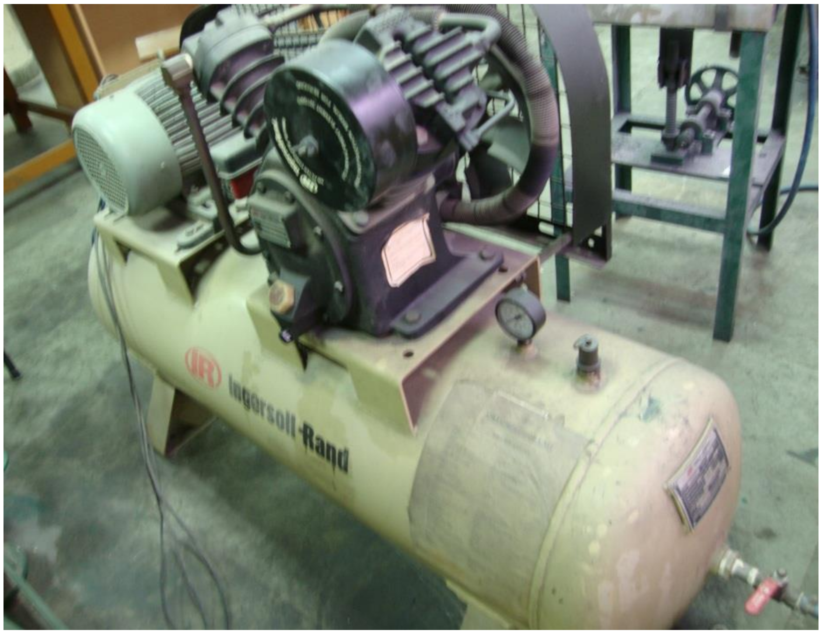

Fig. 12 Compressor used in Abrasive Jet Machine

Table. 4 Specification of compressor used in AJM

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

4.4 Experiment Procedure:

Experiment was conducted to study the MRR (material removal rate) of tempered glass (toughened glass) at different parameters of AJM and these parameters are pressure, angle and abrasive mesh size(microns).

The Al_2O_3(aluminum oxide) abrasive used in the experiment, Aluminum oxide is a chemical compound of aluminum and oxygen with the chemical formula Al_2O_3.It is commonly called alumina,it commonly occurs in its crystalline polymorphic phase α-$Al_2O_3$and the work piece was tempered glass (toughened glass).Toughened glass is physically and thermally stronger than regular glass.For glass to be considered toughened, the compressive stress on the surface of the glass should be a minimum of 69 MPa.

Initially weight the glass work piece which is rectangle in shape (dimensions are 7*3 cm *5mm) with the help of digital balance. After that put the abrasive inside the abrasive hopper. Turn on the compressor and open the gate valve of abrasive hopper. The abrasive grains were mixed with air jet coming from compressor and focused on the specimen with the help of nozzle. After that again weight the specimen and also note the machining time. Find MRR by using this formula.

:

MRR= (Initial Weight-Final Weight)/Time

Table. 5 AJM Process Parameters

Parameter	code	Levels		
		1	2	3
Pressure (kg/cm^2)	A	4	6	8
Angle between the workpiece and nozzle jet (degree)	B	40^o	20^o	0^o
Abrasive(mesh size)	C	1000 (15 microns)	500 (29 microns)	320 (46 microns)

The conversion of mesh size into micron is done by using this formula. The microns values round off values.

Microns = 14,992 *mesh $^{(-1.0046)}$

Essentially, the traditional experimental design procedures are too complicated and not easy to use. A large number of experimental works have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Taguchi methods have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process.

The degree of freedom for three parameters in each of three levels.

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 OA has eight DOF, in which 6 were assigned to three factors (each one 2 DOF) and 2 DOF was assigned to the error.

Table. 6 Taguchi L9 OA for Response(MRR)

Expt. No.	A	B	C	Response[MRR (g/sec.)]
1	4	40^0	1000	-
2	4	20^0	500	-
3	4	0^0	200	-
4	6	40^0	500	-
5	6	20^0	200	-
6	6	0^0	1000	-
7	8	40^0	200	-
8	8	20^0	1000	-
9	8	0^0	500	-

CHAPTER - 5

RESULTS AND DISCUSIONS

5.1 Experiments Conducted:

For applying L9 Taguchi 9 experimental readings have to be taken. These experimental readings are.

Experiment No.1

Pressure (kg/cm^2)	4
Angle (degree	40^o
Abrasive(mesh size)	1000
Initial weight(gram)	25.6382
Final weight(gram)	25.6245
Time(sec.)	4
MRR(g/sec.)	0.0034

Fig.13 Workpiece after experiment No. 1

Experiment No.2

Pressure (kg/cm^2)	4
Angle (degree)	20^o
Abrasive(mesh size)	500
Initial weight(gram)	25.1774
Final weight (gram)	25.1578
Time(sec.)	4
MRR(g/sec.)	0.0049

Fig. 14Workpiece after experiment No. 2

Experiment No.3

Pressure (kg/cm^2)	4
Angle (degree	0^o
Abrasive(mesh size)	200
Initial weight(gram)	25.5980
Final weight(gram)	25.5644
Time(sec.)	4
MRR(g/sec.)	0.0084

Fig.15Workpiece after experiment No. 3

Experiment No.4

Pressure (kg/cm^2)	6
Angle (degree	40^o
Abrasive(mesh size)	500
Initial weight(gram)	25.7710
Final weight(gram)	25.7366
Time(sec.)	4
MRR(g/sec.)	0.0086

Fig.16Workpiece after experiment No. 4

Experiment No.5

Pressure (kg/cm^2)	6
Angle (degree	20^o
Abrasive(mesh size)	200
Initial weight(gram)	25.5457
Final weight(gram)	25.5049
Time(sec.)	4
MRR(g/sec.)	0.0102

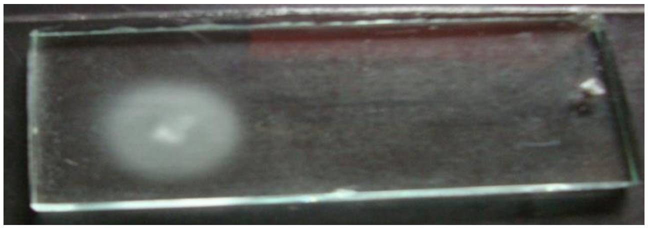

Fig. 17Workpiece after experiment No. 5

Experiment No.6

Pressure (kg/cm^2)	6
Angle (degree	0^o
Abrasive(mesh size)	1000
Initial weight(gram)	25.4685
Final weight(gram)	25.4301
Time(sec.)	4
MRR(g/sec.)	0.0096

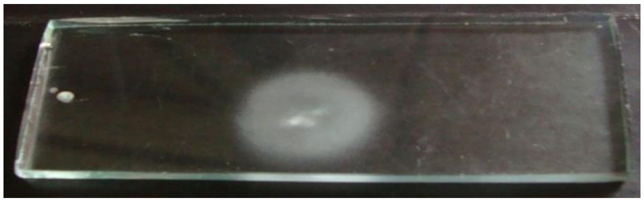

Fig.18Workpiece after experiment No. 6

Experiment No.7

Pressure (kg/cm^2)	8
Angle (degree	40^o
Abrasive(mesh size)	200
Initial weight(gram)	25.2459
Final weight(gram)	25.1955
Time(sec.)	4
MRR(g/sec.)	0.0126

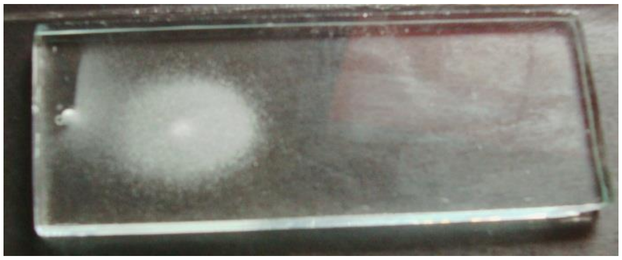

Fig. 19Workpiece after experiment No. 7

Experiment No.8

Pressure (kg/cm^2)	8
Angle (degree	20^o

Abrasive(mesh size)	1000
Initial weight(gram)	25.6185
Final weight(gram)	25.5733
Time(sec.)	4
MRR(g/sec.)	0.0113

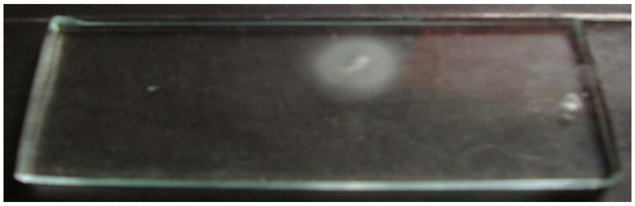

Fig. 20Workpiece after experiment No. 8

Experiment No.9

Pressure (kg/cm^2)	8
Angle (degree	0^o
Abrasive(mesh size)	500
Initial weight(gram)	25.1965
Final weight(gram)	25.1373
Time(sec.)	4
MRR(g/sec.)	0.0148

Fig. 21workpiece after experiment No. 9

Table. 7 Taguchi L9 OA for MRR

Expt. No.	A	B	C	MRR (g/sec.)
1	1	1	1	0.0034
2	1	2	2	0.0049
3	1	3	3	0.0084
4	2	1	2	0.0086
5	2	2	3	0.0102
6	2	3	1	0.0096
7	3	1	3	0.0126
8	3	2	1	0.0113
9	3	3	2	0.0148

The L_9 orthogonal arrays table with 9 rows (corresponding to the number of experiments).

.5.2 Analysis of the S/N Ratio

[27]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 values are calculated by using this equation.

S/N = -10*log (mean square deviation)

The S/N ratio for the larger-the-better is:

$$\frac{S}{N} = -10 * \log_{10}\left[\frac{1}{n}\Sigma\frac{1}{y2}\right]$$

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/row. The S/N ratio values are calculated by taking into consideration above equation. The MRR response table for the pressure, angle and abrasive grit size was created in the integrated manner and the results are given in Table8.

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), 0^0angle (level 3) and 200 mesh abrasive (level 3). Fig.22 shows the effect of the process parameters on the metal removal rate values.

Table.8 Response Table for Signal to Noise Ratios (Larger is better)

Level	Pressure	Angle	Grit size
1	-45.69	-42.89	-42.89
2	-40.50	-41.65	-41.37
3	-37.84 [a]	-39.49 [a]	-39.78[a]
Delta	7.85	3.40	3.11
Rank	1	2	3

[a] Optimum level(Level 3 is optimum level)

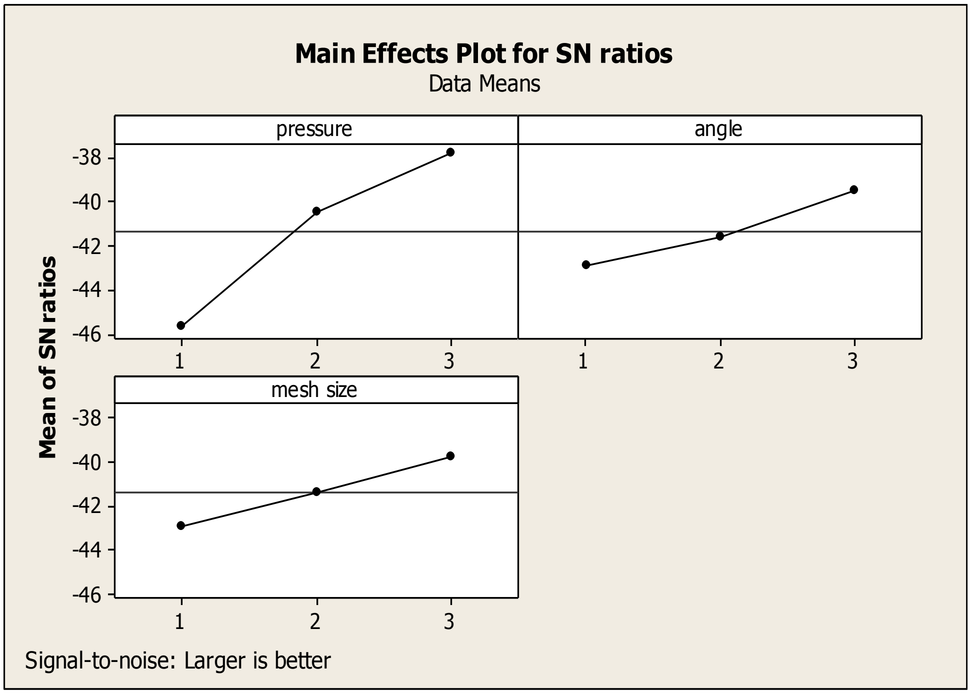

Fig. 22 Effect of process parameters on MRR

The effect of process parameters on the metal removal rate values was shown in Fig. 22. The MRR increases with increasing in Pressure and decreasing inangle and abrasive size in mesh of abrasive. MRR is proportional to the pressure. With the increase in pressure the kinetic energy of the abrasive particle also increases. The kinetic energy of the abrasive particle is responsible for material removal by erosion process. Hence increase in pressure enhancement the MRR. With the decrease in angle between the workpiece and nozzle jet and abrasive mesh size the MRR increase because 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 meshsize decreases, abrasive particle size increases, thus smaller mesh abrasives removes more metal as compared to the particle of larger mesh. Abrasive jet MRR formula 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

According the above formula MRR is directly proportional to mean diameter of abrasive particles, larger size abrasive particles have high MRR than Small particles abrasive and Small particles are less irregular in shape; hence their cutting ability is poor.So large particles size abrasives MRR higher than small particle size.

5.3 Analysis of Variance (ANOVA)

[27]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 as

$$SS_{T} = \sum_{i=1}^{n} (n_{i} - n_{m})^{2}$$

where n is the number of experiments in the orthogonal array and ηi 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 SS_D is the sum of the squared deviations. The ANOVA results are illustrated in table 9

Table .9 ANOVA results for metal removal rate

Source of variation	Degrees of freedom (DOF)	Sum of squares (S)	Variance (V)	F-ratio (F)	P-value (P)	Percentage (%)
Model	6	1.012E-004	1.686E-005	96.65	0.0103	
A	2	8.078E-005	4.039E-005	231.52	0.0043	79.82%
B	2	1.238E-005	6.191E-006	35.49	0.0274	12.23%
C	2	8.002E-006	4.001E-006	22.94	0.0418	7.91%
Error	2	3.489E-007	1.744E-007			0.04%
Total	8	1.015E-004				

{*1.012E-004 means 1.012 times 10 to the -4th power (.0001). It should be 0.0001012}

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.

The P-value reports the significance level (suitable and unsuitable) in Table.9. If P-value < 0.05 level is significant and if P value> 0.05 level is insignificant. In Table.9 model P-value is 0.0103 which is less than 0.05 hence model is significant. 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.9 that the pressure (A), angle (B) and abrasive (C) affect the metal removal rate by 79.82%, 12.23% and 7.91% in the abrasive jet machining(AJM) of tempered glass, respectively. A confirmation of the experimental design was necessary in order to verify the optimum cutting conditions

5.4 Regression Analysis

The correlation between factors (Pressure, Angle and Abrasive mesh size) and metal 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 = - 0.00331 + 0.00366 pressure + 0.00120 mesh size + 0.00146 angle

R^2=0.981

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 is satisfactory.

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

5.5 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 and obtained as 0.0158 g/min.

CHAPTER -6

CONCLUSIONS

This 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(AJM) of tempered glass. In the AJM process, the parameters were selected taking into consideration of manufacturer and industrial requirements.

From the analysis of the results in the AJM process using the conceptual signal-to-noise (S/N) ratio approach, regression analysis, analysis of variance (ANOVA), and Taguchi's optimization method, the following can be concluded from the present study:

- 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 34.04%, 58.09% and 7.57% in the abrasive jet machining of tempered glass , respectively.
- The maximum metal removal rate is calculated as 0.00157 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= 0^0 (B3) and abrasive = 200 mesh (C3).

- Metal removal rate increases with increase in pressure and abrasive size (microns) in abrasive jet machining of tempered glass.
- Metal removal rate increases with the decrease in angle and abrasive mesh size inabrasive jet machining of tempered glass.

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