A THESIS REPORT
ON

EXPERIMENTAL INVESTIGATION OF HELICAL ABRASIVE FLOW MACHINE SETUP FOR DIFFERENT TYPES OF WORKPIECE MATERIAL

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
IN
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SUBMITTED BY
MANSI PANWAR
2K13/PIE/28

UNDER THE SUPERVISION OF

Dr. QASIM MURTAZA
ASSOCIATE PROFESSOR

Dr. REETA WATTAL
PROFESSOR

DEPARTMENT OF MECHANICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY,
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DECLARATION

I Mansi Panwar, hereby declare that the work presented in this report, titled "EXPERIMENTAL INVESTIGATION OF HELICAL ABRASIVE FLOW MACHINE SETUP FOR DIFFERENT TYPES OF WORKPIECE MATERIAL", in partial fulfillment for the award of the degree of M.Tech in Production and Industrial Engineering, submitted in the Department of Mechanical engineering, Delhi Technological University, Delhi, is original and to the best of my knowledge and belief, it has not been submitted in part or full for the award of any other degree or diploma of any other university or institute, except where due acknowledgement has been made in the text.

Mansi Panwar

Roll No. 2K13/PIE/028

M.Tech. Production and Industrial Engineering

Date:

CERTIFICATE

This is to certify that the research work embodied in this dissertation entitled **“**EXPERIMENTAL INVESTIGATION OF HELICAL ABRASIVE FLOW MACHINE SETUP FOR DIFFERENT TYPES OF WORKPIECE MATERIAL**”** submitted by Mansi Panwar, Roll no. 2K13/PIE/28 student of Master of Technology in Production and Industrial Engineering under Department of Mechanical Engineering, Delhi Technological University, Delhi is a bonafide record of the candidate’s own work carried out by him under our guidance. This work is original and has not been submitted in part or full for award of any other degree or diploma to any university or institute.

Dr. QASIM MURTAZA	Dr. REETA WATTAL
Associate Professor	Professor
Department of Mechanical Engineering	Department of Mechanical Engineering
Delhi Technological University, Delhi, India	Delhi Technological University, Delhi, India

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Mansi Panwar

2K13/PIE/28

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ABSTRACT

Abrasive flow machining (AFM), also known as abrasive flow deburring or extrude honing, is an interior surface finishing process characterized by flowing an abrasive - laden fluid through a work piece. During the study different medias, workpieces and pressure ranges were chosen. These fluids are typically very viscous, having the different plasticizers. AFM smoothens and decreases surfaces roughness, and is specifically used to remove burrs; polish surfaces form radii, and even remove material. These experiments were conducted between aluminium, brass, mild steel at a range of 10, 15, 20Mpa. When an abrasive mixed with a polymer of special rheological properties and forced through a restricting medium, the abrasive and polymer will act as a self-forming tool that precisely removes work piece material and improve the surface finish at those areas restricting to the medium flow.

Different relationships between a number of sets of workpiece, media and pressure are obtained using TAGUCHI method and their analysis was performed over ANOVA technique. Styrene butadiene rubber which is the most common natural rubber has given improved outputs among other media. In the % improvement in the roughness came out to be 39.51% and 3.21mg for material removal analysis.

CHAPTER 1

INTRODUCTION

1.1 NON-TRADITIONAL MANUFACTURING PROCESSES

Since beginning of the human race, they have evolved tools and energy sources to power these tools to meet the requirements for creating easier and enjoyable life. In the early stage of mankind, tools used were made of stones for the item being made. When iron tools got invented, desirable metals and more sophisticated articles were produced. Afterwards when people hear the word "machining" they usually think of machines that utilize mechanical energy to remove material from the work piece. Milling machines, saws and lathes machines are some of the most common machines using mechanical energy to remove work material. The tool makes contact with the work piece and the resulting shear causes the work material to flow over the tool. All traditional forms of metal cutting processes use shear as the primary method of metal removal. Besides this the category of nontraditional machining covers a wide range of technologies, including those used on a large scale, and others that are typically used in unique or proprietary applications. These machining techniques generally have higher energy requirements and slower throughputs than those required by any traditional machining, these NTM have been developed for applications where traditional machining operations were impractical, incapable, or uneconomical to use. Nontraditional machining can be thought of as operations which does not use shear as their primary source of energy. For example, in abrasive water jet operations mechanical energy is utilized, but material removal is by erosion.

The NTM processes has its importance in the areas of micro- and nano-machining also where high accuracy and superior surface finish are often desirable which can only be achieved using these NTM processes where the material is removed in the form of atoms or molecules individually or in groups. All these processes are now being widely implemented to generate intricate and highly precise shapes in the workpiece surface areas which are difficult or inaccessible for the traditional machining methods. NTM process selection is often difficult requiring human expertise and being affected by several criteria, and there is always a need for a structured/structural approach for appropriate NTM process selection for a given machining application. The existence of a large number of alternatives available for NTM processes, uncertainties with regards to the process capabilities, lack of versatility and shortage of the experienced planners make it more difficult and challenging for the selection of the NTM processes.

Nontraditional machining methods are typically divided into the following categories:[1]

1. **Mechanical** - Ultrasonic Machining, Rotary Ultrasonic Machining, Ultrasonically Assisted Machining etc.

2. **Electrical** - Electrochemical Discharge Grinding, Electrochemical Grinding, Electrochemical Honing,Hone-Forming, Electrochemical Machining, Electrochemical Turning, Shaped Tube Electrolytic Machining, Electro-Stream etc.

3. **Thermal** - Electron Beam Machining, Electrical Discharge Machining, Electrical Discharge Wire Cutting, Electrical Discharge Grinding, Laser Beam Machining etc.

4. **Chemical** - Chemical Milling, Photochemical Machining.

1.2 ULTRASONIC MACHINING

Ultrasonic machining, which is also known as ultrasonic impact grinding, is basically a machining operation in which a vibrating tool which is oscillating at ultrasonic frequencies is used to remove the material from workpiece, aided by an abrasive slurry which flows freely in between the workpiece and the tool. It differs from most other machining operations because very little heat is production. In this the tool never touches the workpiece and therefore the grinding pressure is rarely more than 2 pounds, making this operation perfect for machining of extremely hard and brittle materials, such as glass, sapphire, ruby, diamond, and ceramics are some of the examples. Here abrasive contained in slurry are driven against the work by a tool oscillating at low amplitude and frequency (15-30 KHz).

1.3 JET MACHINING

In jet machining high velocity jet of water(water jet cutting) or water mixed with abrasive material (abrasive water jet machining) is directed towards the workpiece to cut the material. If a mixture of gas and abrasives are used, process is referred as abrasive jt machining which is not used to cut the materials but for finishing operations like deburring, cleaning, polishing.

1.4 WATER JET MACHINING

A water jet cutter, also known as a water jet is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance. The term abrasive jet specifically refers to the use of a mixture of water and abrasive to cut hard materials such as metal or granite. while the mixture of water and abrasive to cut hard materials such as metal or granite, while the term pure waterjet refers to waterjet cutting without the use of added abrasive, often used for softer materials such as wood or rubber. Water jet cutting is often called during fabrication of machine parts. It is the preferred method of cutting when the materials being cut are sensitive to the higher temperatures generated by other methods. Water jet cutting is dominantly used in various industries, including mining, aerospace and for cutting, shaping and reaming.

1.5 ABRASIVE WATER JET MACHINING

In abrasive water jet machining, the water jet streams accelerates the abrasive particles and those particles only erode the material, not the water. The abrasive water jet is more powerful than a pure water jet and its capable of cutting some hard materials such as metal, glass, stone and composites however none of which can be cut with a pure water jet. Abrasive water jet, by using standard parameters can cut materials with hardness up to or slightly beyond aluminum oxide ceramic (which is often called alumina, AD 99.9).

1.6 ABRASIVE JET MACHINING

In any abrasive jet machining process, a focused steam of abrasives are (of size 10 to 40 microns) carried by high pressure gas or air at a velocity ranging between 150 to 300 m/sec is made to impinge on the work surface with nozzle, and the work material is removed by erosion by the high velocity jet of abrasive particles. The inside diameter (ID) of the nozzle through which abrasives flow is about 0.18 to 0.80 mm and the stand-off distance which (i.e. distance between nozzle tip and workpiece) is kept about 0.3 to 20.0 mm. This process can be easily controlled in order to vary the metal removal rate which depends on flow rate and mesh size of abrasive particles. This process is best suited for machining super alloys or refractory type of materials, and also machining the thin sections of hard materials and making intricate hard holes. The cutting action is having lower temperatures because the carrier gas serves as coolant. When any abrasive particle (like Al2O3 or SiC) having sharp edges hits any brittle and fragile material with a high speed, it makes dent into them and lodges a small particle from it by a tiny brittle fracture. The lodged out or the wear particle is carried away by the air or gas.

1.7 ELECTRIC DISCHARGE MACHINING

EDM sometimes colloquially also referred to as spark machining, spark eroding, burning, die sinking, wire burning or wire erosion, is a manufacturing process from which a desired shape is obtained by using electrical discharges (sparks). In any EDM process, Material removal from the workpiece is done by a series of rapidly recurring current discharges between two electrodes which are generally separated by a dielectric medium and subject to an electric voltage. Also, one of the electrodes is called the tool-electrode, or simply the "tool" or "electrode", while the other one is called the workpiece-electrode, or "workpiece". If the distance between the two electrodes is reduced, the intensity of their electric field in the volume between those electrodes becomes greater than the strength of the dielectric which breaks, allowing current to flow between the two electrodes. This phenomenon is similar to the breakdown of capasitor (condenser), as a result, material is removed from both the electrodes. Once we stop the current s (or it stops, depending on the type of generator), new liquid dielectric is passed into the inter-electrode volume, enabling the solid particles/debris to be carried away and the insulating properties of the dielectric to be restored. Adding new liquid dielectric in the inter-electrode volume is commonly called as "flushing". Also, after a current flow, the difference of potential between the two electrodes is restored to what it was before the breakdown, by which a new liquid dielectric breakdown can occur.

1.8 WIRE ELECTRIC DISCHARGE MACHING

Wire electric discharge machining (wire EDM) is a special form of EDM that utilizes a small diameter wire as the electrode to cut narrow kerfs in the work piece. The work piece is fed progressively and slowly past the wire in order to achieve the desired cutting path. Numerical control is used to regulate the work part motion at the time of cutting. As it cuts, the wire is continuously advanced between a supply spools to present a fresh electrode of consistent diameter to the work. which helps to maintain constant kerfs width during cutting. As in EDM, wire EDM must also be carried out in the presence of a dielectric. Which is applied by nozzle directed at the tool-work interface as indicated in the figure, or the work part is submerged in a dielectric bath. The wire diameter ranges from 0.08 to 0.30 mm, depending on required kerfs width. Materials required for the wire include brass, copper, tungsten, and molybdenum. Dielectric fluids incorporate demonized water or oil. As in EDM this makes the kerfs larger than the wire diameter.

1.9 LASER BEAM MACHING

Evolution of advanced engineering materials, stringent design requirements, intricate shape and unusual size of workpiece bound the use of conventional machining techniques. Hence, it was realized to develop some non-conventional machining approaches known as advanced machining processes (AMPs). **[3]** Today many AMPs are being adapted in the industry such as; electro discharge machining, beam machining processes, chemical machining processes (chemical blanking, photochemical machining), ultrasonic machining (USM), and jet machining processes, but somehow these processes have their own limitations regarding workpiece material, shapes, etc. LBM is one kind of the AMPs which is accounted for shaping almost whole range of engineering materials. The LBMs are widely used for cutting, drilling, marking, welding, sintering and heat treatment. Laser beam is concentrated for melting and vaporizing the unwanted material from the parent material. It is convenient for geometrically complex profile cutting and making small sized holes in sheet metal. Among various type of lasers adopted for machining in industries, CO_2 and Nd:YAG lasers are most authorized. In recent years, researchers have explored a number of ways to reform the LBM process performance by analyzing the different factors that influence the quality characteristics. The experimental and theoretical studies show that process performance can be upgraded considerably by appropriate selection of laser parameters, material parameters and operating parameters. This method is also used to perform turning as well as milling operations but extensive application of laser beam is primarily in cutting of metallic and non-metallic sheets.

1.10 ELECTRON BEAM MACHING

Electron beam machining (EBM) is such a thermal machining process in which high-velocity electrons focused into a narrow beam which are used for instantly heating, melting, or vaporizing the material. Whenever a high-speed electron in a densely focused beam is made to impact with the workpiece surface, most of the kinetic energy of its electrons gets converted into heat. This phenomenon has been well appreciated since the development of electron microscopy when attempts to consider the electron beam as a machining tool were made. The first EBM equipment was created in the 1950s. The beam is easily spotted and defected by electromagnetic focusing lenses and deflection lenses. The power density is also effortless to control. This process can be used for many purposes, including drilling, cutting, annealing, and welding.

1.11 ABRASIVE FLOW MACHINING

Abrasive flow machining (AFM)was developed by the Extrude Hone Corporation, USA in 1960s as a technique to deburr and polish difficult-to-reach surfaces and edges by pouring abrasive laden polymer with some special rheological properties. AFM can be applied to some wide range of finishing operations, providing uniform repeatable and predictable results. In AFM, work piece is held in between the two opposite sided piston cylinder arrangement (Fig. 1). The surfaces and edges of the workpiece are finished by the running medium (abrasive laden polymer) across the workpiece.

Abrasion is high where the medium velocity is high. A rise in pressure and medium viscosity increases material removal rate but whereas surface finish value decreases. The type of machining operation used to produce the specimens prior

to AFM is found to be significantly affecting the improvement of the surface finish. Also the metal removal and surface finish in AFM are significantly altered by the medium viscosity and the 'active grain density' by counting the number of noticeable grains per unit area by viewing over number of randomly chosen areas on medium and developed a force model based on abrasion theory.

AFM process contributes a high level of surface finish and close geometric tolerances with an economically admissible rate of surface generation for a wide range of industrial components. The capability of media in AFM process to finish difficult to reach areas, to follow complex contours and to synchronously work on multiple edges and surfaces, making it more versatile than other all finishing process. AFM removes small quantities of parent material by flowing a semi solid abrasive-laden media through or across the work material. Two vertically opposed cylinders extrude laden media back and forth through passages formed by the workpiece and tooling. This laden media is composed of semi-solid carrier and abrasive grains. The media acts as a 'self-deformable stone' with protruding abrasive particles as cutting tools.

Their surface precision can be controlled/varied by changing the AFM parameters (such as number of cycles, abrasive's concentration, abrasive mesh size and medium flow speed) when the complex hole is polished. Moreover, the micro hole, drilled by EDM, can be further improved in precision and surface roughness by AFM. In the theoretical models we estimate the material removal rate and surface roughness using the finite element method. And the active grain density on the medium surface can also be determined by stochastic simulation. The material removal and surface roughness in AFM are significantly influenced by the medium viscosity. By this the viscosity of medium reduces drastically even with a small increase in temperature. Which means medium viscosity increases with the abrasive concentration and decreases with the abrasive size. Besides, the specific energy and temperature in AFM can be determined by a theoretical model. Observation says that the specific energy remains almost constant with a change in abrasive mesh size, but resulting in higher value for higher hardness of workpiece material.

1.12 BASIC PRINCIPLE OF AFM

An Abrasive flow machining works by a back and forth movement under pressure of an abrasive laden, viscoelastic compound or abrasive media, with the help of a holding fixture and over the area/portion to be polished, deburred and radiused. Abrasive flow machining is a exclusively a mechanical process. A chemically inactive and non-corrosive media, similar to a soft clay, is used to upgrade surface finish and edge conditions. The abrasive particles present inside the media grind away, rather than shear off, the material. In many cases, the similar batch of media can be used on various metals without transferring removed materials between workpieces. AFM has its use for surface or edge conditioning of external, internal, and otherwise inaccessible holes, slots and edges. AFM is highly efficient and accurate, and can be used in one-way or two-way applications very precisely. In a one-way system, the abrasive media flows in only one direction, granting the media to exit the work part for fast processing, easy cleaning, or simple, quick-exchange tooling. But in a typical two-way process, two vertically opposed cylinders extrude the abrasive media in back and forth direction through passages formed by the workpiece and tooling.

1.13 CLASSIFICATION OF ABBRASIVE FLOW MACHINING

AFM machines are classified into two categories according to the direction of flow of abrasive media i.e one way AFM and two way AFM.

1.13.1 ONE WAY AFM PROCESS

The schematic diagram of one way AFM **[4]** process, which was designed and fabricated by Saad Saeed Siddiqui. In One-way AFM process apparatus is arranged with a hydraulically actuated reciprocating piston and an extrusion medium chamber is adapted to receive and extrude medium unidirectional across the internal surfaces of a work piece for those having internal passages formed therein. Fixture guides the flow of the medium from the extrusion medium chamber into the internal passages of the work piece wherein a medium collector collects the medium as the fluid extrudes out from the internal passages. The extrusion medium chamber is provided with an access port to periodically collect medium from the collector into extrusion chamber. The hydraulically motivated piston intermittently withdraws from its extruding position to unblock the extrusion medium chamber access port to gather the medium in the extrusion medium chamber. When the extrusion medium chamber is charged with the working medium, the operation is resumed.

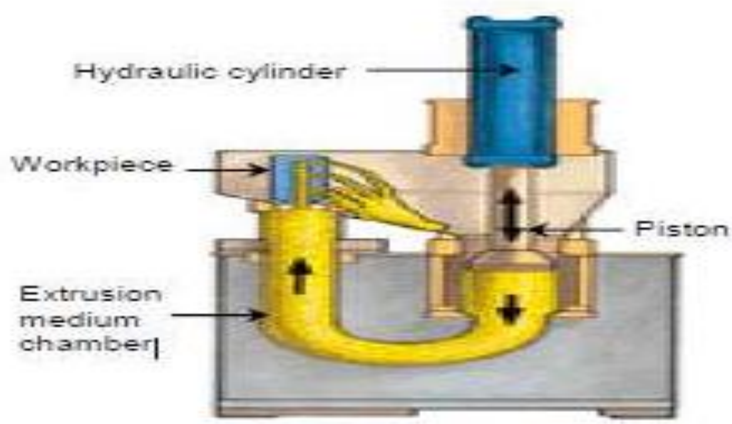

Figure 1.1 Schematic of One-Way AFM [1]

1.13.2 TWO-WAY AFM PROCESS

The Two-way AFM **[4]** machine has two hydraulic cylinders and two medium cylinders. In which the medium is extruded, hydraulically or mechanically, from the filled chamber to the empty chamber via the restricted passageway through or past the work piece surface to be worn out. Typically, the medium is extruded back and forth between the chambers for the desired fixed number of cycles. With this Counter bores, recessed areas and even blind cavities can be finished by using restrictors or mandrels to direct the medium flow along the surfaces to be polished. The schematic diagram of two-way AFM process is shown in the figure.

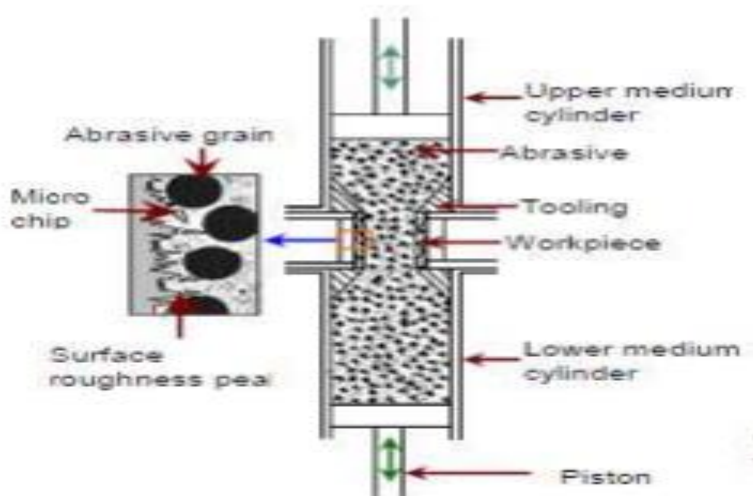

Figure 1..2 schematic of two way afm [5]

1.14 PARTS OF ABRASIVE FLOW MACHINING

Abrasive flow machining required some elements to perform the process. The various elements are fixture or tooling, the machine, and abrasive laden media. The abrasive media determine what kind of abrasive occur, the fixture determines the exact location of abrasion, and media decides the extent of abrasion as the abrasive particles are responsible for direct abrasion on the surface and fixture is responsible for holding the workpiece against the abrasive particles. Pressure, type of drill bit decides the force by which abrasive particles strike the surface.

1.14.1 FIXTURE

Steel, urethanes, aluminum, nylon, Teflon are the material that can be used to make fixture. Aluminum and nylon are easily machinable lightweight materials so they are perfect for fixture material. Steel is rarely used and used only for its strength and durability.

Fixture design is often very important factor in achieving the desired effect from the AFM process as the design of fixture depends on the shape of work piece. In this project the work piece is cylindrical so a proper design of fixture is used which can hold a cylindrical workpiece. Basic function of fixture includes :

- Holding the workpiece in proper position between the media cylinders.
- Directing media flow to and from the areas of the part to be worked on, during the process cycle.
- Protecting edges and surfaces from abrasion due to media flow by acting as a mechanical mask.
- Providing a restriction in the media flow path to control the media action in selected areas.
- Containing the media and completing the closed loop system required for multiple machine cycle operation without loss of media.

If AFM is used to process external edges or surfaces, the tooling contains the part in the flow passage, restricting the flow between the exterior of the part and interior of the fixture. Any number of parallel restrictions can be processed simultaneously with uniform results. To maximize productivity, fixture can be designed for batch production processing of many parts simultaneously if their configuration and size permits.

Figure 1.3 Nylone Fixture

1.14.2 ABRASIVE MEDIA

This technology uses a non-Newtonian liquid polymer containing abrasive particles of aluminum oxide, silicon carbide, boron carbide or diamond as the grinding medium and additives. The viscosity and concentration of the abrasive can be varied most widely used is a high velocity rheopetic fluid. The base material has enough degree of cohesion and tenacity to drag the abrasive grains along with it through various passage/regions. Aluminum oxide and Sic are most suitable abrasive for many application but cubic boron nitride (CBN) and diamond are specifically used for special applications. Abrasive particles to base materials ratio can be varring from 2 to 12. Abrasive are available in different mesh size. The abrasive have limited life. As a thumb rule, when the media has machined an amount equal to 10% of its weight, it must be discarded. Machined parts should be properly cleaned before use, by acetone. The additives are used to modify the base polymer to get the desired flow ability and rheological characteristics of the media. Hydrocarbon gels are commonly used lubricants in the media. All additives are carefully blended in predetermined qualities to obtain consistent formulation. Some of the medias created by mixing them with their respective plasticizers were Silicon Rubber mixed with DOP, Natural Rubber mixed with Parifin Oil, and Butyle Rubber. All these medias were processed on a 2-Roll machine done in IIT Delhi Polymer workshop and and Shri Ram Institute.

The pictorial view of some of the medias are shown below:

Figure 1.4 Silicon Rubber media

Figure 1..5 SBR media

Figure 1. 6 Different abrasive media prepared

1.14.3 MACHINE SETUP

All AFM machines regardless of size are positive displacement hydraulic systems, where work piece is clamped between two vertically opposed media cylinder. By repeatedly extruding media from one cylinder to the other, an abrasive action is produced whenever the media enters or passes through restrictive passage as it travels through or across the work piece. AFM machine controls two crucial parameters for determining the amount of abrasion, the extrusion pressure and the media flow rate. Standard units operate within 10 bar to 200 bar pressure range with flow rates up to 400 liters/ min. AFM systems are essentially provided with controls on hydraulic system pressure, clamping and unclamping of fixtures, volume flow rate of abrasive media, and advance and retract of media piston. Programmable microprocessor control unit can be used to monitor and control additional process parameters at the machine, such as media temperature, media viscosity, abrasive wear and flow speed. Several accessories such as part cleaning station, automatic flow timers, cycle counters, pressure and temperature compensated flow control valves, automatic media lubricant replenishment, and media heat exchangers units may also be integrated to the conventional AFM systems for production applications.

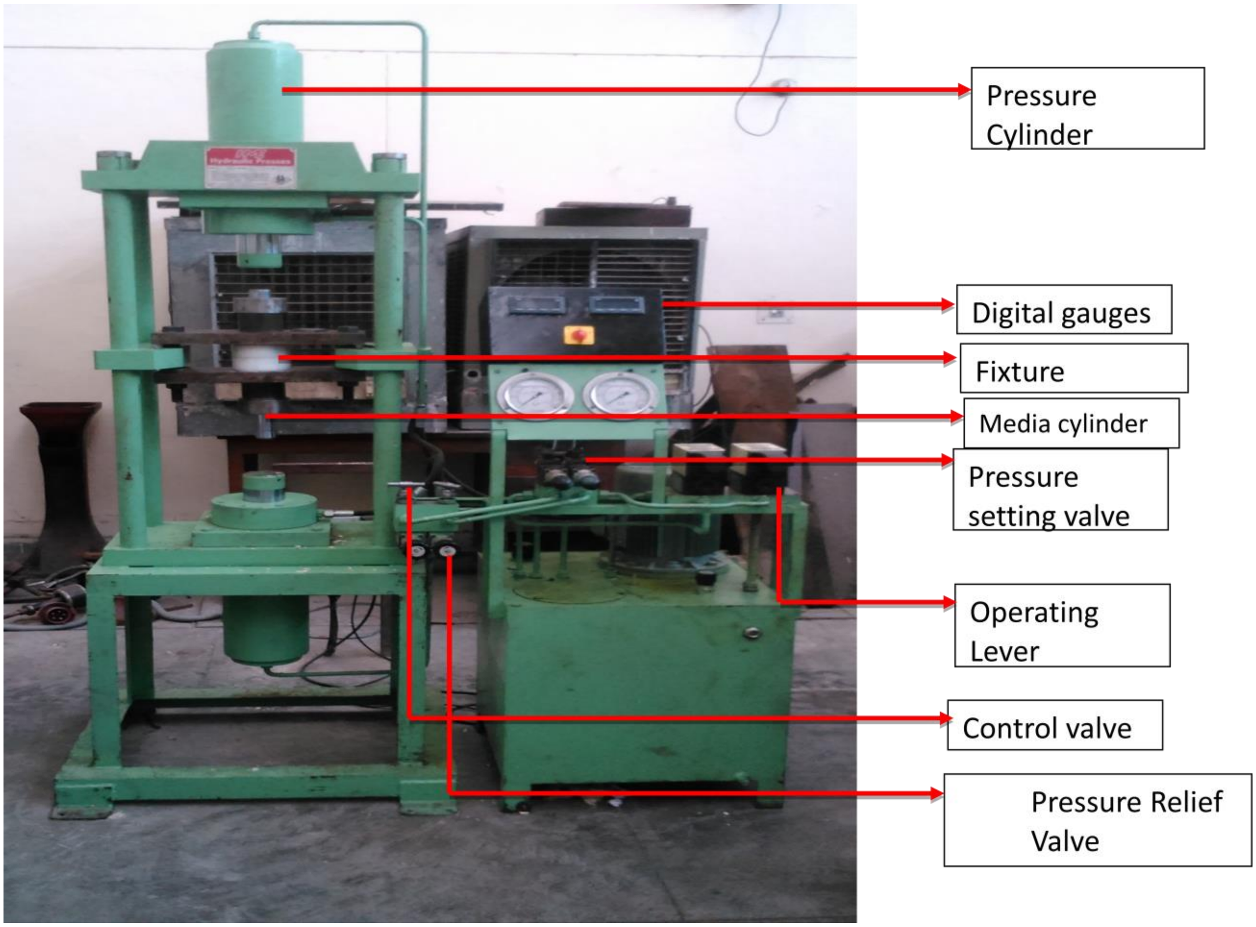

Figure 1. 7 pictorial view of machine setup

1.15 AFM APPLICATIONS AND BENEFITS

1.15.1 ULTRA CLEAN

- Food processing
- Semiconductor (front end) equipment
- Pharmaceutical manufactures
- Ultra clean or high purity devices

Polishing surfaces to mirror-like requirements minimizes the amount of microscopic and/or inaccessible areas that enable contamination or entrapment. Ultra smooth surface finish greatly diminishes the area of concern for surface absorption, chemical contaminants, foreign particulate and bacteria. Additionally, the AFM process minimizes “flow-retardation” due to machining and/or dies and mold “microgrooves”.

AFM allows for extremely fine finishes on very complex geometry and difficult to reach surface configurations often found in prosthetic application and in a broad range of materials.

1.15.2 MOLDS AND DIES

- Mold forming
- Glass forming
- Plastic application

Critical, forming surfaces may be enhanced as much as (X10) on many applications. EDM’s surfaces (all kind), milled surfaces, and ground surfaces can be consistently and uniformly polished to a very low Ra to further enhance speed, part release, and overall quality and production efficiency while preserving critical tolerances.

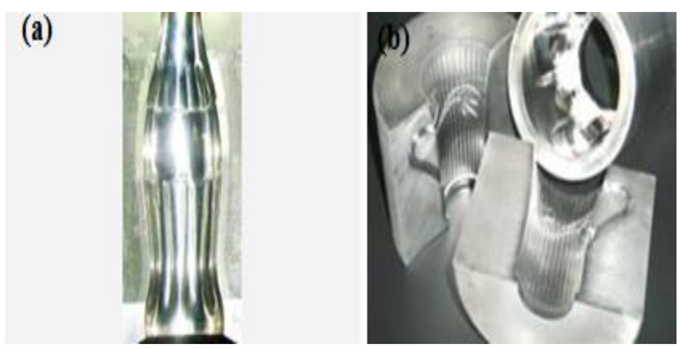

Figure 1. 8 Glass moulds (Dies and moulds)

1.15.3 INTERNAL COMBUSTION ENGINE

- Diesel engine

- Automotive

A high pressure fuel injection system's life cycle can be extended through abrasive flow machining by reducing surface cracks and more uniform surface finish in critical areas of fatigue failure. Reduction of resistance in fuel and exhaust passage enhances performance and efficiency while maintaining critical tolerance parameters. Smoother intake passage allow for more effective gas/air mixing, higher efficiency and a more powerful engine.

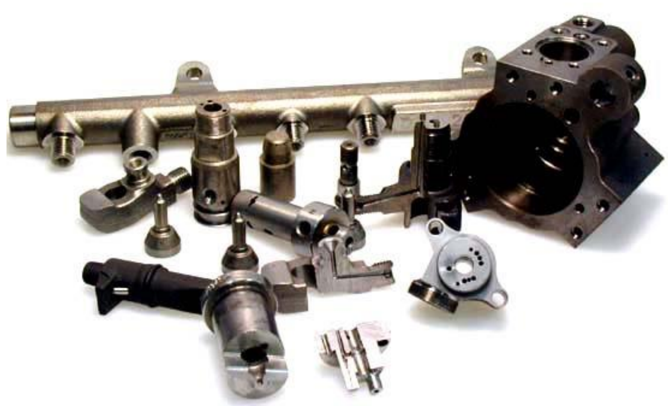

Figure 1. 9 Automotive Components

1.15.4 RADIUSSING

Generates continuous, true-edge radii or round-edge radii, such as jet engine disks.

1.15.5 SURFACE STRESS RELIEF

The ability to smooth out critical fatigue points and remove stress risers that may lead to crack propagation.

1.15.6 POLISHING

Improves surface finish, including complex shapes, and uniformly smoothes and polishes workpiece, while preserving geometry. AFM reaches inaccessible areas of workpieces, such as internal passageways of automotive intake manifolds and hydraulic/pneumatic manifold blocks.

1.15.7 GEOMETRY OPTIMIZATION

Abrasive flow machining can improve air, gas, or liquid flow behavior (flow coefficient) and reduce or eliminate cavitation tendency. Generating laminar flow helps improve volumetric efficiency.

1.15.8 DEBURRING

Abrasive flow machining deburrs internal/external or otherwise inaccessible holes, slots, and edges. Cross-drilled and intersecting holes that present a major problem for conventional deburring methods are easily handled by the AFM media.

1.16 BENIFTS

- AFM can be applied to any metal materials, including titanium, super alloys, hardened, and difficult-to-machine materials.
- Material can be removed from targeted and hard-to-reach locations.
- Roughing and finishing in one pass.
- Media can be engineered to match the application requirements.
- Process control delivers consistent quality and highest repeatability.

CHAPTER 2

LITERATURE REVIEW AND PROBLEM FORMULATION

Abrasive flow machining is a unconventional micro/nano finishing process on which a great extent of research work have been done in the form of research papers, book chapters and patents etc. A brief review of the work has been presented in this section, which has been divided into further sub-sections as follows.

2.1 AFM PROCESS MECHANISM

Rhodes found that [5-7] in any AFM process depth of cut by abrasive particle depends on size, relative hardness, sharpness of abrasive particles used and extrusion pressure. He also stated that medium viscosity plays a vital role in finishing action. The medium flow pattern which influence finishing characteristics depends on machine settings, medium formulation as well as tooling configuration. Always, in any restricted passages the viscosity of medium increases temporarily and gives approximately pure extrusion of the medium. For abrading walls of large passages, high viscosity medium was recommended whereas low viscosity medium was found to be suitable for radiusing edges and for finishing slender passages.

Experimental study done by Przyklenk [8] suggested that, the material removal capacity of high viscous medium was found to be around 300 times greater than that of low viscous base medium. The important factors which influence stock removal and medium velocity include abrasive percentage concentration, abrasive size and also the viscosity of the medium.

Williams and Rajurker [9-11] conducted some additional experiments to study the effect of some process variables like extrusion pressure and medium viscosity on material removal and surface finish.

Loveless et.al.[12] suggested through their experiments that the initial surface roughness and viscosity of medium significantly influence the percentage surface finish improvements.

Later Jain et.al concluded that the abrasive concentration and mesh size on medium viscosity at different temperature ranges. They made-up a capillary rheometer and by which they also conducted some experiments to study rheological properties of abrasive loaded polymeric medium. They also mentioned that if there is an increase in medium viscosity then there is decrease in surface roughness. It is determined by many researchers of the same field that viscosity of polymeric medium is a vital parameter which affect AFM performance.

2.2 SURFACE FINISH AND MATERIAL REMOVAL MECHANISM

Rhodes [6] investigated the basic principle of AFM process and identified its process control variables. He stated through his experiments that when the medium is suddenly forced through the restricted passages its viscosity naturally rises. But major material removal of the work part is observed when the medium is thickened. The abrasion efficiency during AFM will depend upon tooling and fixtures. Higher volume of the medium will be resulting in interaction at more number of times between abrasive particle and the work piece; therefore more abrasion per number of cycle will take place. For homogeneous finishing and small radius of edges, slow medium flow rates are generally suitable .while high flow rate will result in large radii. Also low viscosity medium should be used to get better result when compared to high viscosity medium. Flow pattern medium depends on the speed of slug flow, rheology and passage size. Medium flow rate depends on number and size of passage to be processed.

Perry [13] obtained some principle and typical industrial application of the AFM. i.e. precision deburring, edge contouring, surface finish and removing the thermal recast layers.

William and Rajurker [9-10] used full factorial design in his research and calculated the effect of viscosity of medium and extrusion pressure on material removal and surface finish. Results obtained during metal removal shows that in viscosity main effect was significant while for pressure main effect is not so important.

Jain et.al. [14] Came out with the result that initial surface roughness and hardness of the workpiece affect the rate of material removal during the AFM process. For the case of softer metal in comparison to harder metal, Material removal and change in surface roughness value both were found to be higher. With increase in percentage concentration of abrasive in the medium material removal rate also increases. Among all the process parameter studied, the leading parameter is abrasive concentration followed by abrasive size and number of cycles both. Those machining process used to prepare the work piece before the AFM plays a significant role in process performance of the same. As compared to turned and milled surface wore EDM surfaces are concluded to be more suitable for AFM process. Because different machining surfaces produces different surface textures and contours.

Davis and Fletcher [15] explained the relationship between the number of cycles, temperature, and pressure drop and across the die which are dependent upon the type of polymer as well as the abrasive concentration used in media. An increase in temperature results in decrease in viscosity of media and increase in medium flow rate. While with increase in finishing time the medium temperature increases resulting in change in medium viscosity. The change in temperature is partly due to the internal shearing of the medium and the abrasion process.

2.3 REPRESENTATION OF SURFACE ROUGHNESS

Jain [14] suggested from his investigation that there is a necessity for systematic procedure for the selection of a set of parameters to provide the surface roughness which satisfies the following basic conditions.

1. Defining the geometric features of the surface.
2. Enabling precise interpretations.
3. Measuring by commonly available instruments.

Jain **[14]** concluded that, in production inspection work high quality surface should be tested by checking some of the parameters such as CLA value and mean slope of profile.

He also concluded that for stable and well controllable production process the second parameters need not to be inspected repeatedly.

2.4 MAJOR AREAS OF AFM RESEARCH

Various researches have been done on the effects of some important AFM process parameters. Some of them are discussed below:

2.4.1 NUMBER OF PROCESS CYCLES

A number of cycles are to be provided to get the desired surface finish and material removal rate. Its reported in a number of studies and researches that abrasion is more definite in some initial cycles there after which advancement in the surface finish formalize or reduce in some cases. The number of cycles varies from one to several hundred. Within cycles 1 to 8, a linear dependency between both material removal and surface roughness versus number of cycles was recorded. In AFM process a cycle completes when the forward and backward extrusion back to the initial stage completes.

2.4.2 EXTRUSION PRESSURE

It has been observed that cutting at faster rate increases extrusion pressure, while other parameters remaining fixed. Some of the total pressure is disappeared within the media because of its internal resistance to flow and the remaining is transmitted to abrasion particles touching the surface of work piece. Jain and Jain a researcher also expressed that when pressure is high the enhancement in material removal just contribute to balance out apparently due to localized rolling of abrasion particles

2.4.3 MEDIA FLOW VOLUME

Media flow volume is a very flashy criterion that limits both i.e material removal and surface finish. If media flow volume is increased than material removal also increases. Theoretically it can be explained out that as more no of abrasive particles come in contact with work piece and more abrasion takes place whenever flow volume of media is increased.

2.4.4 MEDIA FLOW RATE

A study showed that media viscosity, extrusion pressure, and passage dimension all determine the media flow rate which is the velocity of the abrasive slug moving through the confining space which influences the consistency of the material removal and the development of edge radius. Rhoades has submitted that media flow rate is not much influential parameter in comparison to material removal. When the rate of flow of slug is slow then its best for uniform material removal and whereas high slug flow rates develops edge radii of large size [Rhoades. Williams et.al. [7]. Concluded if we fix the volume flow rate than the flow rate of media is negligible in respect to material removal. Contrarily, Singh and Jain and Jain claimed that the media flow rate influences both material removal and surface roughness.

2.4.5 MEDIA VISCOSITY

Williams and Rajurkar [10], and has given the result that media viscosity is one of the powerful consideration in any the AFM process. If we fix all parameters, then if viscosity increases it results in enhancement of both material removal and surface roughness. Whereas Przyklenk [16] found the capacity of material removal of the least viscous media vary from the most viscous media.

2.4.6 MEDIA TEMPERATURE

On the basis of experiments performed by Weller [17**],** it can be understood that if temperature increases during refining will results in rapid cutting, where cutting conditions being constant. Jain and Jain **[**18] studied down the heat flow in the medium and the work piece in AFM process. Meanwhile Hull et.al [19] gave away the temperature effect (ranging between 30-70 °c) on media's rheology used and resulted that sometimes media may go through a long lasting change in its physical characteristics if its temperature is increased.

2.4.7 ABRASIVE PARTICLE SIZE

The range of size of abrasive particles which are used in AFM is 8 to 500grit. Observations say that abrasive of smaller size provides good finish and which can also move into complicated and precise passages, whereas bigger abrasives cut faster. As per one thumb rule [20] small abrasives are used if the work surface is having less initial roughness. The depth of penetration and width of penetration both decreases if the mesh size is bigger is what the basic logic behind material removal.

2.4.8 ABRASIVE CONCENTRATION

McCarty [21] a researcher resulted the chances if in media we use a wide range of concentration of abrasive (2 to 12 times weight of carrier media). Siwert [22] concluded that the ratio of base material to the abrasive particle (by weight) should satisfactorily range from 1:4 to 4:1 with 1:1 as the most relevant ratio. If in media we increase the cluster of abrasive, the surface roughness value would go down and there is an increase in material removal [23]. How so ever, the effect is noticeable only up to a fixed % of abrasive concentration, apart from which it becomes irrelevant. If in any media the amount of abrasive particles viscosity enhances, than it results in higher material removal. Also the media continue to be there for a larger cutting force if high concentration of abrasives allows.

2.5 RECENT ADVANCES ON AFM PROCCESS

Some of the recent advances in the AFM process are discussed below.

2.5.1 MAGNETIC AFM PROCESS

Singh and Shan took the silicon polymer base carrier as a medium, hydrocarbon gel and magnetic abrasive particle in Magnetic AFF set up. Some magnetic field is applied all around the workpiece and observed that magnetic field affects the material removal rate and surface roughness both.

2.5.2 ELECTROCHEMICALLY ASSISTED AFM PROCESS

An electro-chemically assisted abrasive flow machining is a process which uses polymeric electrolyte such as related polymers and water gel as base carrier. The conductivity of electrolyte employed in an ordinary chemical machining process is always many times lower than those of the ion conductivity of electrolyte. The conductivity decreases rapidly even more with the addition of some in-organics to the electrolyte. The polymeric electrolyte medium forced it through small inter electrode gap. And this results in greater flow resistance of polymeric electrolyte which takes the form of semi-liquid paste. In flat surfaces experimental investigations have been carried out.

2.5.3 ULTRASONIC FLOW POLISHING

Ultra-sonic flow polishing is combines AFM and Ultra-sonic machining both. The medium is pumped down to the center of the tool which is ultrasonically energized, and flows radially relative to the axes of the tool.

2.5.4 SPIRAL POLISHING

In Spiral polishing process a spiral fluted screw is settled at the center of the hole in workpiece to be finished. Incorporating external energy source the screw is rotated. The rotational motion of the screw raises the medium from lower medium cylinder to upper medium cylinder and tries to finish/polish the hole while passing through it.

2.5.5 CENTRIFUGAL FORCE ASSISTED AFM PROCESS

In this machining process a centrifugal force creating tiny rod is placed at the centre of the medium slug in the region of workpiece finishing. In this region the rod strikes the abrasive particle those comes in contact with it. The angle of shifting of abrasive particle depends on rotational speed and the rod shape. The placing of rod in the centre of the medium slug and providing rotation to it increase the finishing rate by 70-80%.

2.5.6 DRILL-BIT GUIDED AFM PROCESS

In a drill-bit assisted AFF process, a freely rotatable drill bit is holded with a special fixture plates placed in the workpiece finishing zone. By the combination of reciprocation of medium, medium flow rate through the drill bit flute and scooping flow across the flute the actual path of movement of abrasive particle decided. This path makes the abrasive particle to move in an inclined motion rather than to move in a straight-line motion. Also turbulence at the centre is causes frequent reshuffling of abrasive particle. Resulting in the enrichment of material removal rate and finishing actions as well as surface roughness.

2.6 LIMITATIONS OF AFM

- Its finishing rate is low.
- Due to long finishing time, the rheological properties of its medium degrade, and as a result the finishing ability of the medium decreases in the latter half of the useful life.
- The chances of reassembling of abrasive particle is not high in AFM process and in the media slug the abrasive particles those at the centre won’t take part in finishing operation.In commercially existing AFM machine the medium cylinder are in uni-

axis, so finishing of complex surfaces needs complex tooling which increases the production cost.

- In the process of Spiral polishing, CFAAFM, DBGAFM create motion at the centre of the medium slug. This may not be able to force the abrasive particle to reach up to the finishing zone

CHAPTER 3

TAGUCHI

‘Design of experiments’ or experimental design is the development of some report-collecting activity in which distinction is there, it may or may not be under the control of the experimenter. In figures, generally such expressions are used for controlled. In order to obtain clear and exact decisions derived from the observations of the experiment performed a well-planned and implemented experiment is of the ultimate importance’. It is taken as a very valuable policy for achieving such tasks. This science of “statistical design of experiment” was invented with the effort of “Sir Ronald Fisher” in England in the year of 1920s. Sir Fisher started the basic standard of experimental design and the related data-analysis procedure called “Analysis of Variance (ANOVA)” through his labors to advance the profit of agricultural crops. “Box and Hunter, Box and Draper, Hicks are some of the statistical researchers who have developed the theory and applications of experimental design and the related technique of response surface methodology. Different kinds of matrices are implemented for developing experimentations work to study different judgmental variables. Amongst them, Taguchi’s Method is the one that makes heavy use of orthogonal arrays.

3.1 THE CONVENTIONAL APPROACH- DOE

The procedure of describing and exploring all good probable conditions in any experimentation requiring numerous features is recognized as the term ‘design of experiments’ (DOE). In various literatures, this method is also denoted to as ‘factorial design’. The idea of DOE havs been in used in practice since ‘Sir Ronald A’. Fisher’s efforts in agricultural experimentation during the late 1920s. Fisher efficiently planned trials to govern optimal behaviours of land for agriculture to accomplish maximum yield. Abundant applications of this methodology have been developed, specifically in the chemical and pharmaceutical industries. A full exposure of this topic is way beyond the scope of this study.

3.2 EXPERIMENTAL DESIGN AND ANALYSIS TAGUCHI

In Taguchi method has a basic feature of distinction in a procedure through tough design of experiments are reduced. The general objective of Taguchi method is to develop high value product at a cost which is lower 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. The Taguchi method is best used when there are an intermediate number of variables (3 to 50), few interactions between variables, and when only a few variables contribute significantly.

3.3 PHILOSOPHY

1. Quality should be designed into a product, not inspected into it. Quality is designed into a process through system design, parameter design, and tolerance design. Parameter design, which will be the focus of this article, is performed by determining what process parameters most affect the product and then designing them to give a specified target quality of product. Quality "inspected into" a product means that the product is produced at random quality levels and those too far from the mean are simply thrown out.
2. Quality is best achieved by minimizing the deviation from a target. The product should be designed so that it is immune to uncontrollable environmental factors. In other words, the signal (product quality) to noise (uncontrollable factors) ratio should be high.

3. The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system wide. This is the concept of the loss function, or the overall loss incurred upon the customer and society from a product of poor quality. Because the producer is also a member of society and because customer dissatisfaction will discourage future patronage, this cost to customer and society will come back to the producer.

3.4 TAGUCHI METHOD DESIGN OF EXPERIMENTS

The general steps involved in the Taguchi Method are as follows:

1. Define the process objective, or more specifically, a target value for a performance measure of the process. This may be a flow rate, temperature, etc. The target of a process may also be a minimum or maximum; for example, the goal may be to maximize the output flow rate. The deviation in the performance characteristic from the target value is used to define the loss function for the process.
2. Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure such as temperatures, pressures, etc. that can be easily controlled. The number of levels that the parameters should be varied at must be specified. For example, a temperature might be varied to a low and high value of 40 C and 80 C. increasing the number of levels to vary a parameter at increases the number of experiments to be conducted.
3. Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter, and will be expounded below.
4. Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure.
5. Complete data analysis to determine the effect of the different parameters on the performance measure.

3.5 STRATEGY IN EXPERIMENTAL DESIGN

Taguchi recommends orthogonal arrays (OA) for lying out of experiments. These OA's are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. The array forces all experimenters to design almost identical experiments.

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives:

- To estimate the best or the optimum condition for a product or process.
- To estimate the contribution of individual parameters and interactions.
- To estimate the response under the optimum condition.

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trend of influence of each parameter. The knowledge of contribution of individual parameters is a key in deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control.

Taguchi suggests two different routes to carry out the complete analysis of the experiments. First the standard approach, where the results of a single run or the average of the repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal-to-noise (S/N) ratio for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function. By maximizing the S/N ratio, the loss associated can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. The S/N ratio is treated as a response parameter (transform of raw data) of the experiment. Taguchi recommends the use of outer OA to force the noise variation into the experiment i.e. the noise is intentionally introduced into the experiment. Generally, processes are subjected to many noise factors that in combination strongly influence the variation of the response. For extremely ‘noisy’ systems, it is not generally necessary to identify controllable parameters and analyze them using an appropriate S/N ratio. In the present investigation, both the analysis: the raw data analysis and S/N data analysis have been performed. The effects of the selected Helical AFM parameters on the selected quality characteristics have been investigated through the plots of the main effects based on raw data. The optimum condition for each of the quality characteristics have been establish through S/N data analysis. No outer array has been used and instead, experiments have been repeated three times at each experimental condition.

3.6 PROCEDURE FOR EXPERIMENTAL DESIGN AND ANALYSIS IN TAGUCHI

Figure illustrates the stepwise procedure for Taguchi experimental design and analysis. It is described in the following paragraphs.

3.6.1 SELECTION OF OA

In selecting an appropriate OA, the following prerequisites are required:

- Selection of process parameters and/or their interactions to be evaluated.
- Selection of number of levels for the selected parameters.

The determination of parameters to investigate, upon which hinges the product or process performance characteristics or responses of interest . Several methods are suggested by Taguchi for determining which parameters to include in an experiment. These are :

- Brainstorming
- Flow charting
- Cause-effect diagrams

The total degrees of freedom (DOF) of an experiment are a direct function of total number of trials. If the number of levels of a parameter increases, the DOF of the parameter also increase because the DOF of a parameter is the number of levels minus one. Thus, increasing the number of levels for a parameter increases the total degrees of freedom in the experiment which in turn increases the total number of trials. Thus, two levels for each parameter are recommended to minimize the size of the experiment. If curved or higher order polynomial relationship between the parameters under study and the response is expected, at least three levels for each parameter should be considered. The standard two-level and three-level arrays are:

a) Two-level arrays: L_4, L_8, L_{12}, L_{16}, L_{32}

b) Three-level arrays: L_9, L_{18}, L_{27}

The number as subscript in the array designation indicates the number of trials in that array. The degree of freedom (DOF) available in an OA is:

$$F_{LN} = N-1$$

Where f_{LN} = total degrees of freedom of an OA

L_N =OA designation N = number of trials

When a particular OA is selected for an experiment, the following inequality must be satisfied

$F_{LN} \geq$ Total DOF required for parameters and interactions.

Depending on the number of levels in the parameters and total DOF required for the experiment, a suitable OA is selected.

3.6.2 ASSIGNMENT OF PARAMETERS AND INTRACTIONS TO OA

An ‘OA’ has several columns to which various parameters and their interactions are assigned. Linear graphs and Triangular tables are two tools, which are useful for deciding the possible interactions between the parameters and their assignment in the columns of ’OA’. Each ‘OA’ has its particular liner graphs and interaction tables

3.6.3 SELECTION OF OUTER ARRAY

Taguchi separates factors (parameters) into two main groups:

- Controllable factors
- Noise factors

Controllable factors are factors that can easily be controlled. Noise factors, on the other hand, are nuisance variables that are difficult, impossible, or expensive to control. The noise factors are responsible for the performance variation of a process. Taguchi recommends the use of outer array for noise factors and inner array for the controllable factors. If an outer array is used the noise variation is forced into the experiment. However, experiments against the trial condition of the inner array may be repeated and in this case the noise variation is unforced in the experiment. The outer array, if used will have the same assignment considerations.

3.6.4 EXPERIMENTATION AND DATA COLLECTION

The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried for to reduce bias in the experiment.

3.6.5 DATA ANALYSIS

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average responses, interaction graphs, etc.. In the present investigation, following methods are used.

- Plot of mean response curves
- ANOVA for final data
- ANOVA for factors

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of a parameter on the response. Typically, ANOVA for OA’s are conducted in the same manner as other structured experiments.

3.6.6 PARAMETER DESIGN STRATEGY

Parameter classification and selection of optimal levels

ANOVA of raw data and S/N ratio identifies the control factors, which affect the average Kponse and the variation in the response respectively. The control factors are classified into four groups:

Group I : Parameters, which affect both average and variation

Group II : Parameters, which affect variation only

Group III : Parameters, which affect average only

Group IV : Parameters, which affect nothing

The parameter design strategy is to select the suitable levels of group I and II parameters to reduce variation and group III parameters to adjust the average values to the target value. The group IV parameters may be set at the most economical levels.

3.6.7 PREDICTION OF MEAN

After determination of the optimum condition, the mean of the response (u) at the optimum condition is predicted. This mean is estimated only from the significant parameters. The ANOVA identifies the significant parameters. Suppose, parameters A and B are significant and A2B2 (second level of both A and B) is the optimal treatment condition. Then, the mean at the optimal condition (optimal value of the response characteristic) is estimated as:

$$\mu = T + (a_2\text{-}t) + (b_2\text{-}t)$$

$$= A_2 + B_2 - T$$

T= overall mean of the response

A_1, B_2= average values of response at the second levels of parameters A and B respectively

It may sometimes be possible that the predicated combination of parameter levels (optimal treatment condition) is identical to one of those in the experiment. If this situation exits, then the most direct way to estimate the mean for that treatment condition is to average out all the results for the trials which are set at those particular levels .

3.6.8 DETERMINATION OF CONFIDENCE INTERVALS

The estimate of the mean (p) is only a point estimate based on the average of results obtained from the experiment. It is a statistical requirement that the value of a parameter should be predicted along with a range within which it is likely to fall for a given level of confidence.

This range is called confidence interval (CI). Taguchi suggests two types of confidence intervals for estimated mean of optimal treatment conditions.

• CI_{CE} - Confidence Interval (when confirmation experiments (CE)) around the estimated average of a treatment condition used in confirmation experiment to verify predictions. Get; is for only a small group made under specified conditions.

• CI_{POP} - Confidence Interval of population; around the estimated average of a treatment condition predicted from the experiment. This is for the entire population i.e. all parts made under the specified conditions.

The confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{POP}) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_a\,(1, f_e)V_e\ \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]}$$

$$CI_{POP} = \sqrt{\frac{F_a\,(1, f_e)V_e}{n_{eff}}}$$

Where

F_α (l, f_e) = The F-ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e, f_e = error DOF, N = Total number of result, R = Sample size for confirmation experiments, V_e = Error variance,

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean responce}]}$$

3.6.9 CONFIRMATION EXPERIMENT

The confirmation experiment is the final step in verifying the conclusions from the previous round of experimentation. The optimum conditions are set for the significant parameters (the insignificant parameters are set at economic levels) and a selected number of tests are run under specified conditions. The average values of the responses obtained from confirmation experiments are compared with the predicted values. The average values of the response characteristic obtained through the confirmation experiments should be within the 95% confidence interval, $CI_{CE.}$ However, these may or may not be within 95% confidence interval, $CI_{POP.}$ The confirmation experiment is a crucial step and is highly recommended to verify the experimental conclusions.

CHAPTER 4

PROCESS PARAMETER SELECTION AND EXPERIMENTATION

The main process parameters, which may affect the machining characteristics such as material removal and surface finish, are selected. The scheme of experiments is also discussed in this chapter. The experiments were conducted within the ranges of selected process parameters which include different work pieces, media's processed at different extrusion pressure range. Material removal and surface finish were measured. The measured data are also tabulated in this chapter.

4.1 SELECTION OF WORK PIECE

Aluminum, Brass and Mild steel work piece were prepared by drilling, maintain its initial surface roughness in the range of 2.6-3.6μm and dimension 10 mm OD x 8 mm ID x 16 mm length. Few work piece ready for machining is shown in figure-00..The length to diameter (L/D) of the work piece was decided on the basis of the recommendation given by Kohut. Work piece are cleaned by acetone and subsequently measurements of initial surface roughness and weight were taken. The surface roughness was measured in five different locations using Taylor Hobson. The internal cylindrical surface was finished by AFM process. Each work piece was machined for a predetermined number of cycles. The work piece was taken out from nylon fixture and cleaned with acetone before the subsequent measurement.

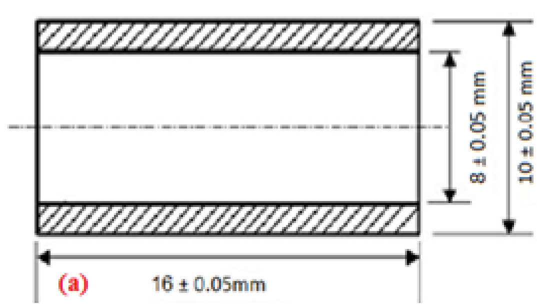

Figure 4. 1 Al, Br, Ms work piece used in trials and its dimensional details

Figure 4..2 Workpieces after machining

4.2 SELECTION OF PROCESS PARAMETERS AND THEIR RANGES

S. No.	Process Parameter	Range	Unit
1	Extrusion Pressure	5-35	MPa
2	No. of Cycle	1-9	Number
3	Temperature	32± 2	°C
4	Media Flow volume	290	cm^3
5	Capacity	25 + 25	Ton
6	Hydraulic cylinder Bore dia-2 No.	130	Mm
7	Hydraulic cylinder Stroke	90	Mm

8	Working Pressure	210	Mpa
9	Maximum Pressure in the Cylinder	35	MPa
10	Stroke Length of Piston	300	Mm

Table4.0.1 Showing selection parameters with their ranges.

4.3 RESPONSE CHARACTERSTICS

The effect of these process parameters were studied on the following response characteristics of AFM process-

1. Percentage improvement in surface finishing (ΔRa)
2. Material Removal (MR)

4.4 PERCENTAGE IMPROVEMENT IN SURFACE FINISHING

The surface roughness was measured at several random locations on the internal cylindrical surface of the work piece. The mean value was taken of the random values of roughness. Then the percentage improvement in surface finishing was calculated from the formula

$$\mathbf{\Delta Ra} = \frac{(\textbf{Initial Ra} - \textbf{final Ra})}{\boldsymbol{Initial\ Ra}} \times \mathbf{100}$$

4.5 MATERAL REMOVAL (MR)

Material removal signifies the amount of material removed from the specimen in a specified number of process cycle. Material removal was calculated from the formula

$$MR = (\text{Initial weight} - \text{final weight})$$

4.6 SCHEME OF EXPERIMENTS

The experiments were designed to study the effect of some of the AFM parameters on response characteristics of AFM process. Taguchi parametric design methodology was adopted. The experiments were conducted using appropriate orthogonal array (OA). An L9 (a standard 3-level OA) having 8= (9-1) degree of freedom was selected for the present analysis. The selected number of process parameters and their levels are given in the table:

Symbol	Process Parameters	Unit	Level 1	Level 2	Level 3
W	Workpiece	Numbers	Al	Brass	MS
P	Pressure	Bar	10	15	20
M	Laden Media	Type	SR	SBR	NR
Polymer to Gel ratio :1:1, Workpiece Material- Aluminium, Brass, Mild steel , media type- silicon rubber, SBR Extrusion Pressure: 5,10, 15 MPa, Media Flow Volume :290cm^3,Temperature:32 ± 2 °C, Initial surface roughness : 1.424 – 5.548 µm.					

Table 4.2 Process parameters and their vales at different levels.

Exp. No.	Run Order	Parameters Trial Conditions				Response (Raw Data)			S/N Ratio (db)
		M	W	P	---------	R1	R2	R3	
		1	2	3	4				
1	1	1(S)	1(A)	1(10)	1	Y11	Y12	Y13	S/N(1)
2	4	1(S)	2(B)	2(15)	2	Y21	Y22	Y23	S/N(2)
3	7	1(S)	3(M)	3(20)	3	Y31	Y32	Y33	S/N(3)
4	5	2(SBR)	1(A)	2(15)	3	Y41	Y42	Y43	S/N(4)
5	8	2(SBR)	2(B)	3(20)	1	Y51	Y52	Y53	S/N(5)
6	2	2(SBR)	3(M)	1(10)	2	Y61	Y62	Y63	S/N(6)
7	9	3(N)	1(A)	3(20)	2	Y71	Y72	Y73	S/N(7)
8	3	3(N)	2(B)	1(10)	3	Y81	Y82	Y83	S/N(8)
9	6	3(N)	3(M)	2(15)	1	Y91	Y92	Y93	S/N((9)
Total						Σ	Σ	Σ	

R1, R2, R3 represents response value for three repetitions of each trial. The 1's,2's, and 3's represents levels 1,2,3 of the parameters, which appear at the top of the column.(---) represents no assignment in the column. Yij are the measured values of the quality characteristics (response).And A, B, C represents Aluminium, Brass, Mildsteel respectively whereas S, SBR, N are Silicon rubber, butyle rubber, natural rubber.

Table 4.3 The L9 (3^4) OA (parameters assigned) with response

4.7 PRECAUTIONS TAKEN DURING EXPERIMENTATION

While performing various experiments, the following precautionary measures were taken:

1. Each experiment is repeated three times to avoided experimental error.

2. The experiments repeated randomly in order to avoid bias, if any, in the results.

3. As the experiments proceeds the cutting edges of abrasive particles wear off and become dull which result in less favorable results are produced in later experiments secondly the particles of work piece material mixed with the media and as the time proceeds the volume of work piece material inside the media increases which deteriorate the finishing action. To avoid this large volume of the media is prepared and after each experiment the used media is taken out from the cylinder and throughout mixed with the fresh media contained in large container. The media for next trial is taken from this mix. For the limited number of experiments conducted, this would ensure with reasonable

reliability that the media used for each of the experiment run contain approximately equal amount of fresh grains(grain with sharp edges)

4. Each set of experiments was performed at room temperature in a narrow range (32 ± 2°C).

5. Before any measurement was taken, the work-piece was cleaned with acetone.

6. The surface roughness was measured in the direction of flow of media and at several random points all over the cavity of the work-piece.

4.8 EXPERIMENTATION

The three process parameters Abrasive media, Workpiece, pressure were selected as in table (2) The process parameters were varied according to the values as shown in table (2). Experiments were conducted according to the test condition specified by the L_9 OA (Table 3). Each experiment was repeated twice in each of the trial conditions. Thus six-six different workpieces were selected out of eighteen having different initial surface roughness depending on the type of workpiece chosen. . In each of the trial conditions and for every replication, the percentage improvement in surface roughness and material removal were measured. The data is recorded in Table 4.4

Exp No.	Run Order	% Improvement in Ra				Material Removal (MR) (mg)			
		R1	R2	R3		R1	R2	R3	
1	1	4.28	2.32	2.48		1.2	1.21	1.1	
2	2	2.22	2.08	3.04		3.8	3.6	3.9	
3	3	7.4	6.8	6.89		2.7	2.5	2.6	
4	4	2.9	2.18	2.66		1.20	1.15	1.21	
5	5	2.25	3.02	2.72		3.76	3.71	3.72	
6	6	8.4	7.6	8		6.1	6.2	6.4	
7	7	3.54	4.48	2.03		1.2	1.4	1.1	
8	8	3.66	2.62	2.94		3.8	3.9	3.2	
9	9	6.8	7.1	6.67		5.5	5.4	5.1	
Total		41.45	38.2	37.43		29.26	29.07	28.33	
		$T_{\Delta Ra}$ = Overall mean of ΔRa=39.026				T_{MR} =Overall mean of MR =3.2018mg			

Table 4.4 Experimental results of various response characteristics

CHAPTER 5

Results and discussions

The standard procedure suggested by Taguchi was used to analyze the data. The average values and mean values of quality/response characteristics for each parameter at different levels are calculated from the experimental data. The main effects of process parameters both for final data and different parameters are plotted. The analysis of variance (ANOVA) of both the data is performed to identify the significant parameters and to quantify their effect on the response characteristics.

5.1 % improvement in roughness

Response Table for Means, L_9 method

Level	Media	Workpiece	Pressure
1	4.167	2.985	4.688
2	4.414	2.715	3.961
3	4.414	7.295	4.348
Delta	0.247	4.580	0.727
Rank	3	1	2

Table 5.0.1 Mean value table for response

The table 5.1 shown above is calculated in Taguchi method of L9 series. In this table responses in the order of ranks and delta are created by the different parameters. Its clear that value 7.295 is maximum of all which comes under third level i.e L3, which is ranked one.

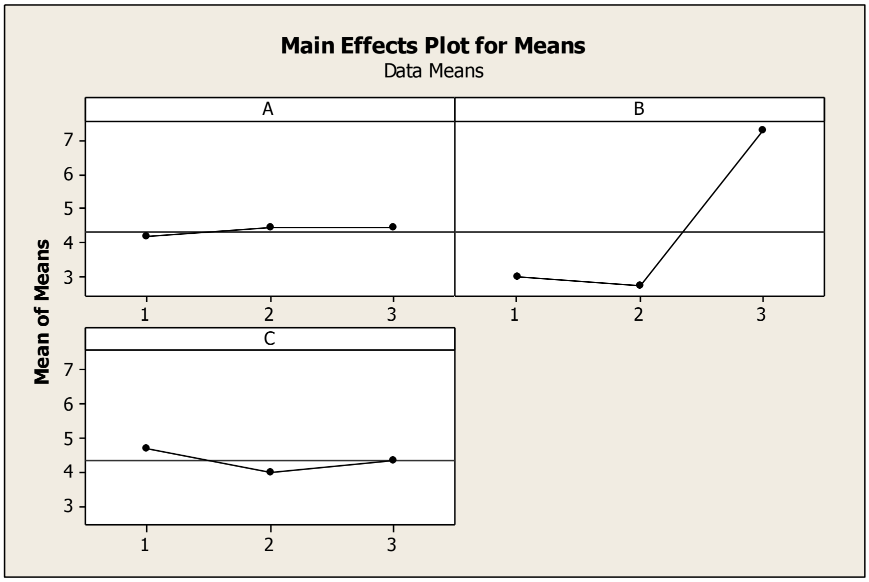

Table 5.0.2 Main effects graph

The three graphs above are plotted in the Taguchi method taken from the mean values of the input table. Graph A,B,C are for Media, Workpiece and Pressure respectively. In all the graphs natural rubber, mild steel at pressure 10Mpa are showing the great effects.

Analysis of Variance for SN ratios

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Media	2	18.82	18.82	9.412	0.94	0.517
Workpiece	2	424.21	424.21	212.107	21.10	0.045
Pressure	2	19.26	19.26	9.632	0.96	0.511
Residual Error	2	20.11	20.11	10.054		
Total	8	482.41				

Table 5.0.3 SN ratio analysis

Response Table for Signal to Noise Ratios

Level	Media	Workpiece	Pressure
1	16.37	11.50	16.71

2	19.90	15.14	20.09
3	17.91	27.54	17.38
Delta	3.53	16.04	3.38
Rank	2	1	3

Table 5.0.4 Response table

The table above is the nominal table for signal to noise ratio where nominal is considered to be the best (10*Log10 (Ybar**2/s**2)). Delta represents the difference between maximum and minimum values. And lowest is the delta highest is the rank of it.

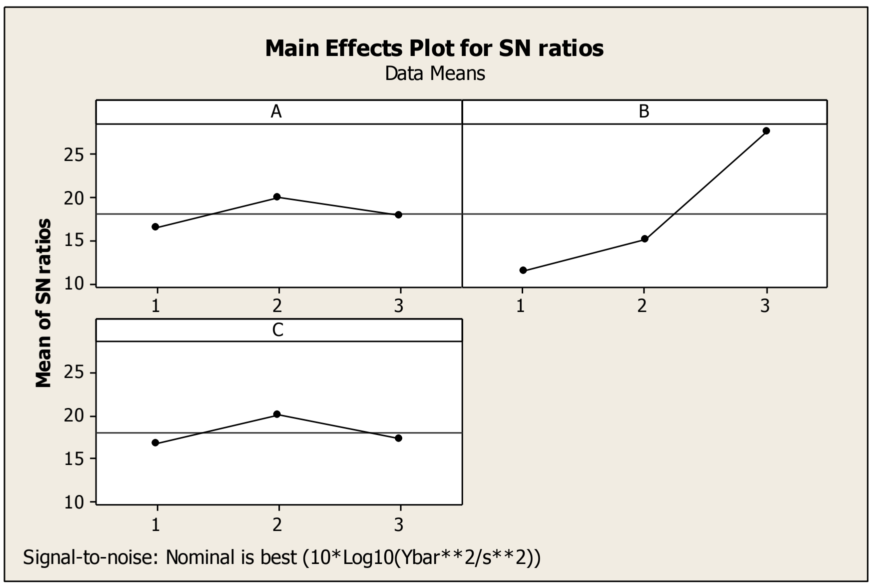

Table 5.0.5 Signal to Noise ratio curve

ONE-WAY ANOVA: RESPONSE VERSUS MEDIA

Source	DF	SS	MS	F	S
Media	2	0.12	0.06	0.01	0.991
Error	6	40.74	6.79		

Total	8	40.86			

Table 5.0.6 Response table for media

Here SS-Sum of Squares, DOF-Degree of Freedom, V-Variance, SS'-Pure sum of Squares. This is a one way ANOVA table between percentage of roughness improvement and media. Where pure sum of squares vale is comes out to be 0.12

S = 2.606   R-Sq = 0.30%   R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled St. Deviation.

Level	N	Mean	St. Dev	---------+-----------+-------------+------------+
1	3	4.167	2.496	-------------------------*---------------------
2	3	4.414	3.106	-------------------------*--------------------
3	3	4.414	2.120	-------------------------*-------------------- ---------+--------+--------------+---------------+-- 2.0 4.0 6.0 8.0

Table 5.0.7 pooled ANOVA table for Media

The confidence level can be taken of 85, 90 or anything but here it has been taken of the standard one i.e 95%. And the standard deviation from the pooled ANOVA comes out to be 2.606

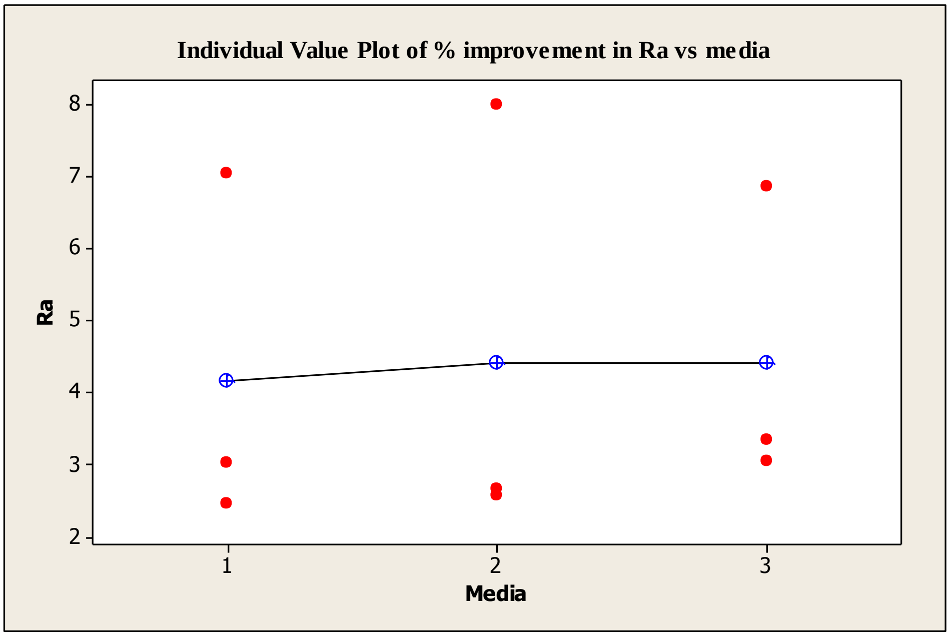

Table 5.0.8 Surface roughness vs Media plot

The graph shown in figure 5.5 states that initially % improvement in Ra roughness sharply increased at level 2, This is due to more number of abrasive particles taking part in machining process and also continues to remove fresh materials from the work surface which lead to increase in MR and surface finish. And then it starts decreasing up to a certain level.

One-way ANOVA: % improvement in R_a versus Workpiece

Source	DF	SS	MS	F	P
Workpiece	2	39.625	19.813	96.05	0.000
Error	6	1.238	0.206		
Total	8	40.863			

Table 5.0.9 Response table for workpiece

S = 0.4542

R-Sq = 96.97%

R-Sq(adj) = 95.96%

Individual 95% CIs For Mean Based on Pooled St. Deviation

Level	N	Mean	St. Dev	---------+---------+------------+----------+----
1	3	2.9853	0.3866	(----------*------------)
2	3	2.7153	0.2990	(-----------*----------)
3	3	7.2953	0.6164	(-----------*----------) --------+------+-------+-------+-- 3.0 4.5 6.0 7.5

Table 5.0.10 Pooled ANOVA table for workpiece

The Pooled StDev comes out to be 0.4542

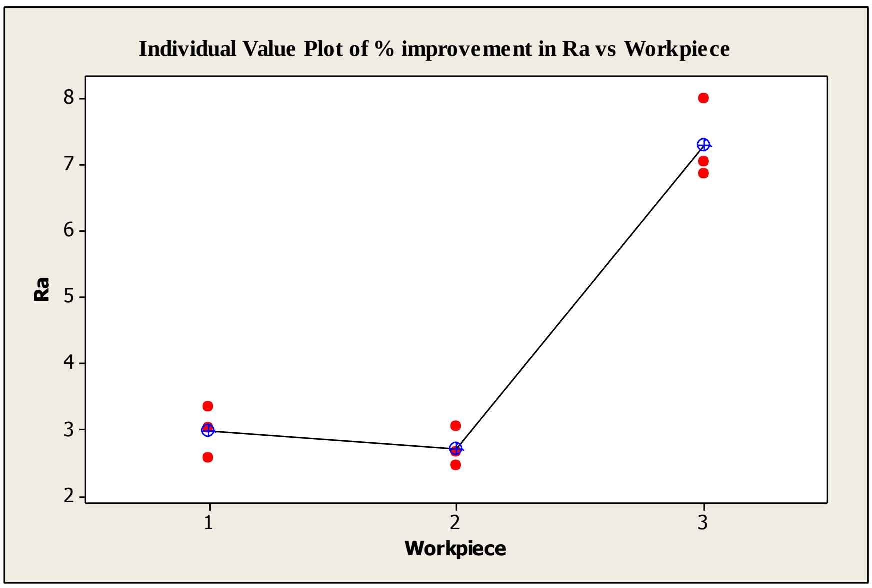

Table 5.0.11 Surface roughness vs Workpiece graph

The graph shown above is plotted between % improvement in surface roughness and three different workpieces i.e Aluminum, Brass, mild steel. Here the roughness improvement in Aluminum is slight more than the brass material and which is found to be very high for mild steel because as both aluminium and brass are soft material there roughness improvement is high but only up to a certain level as after that the abrasive particles does not get the surface to collide and moves in the flow. While Mild steel is a hard material so it gives good improvement.

One-way ANOVA: Surface roughness versus pressure

Source	DF	SS	MS	F	P
Pressure	2	0.79	0.40	0.06	0.943
Error	6	40.07	6.68		
Total	8	40.86			

Table 5.12 Response table for pressure

S = 2.584

R-Sq = 1.94%

R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	St. Dev	---------+-----------+-------------+------------+
1	3	4.688	2.869	------------------------*---------------------
2	3	3.961	3.508	------------------------*--------------------
3	3	4.348	2.348	------------------------*-------------------- ---------+--------+--------------+---------------+-- 2.5 5.0 7.5 10.0

Table5.0.12 pooled ANOVA table for Pressure

Pooled StDev = 2.584

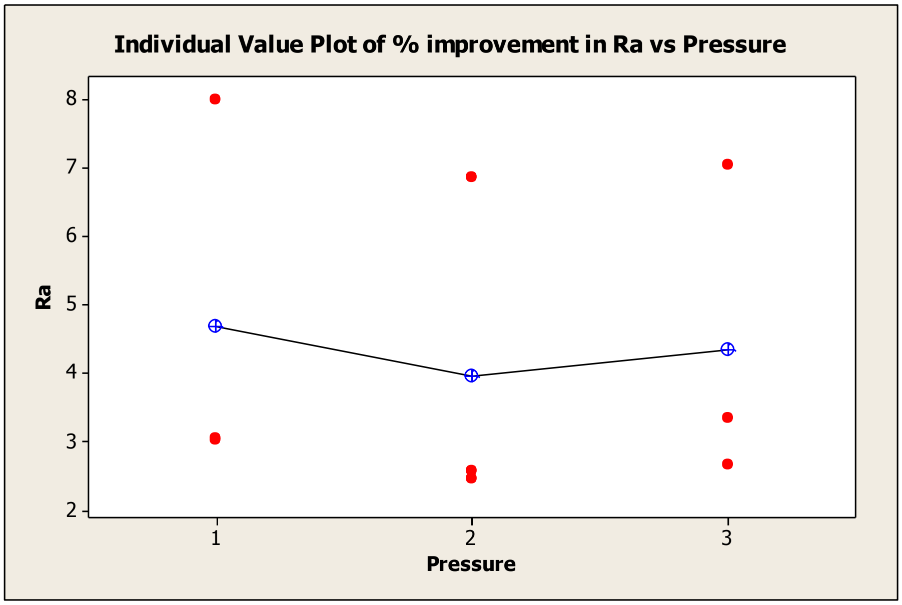

Table 5.0.13 Surface roughness Vs Pressure graph

From figure 5.11 above, initially improvement in surface roughness is more at lower pressure but then decreases at higher pressure and then increases this is because the difference between peak and valley of surface is reducing at level 2 and then increases moderately.

5.2 Material Removal

Response Table for Means, L_9 Method

Level	Media	Workpiece	Pressure
1	2.512	1.174	3.679
2	3.694	3.710	3.406
3	3.400	4.722	2.521
Delta	1.182	3.548	1.158
Rank	2	1	2

Table 5.0.14 Response table for mean

The table 5.12 shown above is calculated in Taguchi method of L9 series. In this table responses in the order of ranks and delta are created by the different parameters. It is clear that value 4.722 is maximum of all which comes under third level i.e L3, which is ranked one.

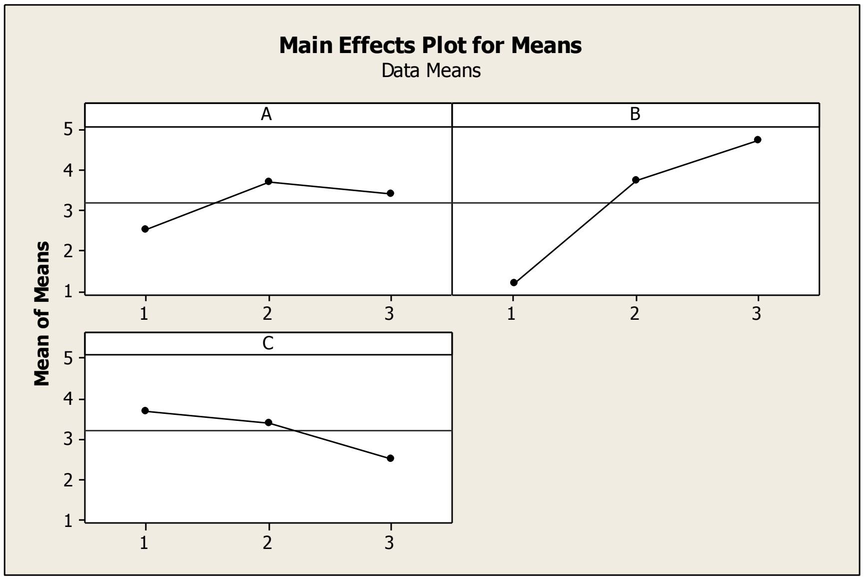

Table 5.0.15 mean value graph

The three graphs above are plotted in the Taguchi method taken from the mean values of the input table. Graph A,B,C are for Media, Workpiece and Pressure respectively. In all the graphs natural rubber, mild steel are showing the great effects at different pressure range which are discussed later.

Analysis of Variance for SN ratios

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Media	2	278.89	278.89	139.45	3.82	0.207
Workpiece	2	46.66	46.66	23.33	0.64	0.610
Pressure	2	26.88	26.88	13.44	0.37	0.731
Residual Error	2	72.96	72.96	36.48		
Total	8	425.39				

Table 5.0.16 SN curve-Variance table

Response table for signal to noise ratio

Level	Media	Workpiece	Pressure
1	27.27	25.06	25.85
2	35.51	30.16	29.12
3	21.99	29.56	29.81
Delta	13.53	5.10	3.96
Rank	1	2	3

Table 5.0.17 Response table for material removal data

The table above is the nominal table for signal to noise ratio where nominal is considered to be the best (10*Log10 (Ybar**2/s**2)). Delta represents the difference between maximum and minimum values. And lowest is the delta highest is the rank of it.

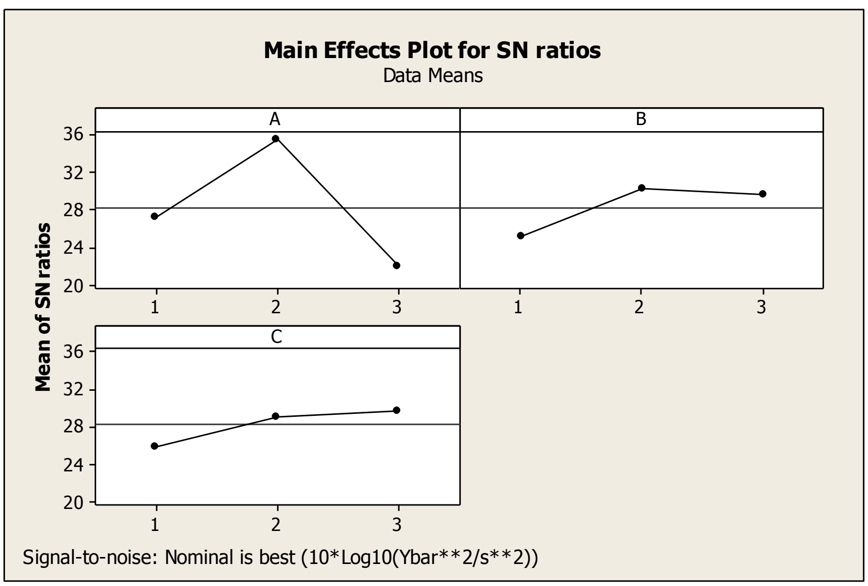

Table 5.18 plot for SN plot

One-way ANOVA: Material Removal versus Media

Source	DF	SS	MS	F	S
Media	2	2.27	1.14	0.27	0.770

Error	6	24.95	4.16		
Total	8	27.22			

Table 5.0.19 response table for MR Vs Media

Here SS-Sum of Squares, DOF-Degree of Freedom, V-Variance, SS'-Pure sum of Squares. This is a one way ANOVA table between percentage of roughness improvement and media. Where pure sum of squares vale is comes out to be 2.27

S = 2.039
R-Sq = 8.34%
R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled St Dev

Level	N	Mean	St. Dev	---------+-----------+-------------+------------+
1	3	2.512	1.300	------------------------*---------------------
2	3	3.694	2.558	------------------*----------
3	3	3.400	2.062	-------------*---------- ---------+--------+-------------+---------------+-- 0.0 2.0 4.0 6.0

Table5.0.20 Pooled ANOVA table for media

Pooled StDev = 2.039

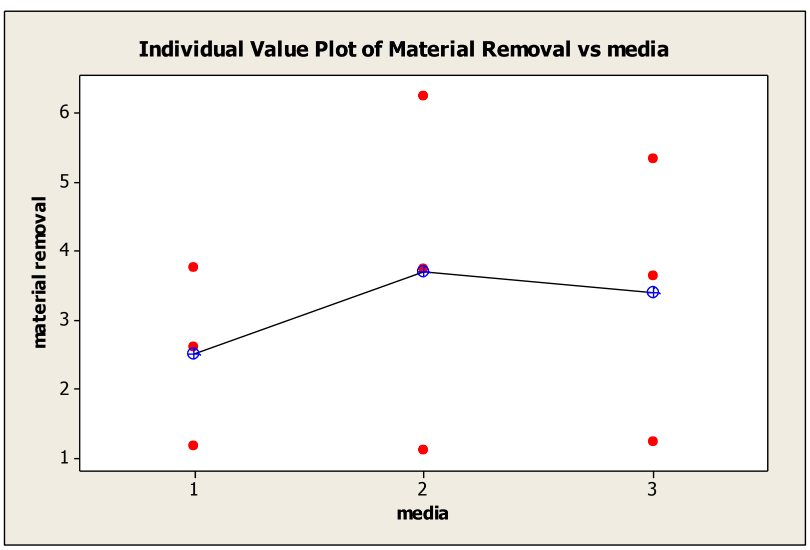

Table 5.0.21 graph for MR and Media

Here in the graph plotted above the material removal for styrene butadiene rubber is maximum, and it is coming least for silicon rubber. Therefore SBR is the best media of all.

One-way ANOVA: material Removal versus Workpiece

Source	DF	SS	MS	F	S
Workpiece	2	20.05	10.02	8.38	0.018
Error	6	7.18	1.20		
Total	8	27.22			

Table 5.0.22 response table for MR and WP

S = 1.094
R-Sq = 73.64%
R-Sq(adj) = 64.86%

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	St. Dev	---------+-----------+-------------+------------+
1	3	1.174	0.058	-----------*--------------
2	3	3.710	0.069	-----------*-----------
3	3	4.722	1.892	-------------*---------- ---------+--------+--------------+---------------+-- 0.0 2.0 4.0 6.0

Table 5.0.23 pooled ANOVA for WP

Pooled StDev = 1.094

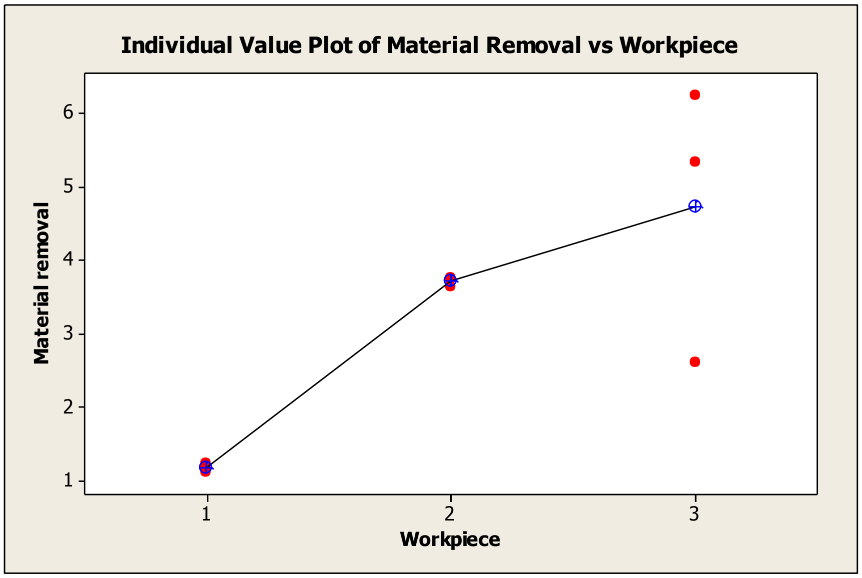

Table 5.0.24 MR Vs WP graph

The graph shown in fig above is between material removal and workpieces. The behaviour of this curve is proportional to the behaviour of individual workpiece. As aluminium and brass are both soft materials then mild steel therefore the material removal for both softer workpieces are less than that of mild steel.

One-way ANOVA: Material removal versus Pressure

Source	DF	SS	MS	F	S
Pressure	2	2.20	1.10	0.26	0.777
Error	6	25.02	4.17		
Total	8	27.22			

Table 5.0.25 Response table for MR and pressure

S = 2.042

R-Sq = 8.07%

R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	St. Dev	---------+-----------+-------------+------------+
1	3	3.679	2.532	------------------*-----------------

2	3	3.406	2.130	----------------*-----------------
3	3	2.521	1.250	-----------------------*---------------------- ---------+--------+--------------+---------------+-- 0.0 2.0 4.0 6.0

Pooled St. Dev = 2.042

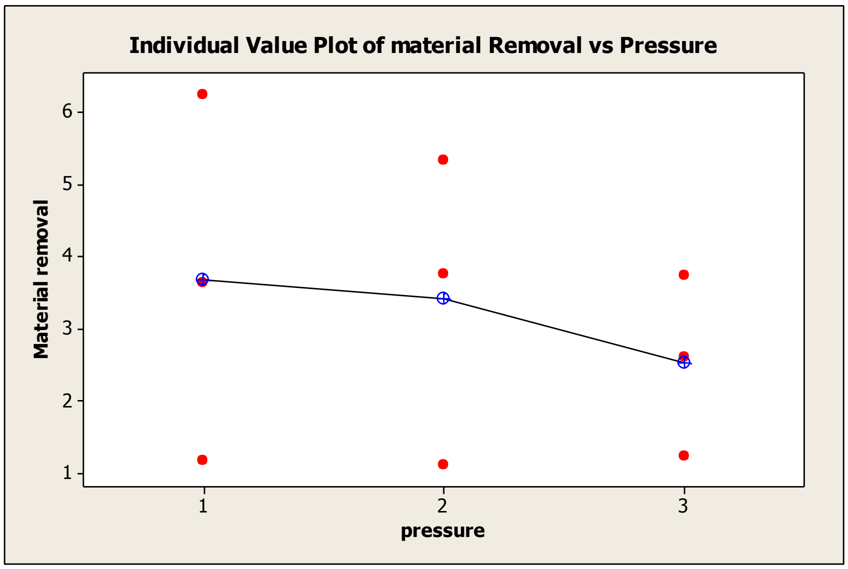

Table 5.0.26 Plot of MR vs Pressure

From the graph plot shown above between material removal and a range of pressure i.e 10, 15, 20Mpa are considered. Here as the value of pressure increases, our material removal rate decrease this is because at lower pressure of media its velocity is low thus allowing more laden particles to collide with the work surface. But as soon as the pressure increases, the contact time between workpiece and media reduces thus material removal is low.

CHAPTER 6

CONCLUSION AND FUTURE PRESPECTIVE

6.1 Conclusions

Experiments were carried out for evaluating performance of some newly developed media(SR, SBR, NR) using vertical type AFM setup to study its performance in terms of the improvement in material removal and surface finish of "**aluminium, brass, mild steel**" work pieces. It has been found that the use of different laden media for different workpieces led to an improvement in the response parameter of percentage improvement in surface finish and material removal.

- For the design of experiment, the Taguchi method approach has been employed. L_9 OA has been used for the plan of experiments.
- The three process parameters viz. Media, workpieces and extrusion pressure all have significant effect for the response parameter of MR and R_a .
- The process parameter Extrusion pressure and different medias are significant for response
- At selected parameters a maximum improvement of 29.51% has been observed in the Surface finish on the inner cylindrical surface of the work piece. And 3.21mg improvement in the material removal rate.

6.2 Scope of future work

- Characterization of media can be done through FTIR and other techniques.
- These result outcomes can be analyzed for different industrial material.
- The set up can be optimized for some other process parameters like different shapes of work materials, flow rate of media etc.

References

[1] Das Shaswata, Chakraboty Shankar, 2011. Selection of non-traditional machining processing analytic network process, Journal of manufacturing system. Vol.30(1), pp. 41-53.

[2] Perry W.B, 1989. Abrasive flow machining principles and practices, Non-traditional conference procedding. Pp.121-127.

[3] Dubey Avinash kumar, yadava Vinod, 2008. Laser beam machining-A review, Int. J. of machine tools and manufecture. Vol.48(6), pp.609-628.

[4] Chauhan Sandeep, Mittal Sushil, 2014. Abrasive flow machining: major research areaand analysis, Int. J. of research in aeronautical and mechanical engineering. Vol.2(1), pp.77-83.

[5] L.J.Rhodes, 1991. Abrasive flow machining, A case study of material processing technology. Pp.107-116.

[6] L.J Rhodes, 1987, Abrasive flow machining with not so-silly putty, metal finishing, pp.27-29.

[7] L.J. Rhodes,1988. Abrasive flow machining, manufacturing engineering. 101, pp75-78.

[8] Przyklenk, 1986. AFM: a process for surface finishing and deburing of workpiece with a complicated shape by means of an abrasive laden medium, ASME. PED.22, pp.101-110.

[9] Williams. R. E, Rajkumar. K.P, 1992. Stochastic modeling and analysis of AFM, trans. ASME, Int. J. Ind. 114, pp.74-81.

[10] Williams. R. E, Rajkumar. K.P,1989. Metal removal and surface finish characteristics in AFM, ASME, PED,38, pp.93-106.

[11] Williams. R.E, Rajkumar. K.P, Rhodes. L.J, 1989. Performance charectrastics of AFM, SAME technical paper, pp.896-906.

[12] Loveless T.R,Williams. R.E, Rajkumar. K.P, 1994. A study of the effects of abrasive flow machining on various machined surfaces, Journal of materials processing technology.47, pp.133-151.

[13] Perry W.B, 1989. Abrasive flow machining principles and practices, Non-traditional conference procedding. Pp.121-127.

[14] Jain, 1999. Modelling and simulation of abrasive flow machining process, Ph.D. Thesis IIT Kanpur.

[15] Davis P.J, Fletcher A.J, 1995. The assessment of a rheological characteristics of various polyborosiloxane (PBS)/ grit mixtures as utilized in the abrasive flow machining process. Proceeding of the institute of mechanical engineers. Vol.209, pp.409-418.

[16] Przyklenk K. "Abrasive flow mahcining- A process for surface fminshing and deburring of work ieces with a complicated shape by means of abrasive laden media", Advances in Non-Traditional /lachining, PED, ASME (1986). Vol. 22 , pp. 101-110.

[17] Weller E.J. "Nontraditional Machining Processes" 2nd edition, *SME* (1984), pp. 52-65.

[18] Jain R.K. and Jain V.K. "Abrasive fine finishing process-a review", int . j. of Manufacturing science and Production (1999), Vol.2(1), pp. 55-68.

[19] Hull J.B., Jones A.R.. Heppel A.R.W., Fletcher A.J., and Trengove S.A. "The effect of temperature rise on the rheolog of carrier media used in abrasive flow machining (1992)", Surface Engineering , Vol. II, Engineering Applications, pp. 235-244.

[20] William R.E.. and Rajurkar *K.P.* Rhoades L.J. "Performance Characteristics of abrasive flow machining", SME Technical paper No. FC 89-806 (1989).

[21] McCarty R.W. "U.S. Patent No. 3521412". (1970).

[22] Siwert D.E. “Tooling for the extrude hone process”, Proc. SME International Engineering Conference (1974), pp. 302-305.