EXPERIMENTAL INVESTIGATIONS ON SIMULTANEOUS FINISHING OF SURFACES WITH ABRASIVE FLOW MACHINING

A dissertation report submitted in partial fulfilment of
the requirement for the award of the degree of

Master of Engineering

in

Production Engineering

Submitted By

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CERTIFICATE

I hereby declare that the report entitled **"Experimental Investigations on Simultaneous Finishing of Surfaces with Abrasive Flow Machining"** is an authentic record of my study carried out as requirements for the award of degree of Master of Engineering in Production Engineering at Thapar University, Patiala under the supervision of Dr. Vivek Jain & Dr. Dheeraj Gupta, Assistant Professor, Thapar University, Patiala during July 2014 to June 2016. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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ABSTRACT

Abrasive flow machining (AFM) is a non-traditional finishing process used to deburr, chamfer, polish, remove recast layers, and to produce compressive residual stress. AFM can be mostly used to polish and deburr internal parts, through holes, intersecting holes and freeform surfaces which are difficult to finish with other traditional finishing processes. It can be a high potential candidate in the simultaneous finishing of the workpiece, instead of separately finishing of internal and external surfaces of the workpiece with other non-conventional processes. The present research initiatives are based on the simultaneous finishing of the ring-shaped cylindrical aluminum alloy workpiece. For accomplish the main objective of the simultaneous finishing of the workpiece the fixture setup is designed and fabricated. The hydraulic system of a Universal Testing Machine is used for actuation of the media piston in the present work. The present study initiatives identify the process parameters such abrasive mesh size, concentration of abrasives in media and number of passes that significantly affect the change in surface roughness of the inner, outer and side surfaces, and the amount of material removal. The L27 full factorial design has been adopted in the present study for the optimization of the experimental study. Experimental investigations have been carried out on the abrasive flow machining setup designed and developed by the author. The silicon polymer abrasive media has been prepared. The parameters selected for the present study is abrasive mesh size, concentration of abrasives in media and number of passes at three level each. Work material, abrasive type, working temperature, media, media flow per pass, the polymer to gel ratio was kept constant in the present investigation. It has been observed from an experimental investigation that the abrasive mesh size, concentration of abrasives in media and number of passes have a significant effect on both changes in surface roughness and material removal. The percentage improvement in surface roughness of the internal, external and side surface of the ring-shaped workpiece are observed in this study are 35, 37 and 27% respectively. The main objective of the simultaneous finishing is achieved by the specially designed fixture and the same objective may be applied for simultaneous finishing of the workpiece, specifically deep groove ball bearing in one go instead of separately finishing of internal and external surfaces with traditional finishing processes.

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Chapter I – INTRODUCTION

Smart engineering materials namely, ceramics, polymers, composites, and super-alloys are developed because of the advancement of the material science. These materials have large uses in the modern manufacturing industries such as aircraft, automobiles, cutting tools, dies and mould manufacturing industries. Machining of these materials are difficult and costly besides this tight tolerances are utmost important in the modern era. Precision machining of complex and complicated shapes and/or sizes, machining of unable to reach surfaces at micro or nano levels with narrow tolerances leads to the development of new advanced non-conventional machining process.

1.1 Role of Surface Finish

The performance of the manufactured product can be determined by the quality of the surface of the product. Surface quality has an effect on product performance such as attractiveness, assembly fit etc. that a probable client may require for the merchandise. External boundary of the object with its surroundings, which can be any other object, a space, a fluid or combination of those can be termed as the surface. The surface encloses the objects bulk mechanical and physical properties.

Once a manufacturing object is held in hand, the surface has a tendency to touch. Commonly, the dimensions of the objects are specified in the drafting in which assorted surfaces are relating with each other. These nominal surfaces of the manufactured parts are outlined by the line in drawings. The nominal surfaces of the objects are defined by the straight lines, spherical holes, perfect circles, perpendicularity, and absolute straightness.

A range of the manufacturing processes is used to create the designed components. In general, manufacturing results in the variation in the surface characteristics. It is important to understand the technology used for the generation of surfaces. Then after only the basis causes of deviation can be determined and fixed to obtain great results and physical properties.

1.2 Purpose of Surface Preparation

Surfaces are important as a result of numerous industrial and technological reasons. These reasons could also be totally different depending on different applications of the merchandise.

The main objectives are delineated below,

- All smooth surfaces that are free from scratches and blemishes give a good aesthetic look. This all add value to the product and provides a favourable impression to the purchasers.
- Smooth surfaces free from scratches and sharp corners and edges provide safety to users.
- Friction and wear also determined by surface conditions. In the case of pairing components, the pairing surfaces should be utterly finished to avoid wear and energy loss because of friction.
- Good quality surfaces enhance mechanical and physical properties. Any surface flow will act as some extent of stress concentration.
- A slightly rough surface having a uniform and constantly maintained the value of surface roughness provides anti-glazed property to the same.
- Smooth surfaces improve the capability to create good electrical contacts.

1.3 Characteristics of Surface

Characteristics of surfaces include surface integrity, surface texture, in addition, takes care of relationship between producing processes and characteristics of generated surfaces. A surface is usually examined by an enlarged cross-section of the surface of the part created. The majority of the part observed as substrate contains a grain structure that depends on the previous processing of the metal. The outside of the machine part is termed surface whose topography is pre-decided. The surface might have roughness, waviness, and flaws. It should even have some pattern or directional pattern depending on the method used. All these are represented as surface texture. The elements of surface texture are outlined below and shown in figure 1.1.

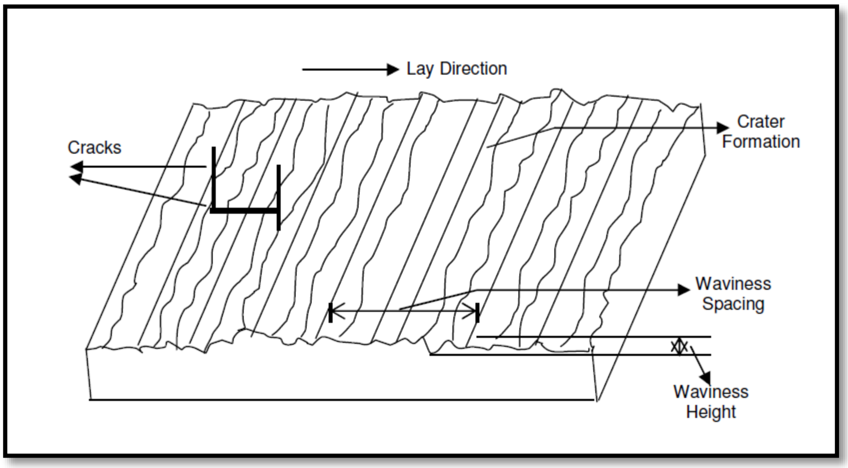


Figure 1.1: Elements of surface textures

- **Surface Roughness**

It refers to small, finely spaced deviations from the nominal surface that are determined by the material characteristics and also the method used.

- **Waviness**

It is outlined as the deviations of much larger spacing occurring as a result of work deflection, vibration, heat treatment and different similar factors. Roughness is usually superimposed on the waviness.

- **Lay**

Lay is that the predominant direction or pattern of the surface texture. It is the results of and determined by the manufacturing technique accustomed generated surface.

- **Flaws**

Flaws are irregularities that occur generally on the surface. Flaws don't seem to be the characteristics of the method however these are the faults. Examples of flaws are cracks, scratches, inclusions, etc.

1.4 Surface Roughness

Surface roughness and surface finish are opposite to each other, these are quantitative parameters. Surface roughness is often expressed in units of length when it’s measuring.

Measurements of finely spaced deviations of the actual surface from the datum surface within the units of length (µm) are the measuring of surface roughness. Lesser the value of surface roughness higher the surface finish is claimed. There are two common ways of expressing measured value of surface roughness.

As per Average Roughness technique, the surface roughness is the average of vertical deviations from the nominal surface over a given surface length.

$$\textbf{Average Roughness} = \int_0^l \frac{(Y)}{L}\, dx$$

where,

Y = Vertical deviations from nominal surface, and

L= Specified length on the surface.

According to the root mean square approach, “Value of surface roughness is the square root of the mean of the squared deviations from the nominal surface over the sampling length.” RMS value is often discovered more than the arithmetic average as a result of larger deviations plays a more prominent role.

$$\mathbf{R_{rms}} = \int_0^l \sqrt{\frac{|Y|^2}{L}}\, dx$$

1.5 Surface Finishing Processes

Final finishing operations in producing of precise components are continuously of concern because of their most critical labour intensive and least controllable nature. In the time of nanotechnology, deterministic high preciseness finishing strategies are of utmost importance and are the requirement of present manufacturing situation. The necessity for high preciseness in manufacturing was felt by manufacturers worldwide to enhance exchangeability of parts, improve quality control and longer wear/fatigue life. Manufacturing method employed to manufacture determines surface finish level. Some processes are inherently capable of producing higher surfaces than others.

Taniguchi [1] was first to review the historical progress of possible achievable machining accuracy throughout the twentieth century. The probable developments in micro technology and nanotechnology are also calculated by him as shown in figure 1.2.

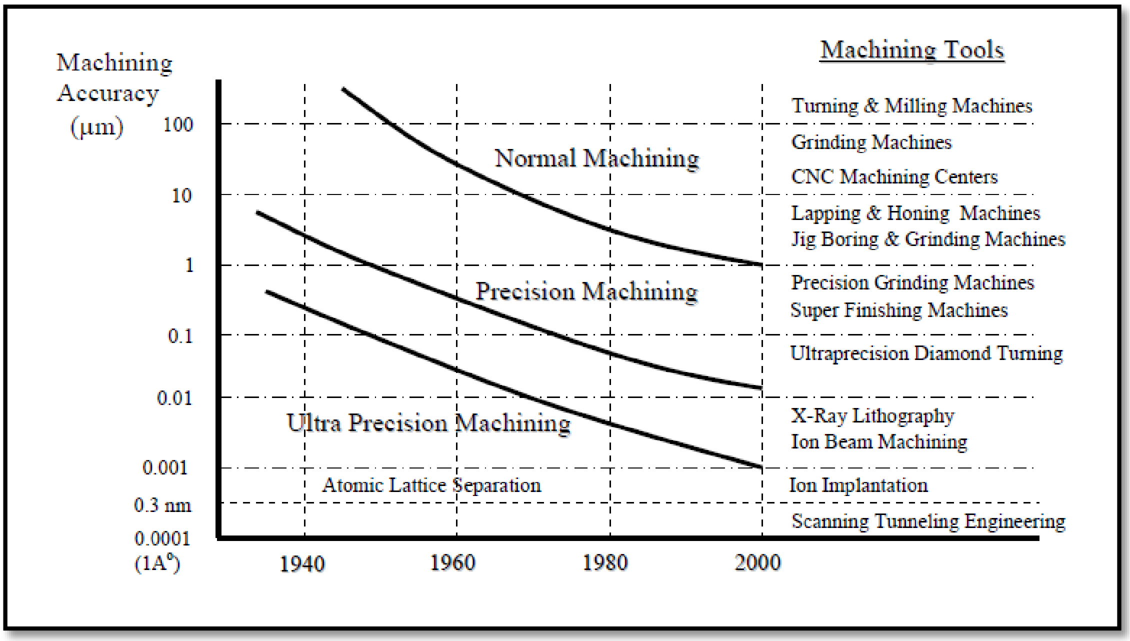


Figure 1.2: Achievable Machining Accuracy [1]

The machining processes were classifieds into three categories on the premise of possible accuracy viz. normal machining, precision machining and ultraprecision machining. Ultraprecision machining is the processes by that the best possible dimensional accuracy is achieved at a given point of time. This will be a relative definition that varies with time. It has been expected that by 2000 AD, machining accuracies in ancient processes would reach 1 μm whereas in precision and ultra precision machining would reach 0.01μm (10 nm) and0.001μm (1 nm) respectively. The author also predicts the possible achievable machining accuracy in the next two decades according to the present advances in manufacturing technology. These accuracy targets for today’s ultraprecision machining cannot be achieved by simple extension of ancient machining processes and techniques.

Nanotechnology was initially used to classify integrated manufacturing technologies and machine systems which give ultraprecision machining capabilities within the order of 1 nm. Since then ultra precision technologies have grown quickly over recent years and have a tremendous impact on the development of latest products and materials. Nanotechnology is the target of ultraprecision machining because the theoretical limit of accuracy in machining of substance should be the dimensions of an atom or molecule of the substance. With the arrival of recent materials, manufacturing is facing challenges in machining them to fulfil their functional necessities. Because the demand moves from the micro technology (1μm accuracy capability) to the nanotechnology region (1 nm accuracy) the systems engineering demands a speedy increase in stringency and complexness. The conventional finishing processes alone are thus incapable of manufacturing needed surface characteristics to satisfy the demand of nanotechnology. Even in certain cases these processes are used, on the other hand, they need costly equipment and enormous labour, finally leave them economically incompetent.

New advanced finishing processes were developed in previous few decades to beat limitations of ancient finishing processes in terms of higher tool hardness demand and precise control of finishing forces throughout the operation. This helped in finishing tougher materials and effort higher in process control over final surface characteristics. Another limitation relaxed by some advanced finishing processes exploitation loose abrasives is to finish sophisticated geometries by amplifying the reach of abrasive particles too difficult to reach regions of the work surface. In this approach, newly developed finishing processes are to a large extent useful in meeting needs of 21st-century manufacturing.

The surface finish of the machined and manufactured components is a very important requirement to make sure their durable performance.

Some traditional and advanced finishing processes are shown in figure 1.3,

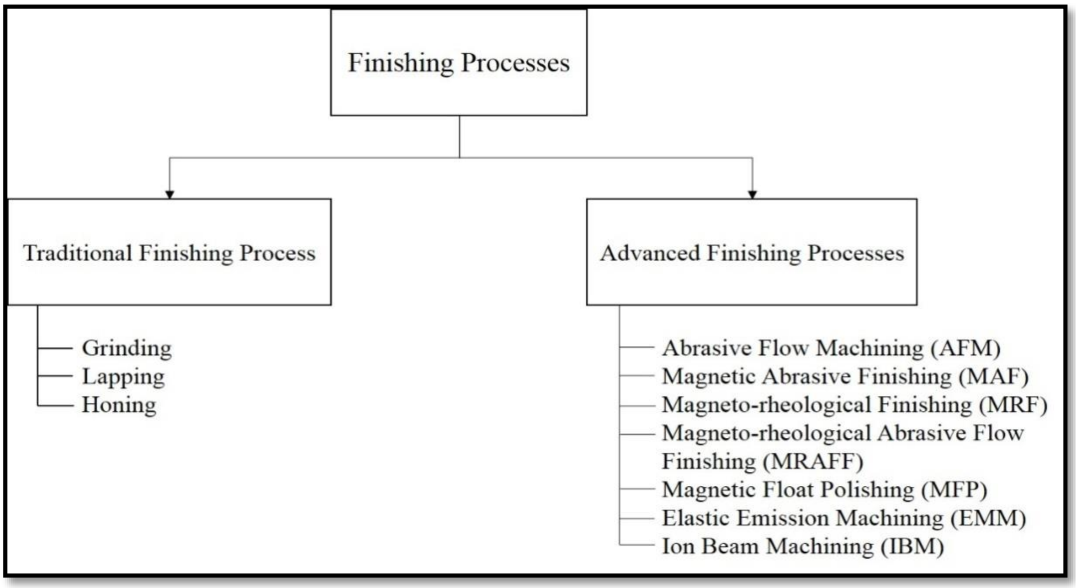


Figure 1.3: Various Finishing Processes

1.5.1 Traditional Finishing Processes:

Before continued discussion on advanced ultra-precision finishing processes, it's useful to know the principle of action of commonly used nonconventional finishing processes – grinding, lapping and honing. All these processes use multipoint cutting edges in the form of abrasives, which can or cannot be bonded, to perform cutting action. These processes are in use from the earliest times because of their capability to generate smooth surface at close tolerances. The Higher hardness of abrasive particles is a crucial requirement for the process. If properly conducted these abrasive machining processes will manufacture a surface of higher quality with a controlled surface roughness combined with a desirable residual stress distribution and freedom from the surface and sub-surface damages.

- **Grinding**

Grinding is the most generally used abrasive finishing method among all nonconventional processes utilized in production. In grinding the material is removed from the work surface by the relative motion of the cylindrical wheel having abrasive particles embedded on its outer boundary. The abrasive particles are bonded together to make porous revolving body which when coming in contact with a piece of work leads to material removal. Grinding in a very broad perspective is principally divided into two regimes i.e. stock removal grinding (SRG), and form and finish grinding (FFG).

In SRG, the main objective is to remove the unnecessary material from the surface, whereas in FFG, the surface quality is the main concern. The abrasives on a wheel are firmly bonded with a specific binder and at a similar time also have the possibility to allow grain fracture to renew cutting edges of the wheel. Abrasive grain wears quickly on grinding tougher materials, therefore, a less strongly bonded wheel is most popular for operation. Porosity on the grinding wheel could be a controllable factor to produce rooms to accommodate chips.

Wheels bonded with glass are strongest and hardest whereas organic bonds are of lower strength. The size and distribution of grits together with wheel structure play a crucial role in grinding performance.

A correct selection of wheel for finishing requirements is extremely important. The application of grinding is especially available for simple geometries like cylindrical or plane surface where size is restricted by wheel movement.

➢ Lapping

In lapping, loose abrasives are used to finish the surface. It works on the body abrasive wear principle in which finishing action takes place through abrasion by hard particles trapped between work surface and a comparatively soft counter formal surface known as a lap. When introducing abrasive slurry between work and lap surface, the workpiece is held against lap and moved in random ways under pressure.

Simple three-dimensional shapes and curved surfaces (concave, convex etc.) to some extent is finished by designing compliant lap. As this method is mostly utilized for improving surface finish and accuracy, the quantity of material removed is insignificant.

➢ Honing

Honing is another abrasive finishing method usually used to finish internal cylindrical surfaces. The random cross-marked surface with the good surface finish is generated with the abrasives in the form of stick or stones carried in an expanding and oscillatory mandrel. The stick pressure on the work surface is relatively more than lapping. The surface created after honing has self-lubricating property because of oil holding capability in cross-hatched pattern.

1.5.2 Advanced Finishing Processes

There are several advances taking place in the finishing of materials with fine abrasives, together with the processes, the abrasives, and its bonding, making them capable of getting nanometer order surface finish. Earlier there has been a limit on the fine size of abrasives (a few μm) but nowadays, new advances in materials syntheses have enabled the production of ultra-fine abrasives within the nanometre range. Abrasives are utilized in a range of forms including loose abrasives (in polishing, lapping), bonded abrasives (in grinding wheels), and coated abrasives for manufacturing components of varied shapes, sizes, accuracy, finish and surface integrity.

The electronics and computer industries are forever in demand of higher and better precision for large devices and high data packing densities. The greatest precision procurable through finishing is when chip size approaches atomic size (~ 0.3 nm). To finish surfaces in nanometre range, it's needed to remove material in the form of atoms or molecules on an individual basis or in the groups. Some processes like Elastic Emission Machining (EEM) and ion beam Machining (IBM) work directly by removing atoms and molecules from the surface. Other processes based on abrasive wear remove them in clusters. On the basis of energy used, the advanced finishing processes may be classified into mechanical, thermo-electrical, electrochemical and chemical processes as described in figure 1.4.

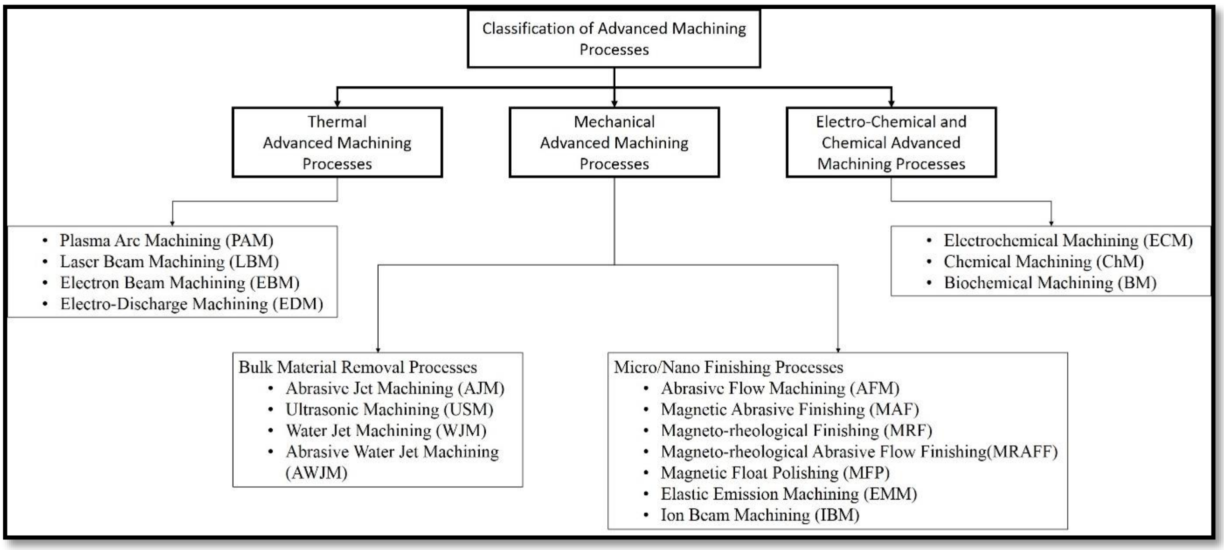


Figure 1.4: Classification of advanced machining processes

The performance and use of certain specific process rely on work material properties and functional demand of the component. In mechanically advanced finishing processes, very precise control over finishing forces is needed. Many newly developed advanced finishing processes use the magnetic/electric field to externally control finishing forces on abrasive particles. To name a couple of, this magnetic field assisted finishing processes include Magnetic Abrasive Finishing (MAF), Magnetorheological Finishing (MRF), Magnetic Float Polishing (MFP), and Magnetorheological Abrasive Flow Finishing (MRAFF). Chemo-Mechanical polishing (CMP) uses both chemical etching and mechanical wear to attain surface finish of nanometre and planarization. Chemomechanical polishing (CMP) is the most preferred process utilized in the semiconductor industry for silicon wafer planarization and finishing. Because of material removal in fine abrasive finishing processes is extremely little, they can be used successfully to get nanometer surface finish and very low value of dimensional tolerances. Advanced abrasive finishing processes belong to a subset of ultra-precision finishing processes that are developed for getting nanometer order surface finish.

Surface finish obtainable from different finishing process is compared in table 1.1.

Sr. No.	Finishing Process	Workpiece	Ra (nm)
1	Grinding	-	25 - 6250
2	Honing	-	25 – 1500
3	Lapping	-	13 – 750
4	Abrasive Flow Machining (AFM) with SiC abrasives	Hardened Steel	50
5	Magnetic Abrasive Finishing (MAF) with diamond abrasives	Stainless Steel rods	7.6
6	Magnetic Float Polishing (MFP) with CeO_2 abrasives	Si_3N_4	4.0
7	Magnetorheological Finishing (MRF) with CeO_2 abrasives	Flat BK7 glass	0.8
8	Elastic Emission machining (EEM) with ZrO_2 abrasives	Silicon	<0.5
9	Ion Beam Machining	Cemented carbide	0.1

Table 1.1: Surface finishes obtainable from some advanced finishing processes

Although all the advanced finishing processes have gained over other processes, Abrasive Flow machining has a more advantageous process to finish internal complex geometries which are not easily finished with traditional finishing processes. So Abrasive flow machining was chosen for the finishing of cylindrical ring externally and internally, simultaneous finishing.

1.6 Abrasive Flow Machining (AFM)

Abrasive Flow machining (AFM) is a non-traditional machining process that may be used to deburr, radius, polish, remove recast layers, and to produce compressive residual stresses.

It is a process of polishing and smoothening internal surfaces and thereby producing controlled radii. The abrasive media is flown across the surface to be super-finished either in a single direction or two-way and this extrudes through the workpiece thereby finishing and smoothening the surfaces. In the case of one-way systems, the media is flown/passed through the workpiece and it returns from the other end. Whereas in a two - way method, two vertically opposite hydraulic cylinders, push the abrasive mixed media to and fro. The process is specially employed in contours that are tough to polish and such internal passages, cavities, edges and bends. The schematic diagram for abrasive flow machining is shown in figure 1.5.This process was first patented and described by the Extrude Hone Corporation in 1970 [2].

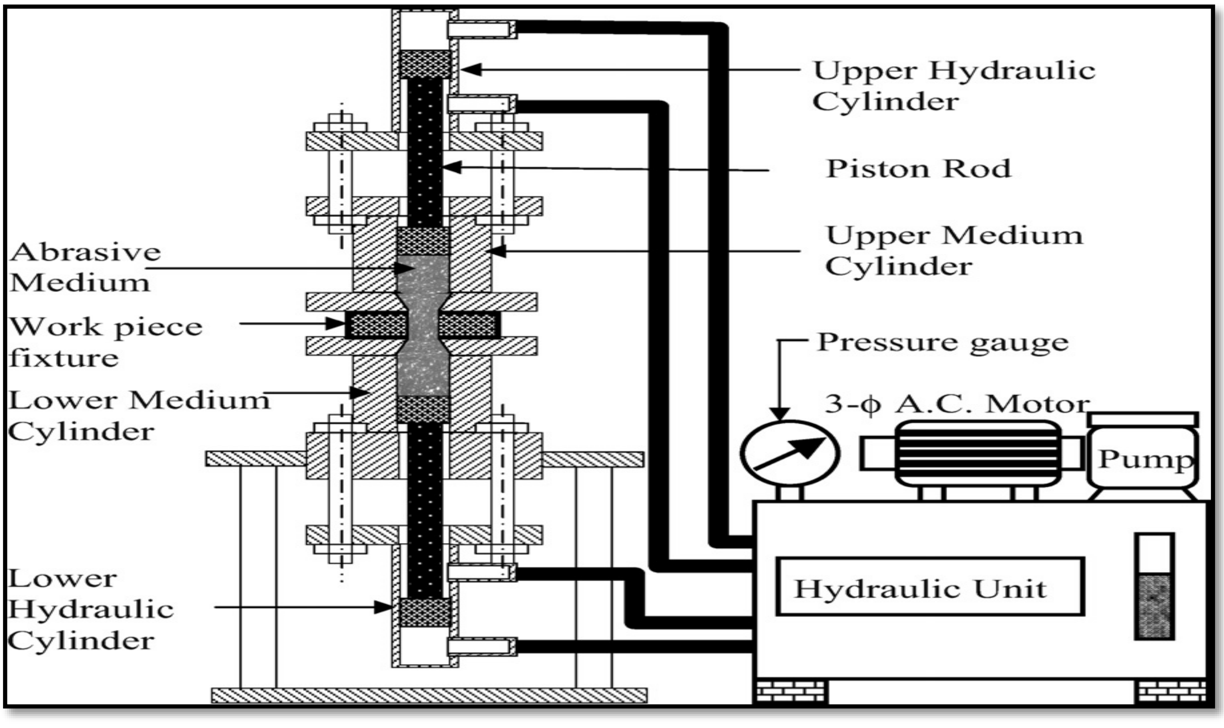


Figure 1.5: Schematic diagram of abrasive flow machining [23]

The AFM process is widely used in a range of various finishing operations. At a given time, it can process a number of components or different areas of the identical workpiece. The areas which are not accessible and such complicated internal passages can also be very effectively finished. The automatic AFM systems are capable of handling thousands of components per day, thereby considerably reducing the labour costs and eliminating tedious handwork. Through proper knowledge and control of the process parameters, this process can be effectively used for a number of super-finishing operations thereby achieving very precise and uniform results. Practical applications of this method could be in any of the situations whereby the media could be flown across.

The design of the many products necessitates the machining of intersecting bores, flats, slots, keyways and splines, and the machining of these various shapes always produces a sharp corner or a raised burr at the conjunction of such surfaces. AFM is particularly helpful where such intersecting surfaces occur within the internal part of a workpiece that cannot be finished by the standard methods of grinding, lapping or the usual best-known types of honing. The end use of many products in the aeromotive, aircraft and aerospace industries is such that a little particle of metal could cause failure to the whole engine or another operating system. The flaking off of a projecting burr, therefore, is a risk that's always present within the assembly of these products. Again, the sharp corner resulting from the above-named machining operations may be a point of stress concentration and potential failure of a vital part. The removing of the sharp corners with a radius materially reduces this stress concentration.

The most time consuming and a labour intensive section of the manufacturing method in today’s industry is the final finishing of complicated and precision parts. This consumes as much as 5–15% expenditure of the overall manufacturing process [4, 5].The process can deburr holes as small as 0.2 millimetre and radius edges from 0.025 to 1.5 mm. Tolerances can be held to ±5 µm [3].AFM is becoming popular due to its ability to provide predictable, repeatable and consistent results [4]

1.7 Purpose of AFM

The main purposes of this process are,

a) provide a means of removing burrs from the interior and exterior surfaces of assorted products,

b) improve the surface finish of surfaces created by various machining operations, or which cannot be improved by conventional ways especially internal complex geometry or freeform geometry,

c) provide a means of adding a radius or a removing of sharp corners of the product,

d) provide a means of finishing the inside cylindrical part of the straight bored product to exceptionally fine finish,

e) improve surface finish quality in non-symmetrical or otherwise inaccessible cavities, galleries or manifolds, and

f) provide a means of automatically or semi-automatically performing these operations, with a controlled cycle, eliminating the operator variable and its resultant high cost and low quality.

1.8 AFM Principle

In abrasive flow machining process, a semi-solid media is used which contains carrier in the form of polymer base containing abrasives in required proportion. The media is extruded across the given surface, which is to be machined under the given pressure. The media acts as a deformable grinding tool when it subjected to some restriction due to an uneven surface. The special deformable ability of media is responsible for its motion through any shape and size of passage. Figure 1.6 illustrates the basic operation and principle of AFM Process.

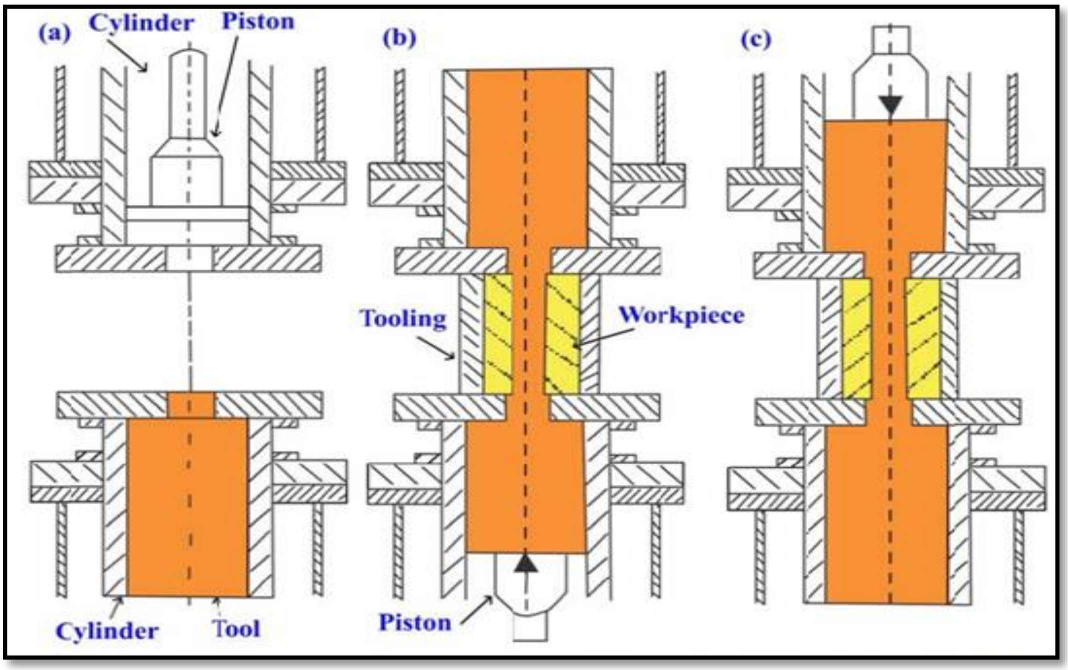


Figure 1.6: Basic operation and principle of abrasive flow machining process

Restricted media flow passage are a prerequisite at the surface to be processed by AFM, wherein media behaves like deformable grinding stone, abrading the material, and provides good surface finish all over the surface. Normally, the fixture is required to provide restriction or to guide and focus the media to required location in the workpiece.

The clamping of the workpiece is made of the two media cylinders, which are hydraulically operated and placed in opposite directions. Lower media cylinder is filled with required volume of abrasive-laden media (Figure.1.6 a). The media is then extruded through the workpiece into the upper media cylinder (Figure.1.6 b). The procedure is reversed and the media is fed back through the workpiece into the lower cylinder (Figure.1.6 c). A process cycle is constituted by a combination of these up and down strokes.

1.9 Components of AFM

To describe the process technology, three elements namely,

a) Machine,

b) Media, and

c) Tooling

The machine decides the extent of abrasion, the media determines what kind of abrasion will occur and the fixture determines the exact location of abrasion.

1.9.1 AFM Machine

All machines regardless of size are positive displacement hydraulic systems, which force the abrasive laden media through the fixture workpiece at a chosen pressure and flow rate. Standard AFM system operates within l0 bar to 200 bars and with the flow rates up to 400 litres/min. AFM systems are basically provided with controls on hydraulic system pressure, volume flow rate of media, clamping and unclamping of fixtures, and advance and retract of media pistons. The accessories such as cycle counters, automatic flow timers, volumetric displacement systems, media heat exchangers, pressure and temperature compensated flow control valves are integrated to typical AFM systems for production applications.

1.9.2 AFM Media

An essential component of the AFM method is the media, which is considered a proprietary item by machine manufacturers. It contains base material or carrier, abrasive grains, and proprietary additives. Most widely used carrier could be a high viscosity rheopectic fluid (at any constant rate of shear, its apparent viscosity increases with time to some maximum value). The base material has enough degree of cohesion and tenacity to drag the abrasive grains along with it through various passages/regions. Aluminium oxide and silicon carbide are most suitable abrasives for many applications however boron carbide and diamond are specifically used for special applications. Abrasive grain to base material ratio can vary from 2 to 12. The additives are primarily used to modify the base material properties to get desired flowability and rheological characteristics of the media. Hydrocarbon gels are often used lubricants in the media. All additives are carefully mixed in predetermined quantities to acquire consistent formulations.

Some purposes of the media in AFM are,

a) to transport the abrasive grains through the product being deburred or finished, in order to allow the abrasive particles to remove the upraised material/metal and to round the corners as it passes.

b) to hold the abrasive particles in suspension because of it, they will be pressed firmly against the surface of the product when the medium passes through the openings, so that the abrasive effect is at a maximum, and uniformly distributed over the surface treated

c) to provide a comparatively firm backing for the abrasive, when the medium is under pressure, in order to enhance the abrasive's cutting action against the surface being deburred, while still being plastic enough to flow through the product so as to reach all required surfaces.

1.9.3 AFM Fixture

The primary function of a fixture is to carry the workpiece in correct position between two opposite cylinders and direct the media by restricting it to the areas to be worked throughout the process cycle. When necessary, the fixture can shield edges or surfaces from abrasion by acting as a mechanical mask. The main material used for fixture manufacturing is steel, urethane, teflon, and nylon. The fixture design may be simple or very complicated depending upon the workpiece configuration.

1.10 Classification of AFM

AFM process can be principally classified into two classes as shown in figure 1.7.

- One Way AFM
- Two Way AFM

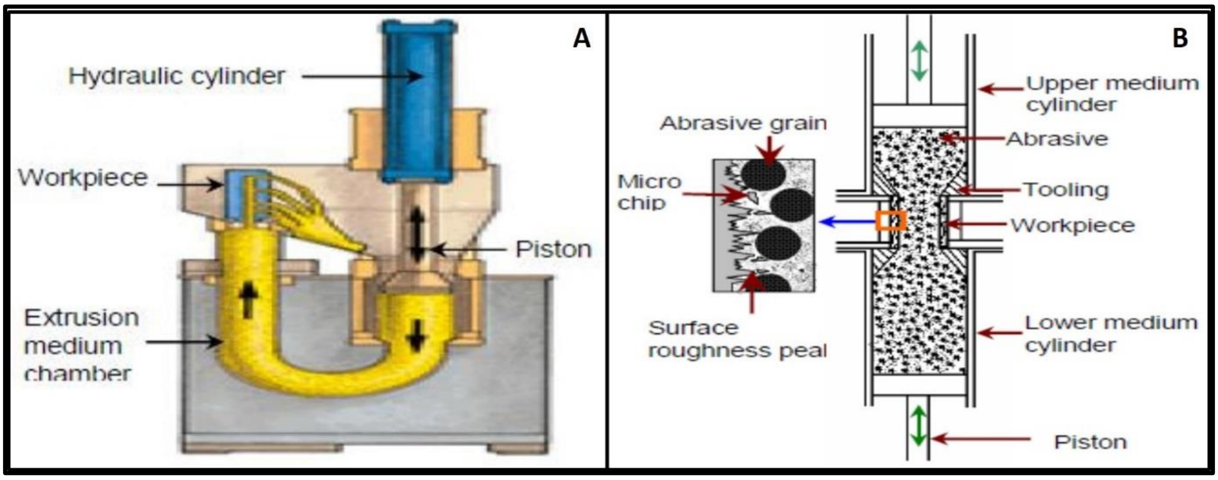


Figure 1.7: Schematic diagram for (a) one-way AFM, and (b) two-way AFM

1.10.1 One-way AFM

One-way AFM [6] process apparatus consist of a hydraulically moved reciprocating piston and an extrusion media cavity to receive the media, and extrude the media in uni-directionally across the internal surfaces of a workpiece having the internal passages formed therein. Fixture directs the extrusion media from the extrusion media chamber to the internal passageways of the workpiece while the media collector collects the media which is extruded out from the internal passageways of the workpiece. The hydraulically actuated piston often withdraws from its extrusion position to access the media chamber port to collect the medium in the extrusion media chamber. When the extrusion chamber is charged with media, the operation is resumed.

1.10.2 Two-way AFM

Two-way AFM [7] machine has two media cylinders and two hydraulic cylinders. Media is extruded in between the filled media chamber to empty media chamber, mechanically or hydraulically. The media passed through the controlled passages or the workpiece surface to be abraded. The media is extruded to and fro between the media chamber for the required number of cycles. Recessed areas of the workpiece, counter bores and even blind holes can also be finished by using mandrels or restrictors to direct the media flow along the surfaces to be finished.

1.11 Mechanism of material removal in AFM

The mechanism of material removal in AFM is shown in figure 1.8 and discussed later on.

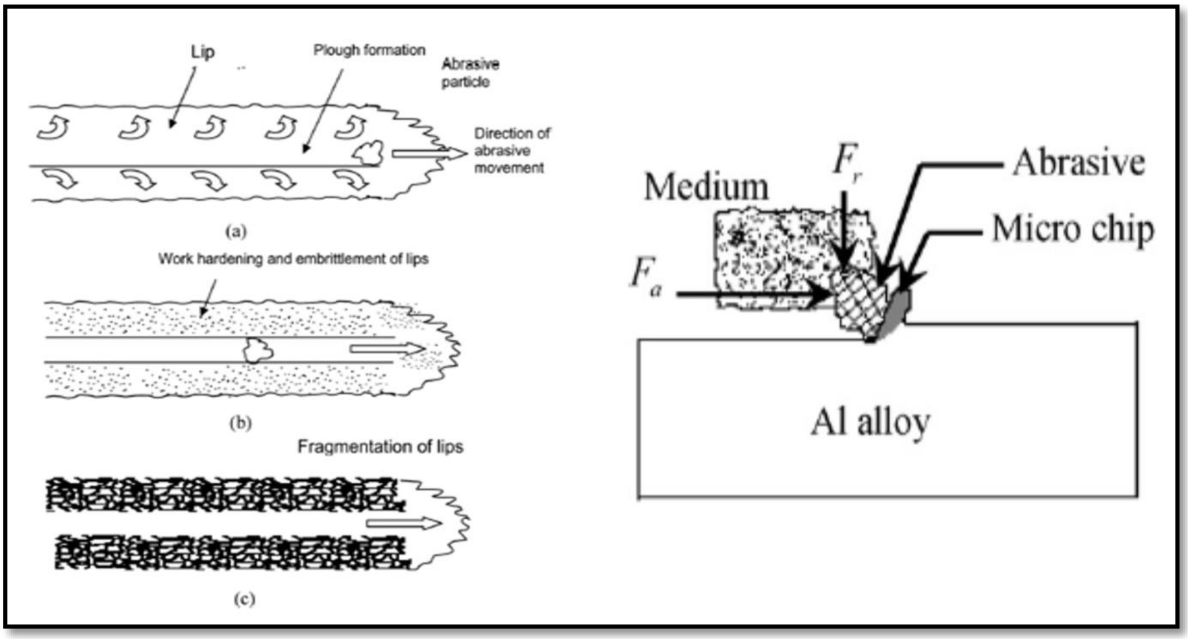


Figure 1.8: Schematic representation of mechanism of machining in AFM [23, 38]

(1) At the beginning, the material is ploughed by the fine abrasives that come in contact with the workpiece surface as they rub the workpiece surface with high pressure. The metal / material flow occurs in the direction of the abrasive flow, as well as in lateral direction, resulting in the formation of lips.

(2) At the lips, the work hardening of material is observed because of a continuous flow of abrasives particles through it. Flowing abrasive particles are responsible for the enormous plastic flow with considerable stress concentration.

(3) The further flow of abrasive particles through workpiece surface causes continued work hardening which results in the embrittlement and fragmentation of the lips into the microchips.

1.12 AFM Process Parameters

The AFM input process parameters are classified as given below:

(1) Parameters controllable by the machine: Extrusion pressure, Number of process cycles, media flow volume, and media flow speed

(2) Parameters controllable by the media: abrasive type (silicon carbide, aluminium oxide, boron carbide, diamond etc.), abrasive grain size, shape and concentration, media viscosity, media rheology.

(3) Parameters controllable by the tooling and workpiece configuration: type of passage (cylindrical, rectangular or complex), the length of the passage, cross-sectional area, initial surface roughness.

The fishbone diagram for AFM input process parameters is shown in figure 1.9.

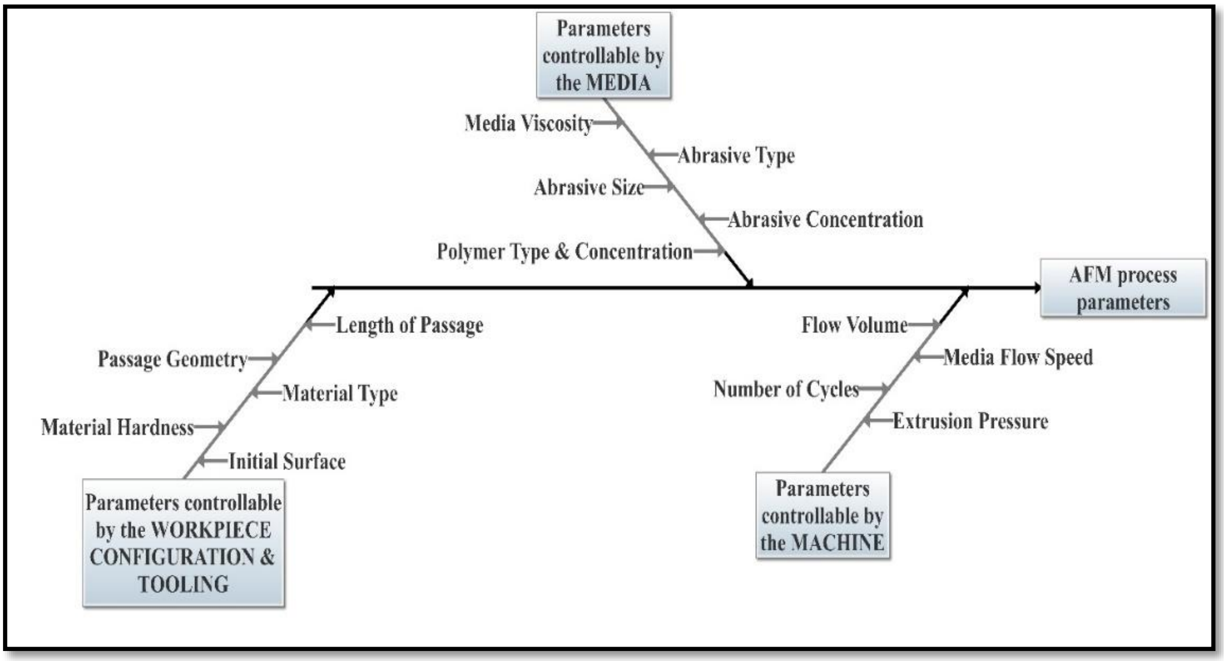


Figure 1.9: Fishbone diagram for AFM input process parameters [8]

The output process parameters taken by various researchers is enlisted below,

(1) Surface Roughness/ Finish

(2) Amount of Material Removal

The researcher claimed some relation in between the input and output parameters, which are discussed below;

- **Extrusion Pressure**

Extrusion pressure strongly affects the force acting on abrasive grains and therefore considerably affects the surface roughness of the machined part.

- **Number of Cycles**

The travel of media from lower media cylinder to the upper media cylinder and then back to lower media cylinder is known as a cycle. Several cycles are required to obtain a particular amount of material removal and final finishing of the workpiece. The various researcher has delineated that the amount of material removal and improvement in surface finish occurs in some of the initial cycles and then it stabilizes.

- **Media Flow Volume**

These are the dominant process parameters controlling the amount of abrasion by the specific media composition. With all other factors constant, the greater the volume of media flow will cause more abrasion. If the two passages of different cross-sectional areas are provided with the same volume of flow, the smaller passage will, therefore, be abraded more than the larger passage.

- **Media Flow Rate**

The literature on AFM strongly recommends that with an increase in flow rate there was an increase in material removal, but that affects not considerably.

- **Media Viscosity**

Media viscosity is the significant parameter affection the quality of surface finish and amount of material removal in AFM process.

Passage Size (mm)	**Media Viscosity**				
	Low	**Low to Medium**	**Medium**	**Medium to High**	**High**
Minimum	0.4 mm	0.8 mm	1.6 mm	3.2 mm	6.4 mm
Maximum	3.2 mm	6.4 mm	12.8 mm	25.4 mm	50.8 mm

Table 1.2: General guidelines to choose viscosity of media for varied passageways

Media viscosity is affected by the type of abrasives, size of grains and its concentration. It is also highly affected by the operating temperatures. In general, an increase in temperature causes an appreciable decrease in media viscosity, which may lead to settling of grains thereby influencing the flow properties and overall abrasion process. The table 1.2 gives general guidelines to choose viscosity of media for varied passageways with 2:1 length to width ratio.

- **Abrasive Grain Size**

Abrasive grain sizes range used in AFM varies from #220 mesh (tiny hole applications) to #60 mesh (roughing and stock removal applications). Larger abrasives grains cut faster while smaller size abrasive gives a better finish and can reach into complex and narrow passages.

- **Abrasive Concentration**

The higher the concentration of the abrasive in the media, higher will be the material removal rate and hence the more quality surface finish is achieved. After the increase in the concentration of abrasive in the media more than 70% - 80%, there was no remarkable improvement in material removal is observed because of more hindrance by abrasive to the other abrasives and hence it gives no improvement in active grain density.

- **Process Capabilities**

The surface finish improvement by AFM process is l0 times than that of the original surface finish provided the surface finish is in the range of 28-280 µm. Holes diameter must be at least 0.2 mm and dimensional tolerances achievable must be up to ±0.005 mm.

1.13 AFM Advantages

- Inaccessible areas which are not finished with other conventional process are easily finished with AFM process
- The finishing rate with AFM is much faster than the manual methods of finishing like grinding, honing etc.
- In AFM, polishing and deburring operation can be combined in one stage.
- With AFM, the higher surface finish with tight tolerances is possible.

1.14 AFM Disadvantages

- AFM is a costly process as it requires high capital investment because hydraulic system is expensive.
- The cost of abrasive media is very high and is unusable after some processes.
- The work holding fixture is at times expensive because as soon as design or size or shape of the workpiece is changed, the fixture has to be changed.
- Processing of blind holes with AFM process is difficult because there was no relative movement of the abrasive with the workpiece surface, and hence, no abrading action is taking place.

1.15 AFM Application

The process was at first developed for effective de-burring of hydraulic control blocks. Later on, the field of applications got rapidly distributed into defence, medical and manufacturing units. The inaccessible areas in components that are very tough to finish with traditional processes can be easily finish machined by AFM method. The typical applications of AFM are in improving aerofoil surfaces of compressor and turbine parts, edge finishing of holes and attachment features, improvement in fatigue strength of disks, blades, hubs and shafts with uniform polishing on its edges. The adjustment of air flow resistance in vanes, blades, combustion liners, nozzles, and diffusers, finishing of fuel spray nozzles, fuel control bodies, bearing components, reworking the parts to remove coke and carbon deposits and to enhance its surface integrity.

1.16 Dissertation Organization

Chapter 1: It represents the necessities of finishing in the precision machining and detail description of abrasive flow machining process used to finish in the internal complex surfaces.

Chapter 2: It contains the literature study on the effect of process parameters on the process responses and then after some recent developments in AFM has been discussed. Finally, the literature gap and analysis has been devised based on the gaps identified from the past work. This chapter extends the problem formulation, the aims of the present study and design of the present methodology.

Chapter 3: This chapter contains the design and fabrication of the fixture setup for accomplishing the simultaneous finishing, workpiece properties, input and output parameters. The experiments planned according to the design of experiments are discussed in this chapter.

Chapter 4: This chapter includes brainstorming discussion on the effect of input variables on the change in surface roughness, percentage improvement in surface finish and amount of material removal. Workpiece surface characterization by surface roughness tester and Leica μ-scope are discussed in this chapter.

Chapter 5: Conclusions are explained along the groundwork of the present work in this chapter. Further, future scope in the field of simultaneous finishing of the workpiece, specifically, deep groove ball bearing is also suggested in this chapter.

Chapter II – LITERATURE REVIEW

Experimental investigations have been disbursed by various investigators to analyse the consequences of process parameters like a number of cycles, extrusion pressure, viscosity, abrasive concentration and grain size on the output responses namely, surface finish and material removal during AFM.

Rhoades studied the basic principle of AFM and delineate that the depth of cut primarily depends on extrusion pressure, abrasive grain size, relative hardness, and sharpness [3-5]. The axial forces in AFM are highly subjected to the behaviour of the AFM medium. The flow pattern of the abrasive medium depends on the characteristics of the applied medium, machining parameters, as well as the shape of the workpiece and the tooling [5].

Loveless et al. (1994) discussed the effects of AFM on surfaces created by turning, milling, grinding, and wire electrical discharge machining. They stated that the best improvement in the surface quality was obtained on the WEDMed surfaces. The results show that the type of machining method affected both metal removal and surface finish results and medium viscosity considerably affected only surface improvement while extrusion pressure did not have a major effect in this [9].

Jain et al. (1999) generated an estimation of material removal and surface roughness acquire during AFM, and found that increasing a piston speed, change in fraction concentration of grain, and increase in extrusion pressure would decrease the surface roughness value and increase material removal. While more than a certain value of speed and pressure, it would worsen the surface quality because of increase in depth of indentation of the abrasives, and the minimum surface value is equal to the critical surface roughness [10].

Jain and Jain (2000) used a neural network for modelling and optimum selection of input parameters of AFM process. Authors took input parameters as v is the media flow speed (cm/min), c the percentage concentration of abrasive, d the abrasive mesh size, and n the number of cycles. They took output parameter as Material Removal Rate & Surface Roughness [11]. By use of neural network author's derived equation for Material Removal Rate, Surface Roughness,

$$\mathrm{MRR} = 5.285*10^{-7}*v^{1.6949}*c^{3.0776}*d^{-0.9371}*n^{-0.1893}$$

$$\mathrm{Ra} = 282751.0*v^{-1.8221}*c^{-1.3222}*d^{0.1368}*n^{-0.2258}$$

Authors found that optimum condition for maximum Material removal & minimum surface roughness for Al material was media flow speed = 85cm/min, percentage concentration of abrasive by wt. = 44%, abrasive mesh size = 101.

Jain and Adsul (2000) studied the AFM method parameters, such as four types of mesh sizes and concentrations, the number of process cycles, different media flow speeds on aluminium and brass, simulating soft and hard materials, respectively. They concluded that leading parameters are the mesh size, abrasive concentration, and a number of process cycles. The effect of flow rate is less as compared to the other AFM process parameters [12].

Alitavoli and Mehran (2005) use input parameter as media flow speed, percentage concentration of abrasive, abrasive mesh size, the number of cycles & output parameters as material removal rate, surface roughness. Authors concluded that with an increase in media flow speed, abrasive mesh size, abrasive concentration & no. of cycles; the Material removal increase. The author also concludes that Material removal in aluminum is greater than brass for same input condition [13].

Jain and Jain (2004) use the stochastic simulation to measure the active grain density in AFM. Active grain density increases with an increase in abrasive concentration and active grain density are higher for a smaller grain diameter for a specific concentration. [14].

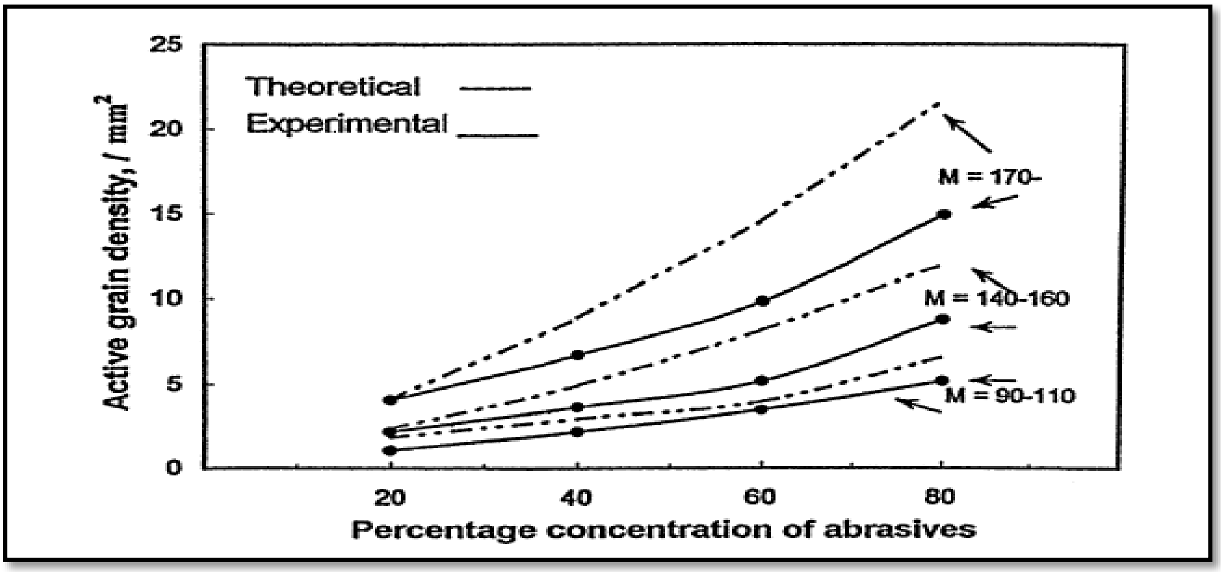


Figure 2.1: Variation of active grain density with percentage concentration and mesh size [14]

Marochkin (1959) suggested three different regimes of grain workpiece interfaces namely, chip regime, the plastic regime, and elastic regime [15].

Gorana et al. (2004) studied the axial and radial forces during AFM using a two component disc dynamometer. It was examined that extrusion pressure, the concentration of abrasive grains and abrasive particle sizes affect the cutting force, active grain density and hence a reduction in surface roughness value. The author found that applied extrusion pressure has the strongest effect on the measured axial force. The concentration of abrasive grains and active grain density have only minor effect in their experiments. The author concluded that the reduction in the surface roughness of workpiece is linearly proportional to the force ratio (Fr/Fa). Scanning Electron Microscopy (SEM) shows that ploughing and rubbing are the possible mechanisms for the material removal [16].

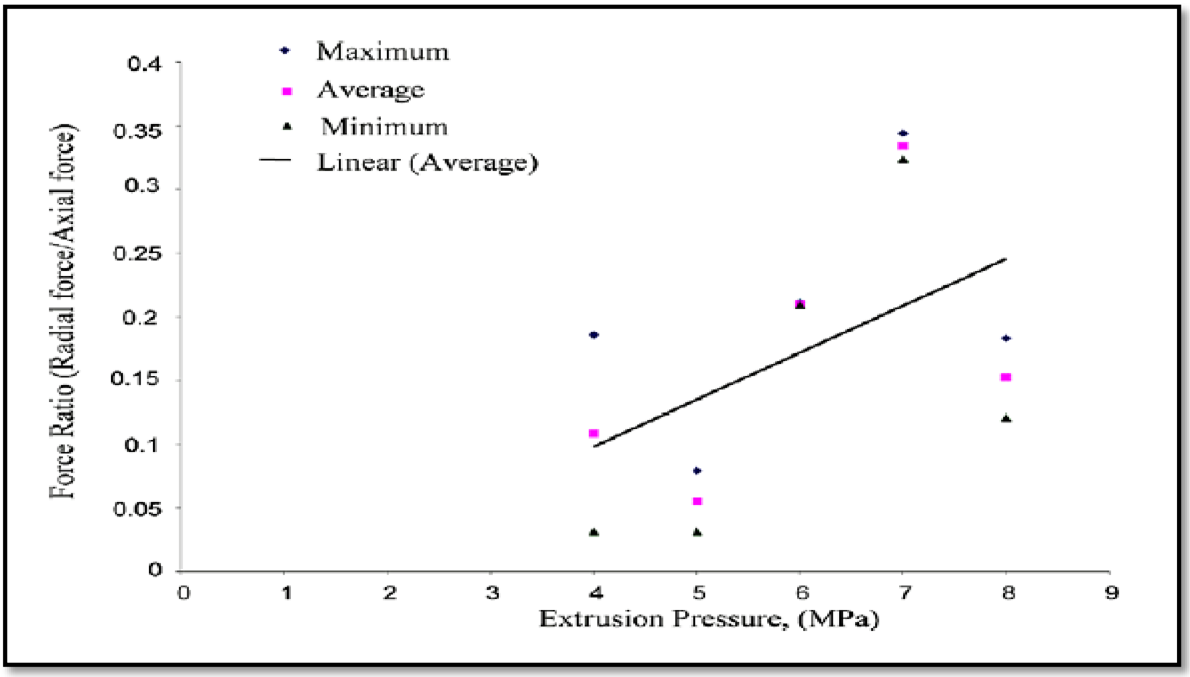


Figure 2.2: Variation of force ratio with extrusion pressure [16]

In another paper, **Gorana et al.** (2006) studied the modes of work material distortion under the realistic condition of grain-workpiece interface. The AFM results show that axial force, radial force, active grain density and depth of indentation, all have a considerable effect on the material deformation. The result suggested that care should be taken while evaluating and interpreting the force acting on the single grain, followed by the grain depth of indentation which is used for estimating the mode of material removal. The two established grain-workpiece interaction parameters, namely, the minimum load required for chip formation and the minimum depth of indentation, were found to correlate well with the mode of material deformation. The experimental and theoretical results manifest that rubbing the mode of material deformation is dominated in the study while some evidence of the ploughing is also present. They conducted the scratching experiment to acquire basic knowledge of the action of abrasive grain on the material surface during the AFM process [17].

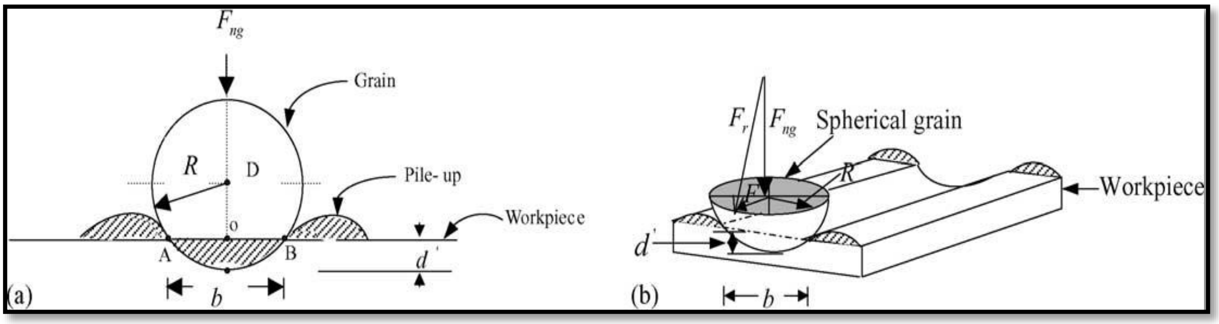


Figure 2.3: (a) Indentation of a grain into the workpiece with side pile-up and (b) Hemisphere normal to the direction of motion [17]

Fang et al. (2007) deliberate the abrasive particle movement pattern as an important factor in approximating the wear rate of materials, especially, as it is closely associated with the burring, buffing and polishing efficiency of the abrasive flow machining (AFM) method. There are usually two types of particle movement patterns in the AFM method, i.e. sliding–rubbing and rolling [18].

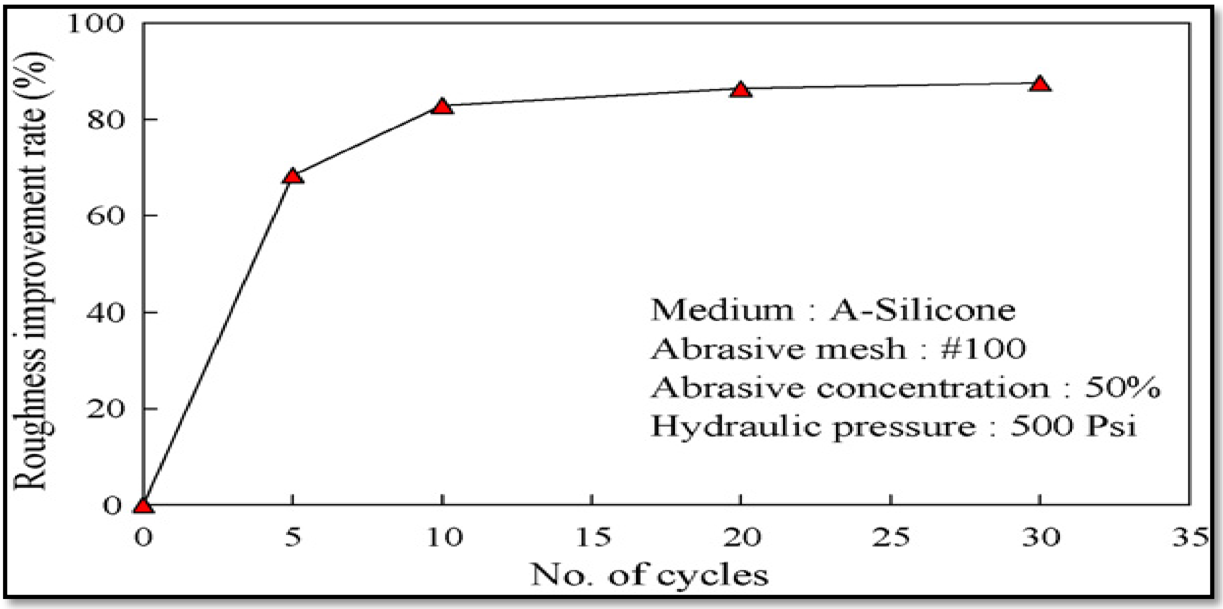


Figure 2.4: Effect of no. of cycles on the roughness improvement rate [19]

Wang et al. (2007) discussed the efficiency of abrasive gel in material removal & effect of it on the surface roughness. They proposed that the silicone rubber (or vinyl silicone polymer) as the best material for media because of its cost effectiveness. They also concluded that 80% of surface improvement occurs within the 5th number of cycle. Small abrasives produce a smoother surface than large sized abrasives [19].

Song et al. (2008) examine the temperature dependence and its effect on surface roughness. Experimental results show that the media at high temperature leads to less improvement in surface roughness. The author concluded that media will have good machining performance in the initial few cycles then media temperature rise quickly. They conclude that the best workable temperature should be below 25 °C throughout the AFM [20].

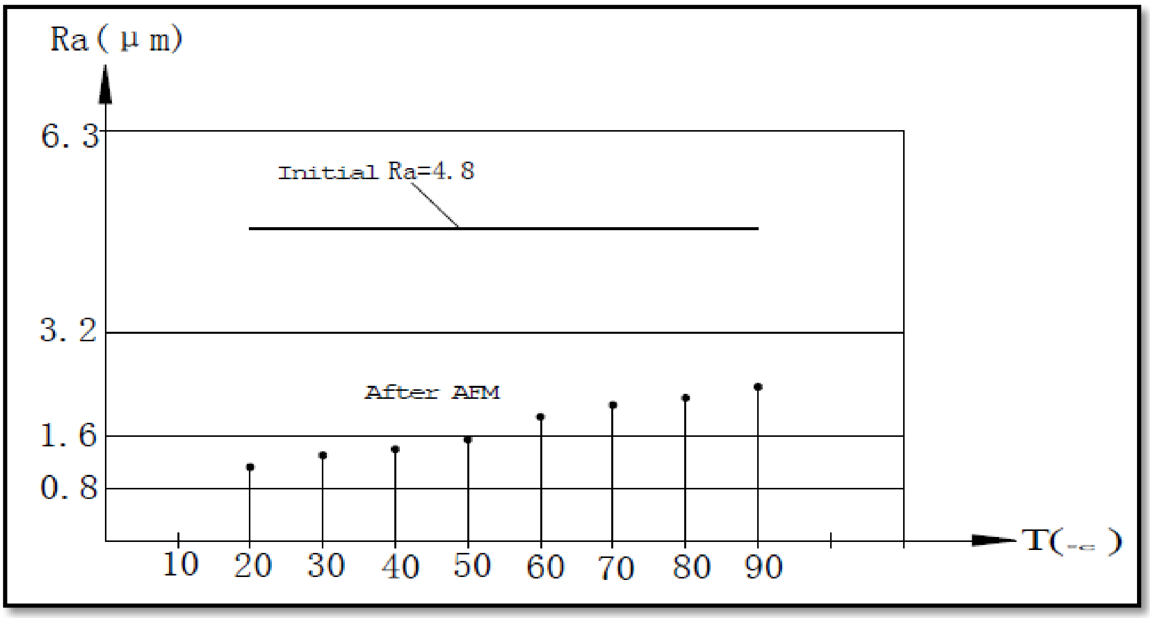


Figure 2.5: Effect of temperature on surface roughness [20]

Fang et al. (2009) studied on the work efficiency of AFM primarily based on the media temperature. They state that media viscosity decreases incessantly with increasing temperature. Media temperature increases with increasing cycles, which means that media viscosity decreases with cycles increasing. Work efficiency directly proportional to the media viscosity, with a decrease in viscosity of media rolling tendency of abrasive particle, is an increase, which causes a decrease in work efficiency [21].

Kar et al. (2009) developed new substitute media for the AFM process from the different viscoelastic base materials (butyl rubber and natural rubber), silicon carbide abrasives and naphthenic oil. The performance of media is evaluated by AFM apparatus. The butyl rubber based media shows good performance as compared to natural rubber based media. As the abrasive concentration increases, the improvement in surface roughness is increased. But at the high percentage (above 78%) of abrasive, the flow becomes difficult as well as carrier acts as an insufficient binder to hold the abrasives. It contains abrasives of mesh size 220 was good as compared to the media with 800 and 1200 mesh sized abrasives [22].

Sankar et al. (2009) initially works with aluminium alloys and two types of Al alloy/SiC MMCs (10% and 15% volume fractions of SiC) and then fine finished with AFF process. New styrene butadiene rubber (SBR) media was developed and used in the AFF process during the finishing of the all three types of workpiece materials. They concluded that as soon as the extrusion pressure is increased up to 6MPa, the surface finish increases then on further increases, surface finish decreases slightly. Surface finishing increases gradually as a weight percentage of naphthenic oil increases up to 10% and then starts decreasing. The number of cycles to achieve required surface finish is also increased as soon as the hardness of the workpiece material is increased [23].

Singh et al. (2011) investigate the effect of finishing process on Al-SiC MMCs by AFM process. They takes MMC's composition as 0%, 5%, 10%, 15% wt. of SiC in Al. The author takes input parameter for investigation as extrusion pressure, a number of cycles, abrasive mesh size, and abrasive concentration and AFM media viscosity grade. And output parameter as average surface finish improvement, ΔRa& material removal, MR. The author concluded that percentage of improvement in surface finish is high on Al/15%SiCp-MMC specimen & Low media viscosity grade generates better improvement in surface finish [24].

Williams and Rajurkar (1989) found that the metal removal rate of the middle hole was 30% more than that inside holes. When they performed experiments of extrusion abrasive flow for producing the parts of four side holes and a centre hole [25].

Siddiqui et al. (2010) consider vent for media outflow in work-piece surface considerably affects the output parameters, material removal, and surface roughness value in AFM. A workpiece having a single vent for the media outflow have higher material removal rate than the workpiece surface have multiple vents for media outflows. A workpiece having single passage/vent have higher material removal rate and more enhancement in the change in surface roughness value in abrasive flow machining. The performance measures are decreases with increase in a number of vents/passages through the workpiece. The change in surface roughness increases with increase in the length of the passage and decreases with increase in the cross-sectional area of the passages. It is also observed that the pressure decreases with increase in the length of media flow travel [26].

Walia et al. (2009) reported that enhancement in performance could be achieved by improved fixturing. [27].

Brar et al. (2011) concluded that smaller size abrasive gives better surface finish and can reach into complex and narrow passages while larger one cut faster. The reason for a decrease in material removal is that with an increase in mesh size, the depth of penetration, as well as the width of penetration, decreases [28].

Bahre et al. (2012) performed parameter study on one-way AFM regarding the effect of the piston pressure on the surface finish. Two machining strategies with a combination of roughing and finishing are compared to the machining with high and low pressure in this study [29].

2.2 RECENT DEVELOPMENTS IN AFM

Though there are many benefits of AFM process, it has some disadvantages also, such as low productivity. The time to achieve the desired surface finish is longer in AFM process as compared to alternative finishing processes. With a hybrid approach to AFM, many researchers are tried to overcome this difficulty and they reported improvement in process efficiency of AFM with it.

2.2.1 Orbital AFM

Orbital AFM [30] combines orbital grinding and abrasive flow machining. An extra mechanical motion is given to the medium to enable it to finish three-dimensional forms that are not attainable with conventional AFM. The motion is typically a planetary oscillation that makes relative displacement between tooling and the workpiece.

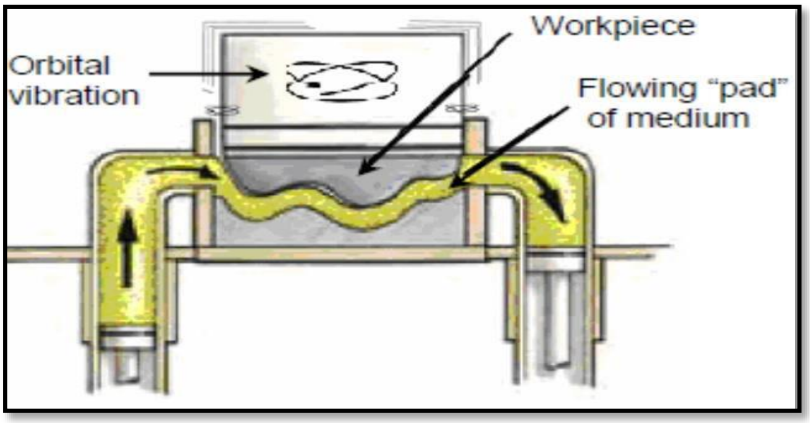


Figure 2.6: Schematic diagram of orbital AFM [30]

The oscillations can be in the horizontal or vertical or combination of both the planes, yielding an elliptical or gyratory polishing action. Orbital polishing is made employed in polishing the edges and surfaces in complicated shapes and cavities like bottle molds, coining dies and aluminum wheels along with high precision and accuracy.

2.2.2 Magnetorheological AFM

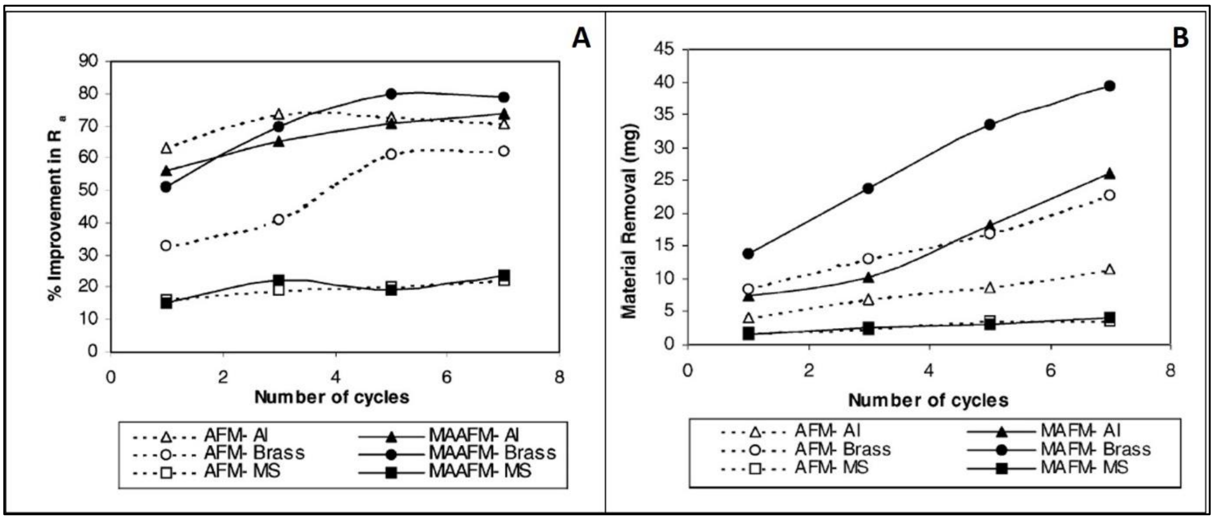


Figure 2.7: Effect of magnetic field on

a) Percentage improvement in Ra& b) Material Removal MR of various materials [31]

Singh and Shan (2002) applied magnetic field around the workpiece in AFM and observed that magnetic field significantly affects the material removal and change in surface roughness [31].

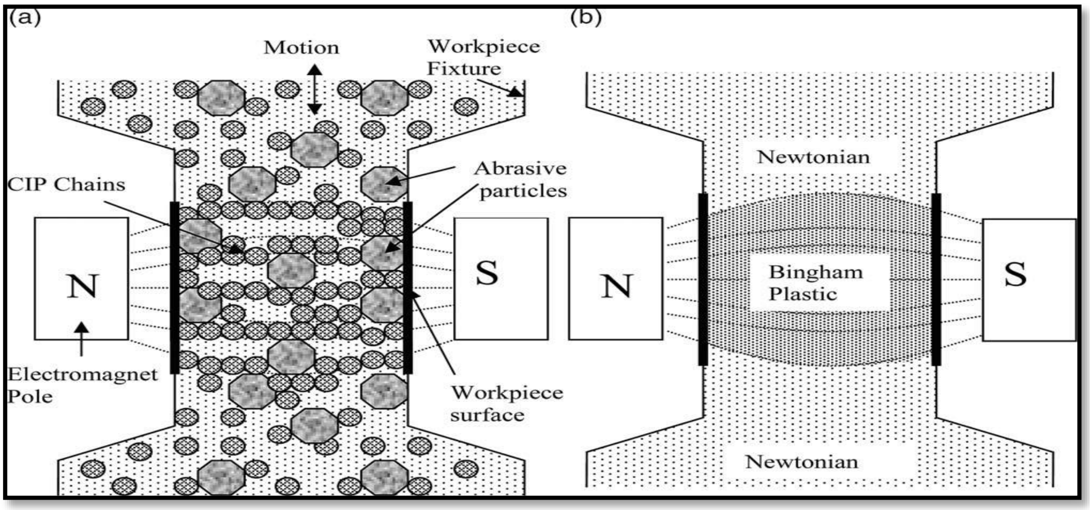


Figure 2.8: Magnetorheological abrasive flow machining process:
a) Mechanism of Magnetorheological abrasive flow machining process
b) Change in rheological behaviour of MR polishing fluid during finishing [32]

Jha and Jain (2004) also applies a magnetic field to flowing media in AFM process for further study. Media for MRAFF process contains Abrasives and carrier medium with Carbonyl Iron Particles. Because of the effect of magnetic field on the CIPs, the modification of the distribution pattern of abrasive particles occurs, hence number of abrasive particles could take part in the abrasion process is increases [32].

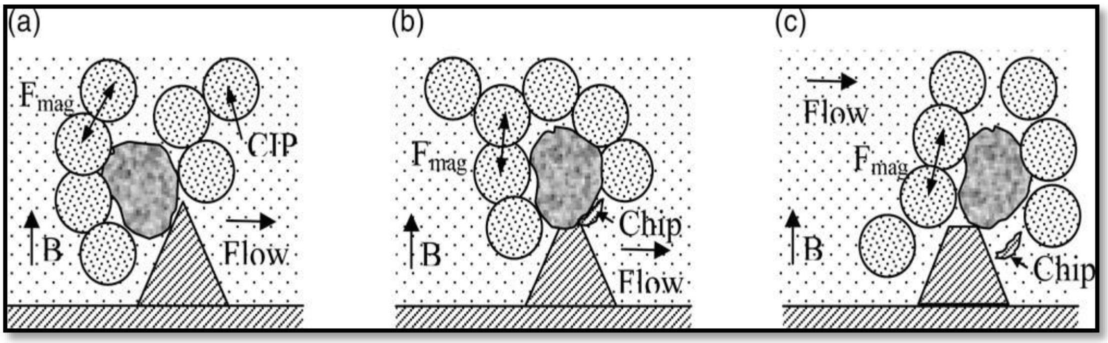


Figure 2.9: Finishing action on a single profile in presence of external magnetic field [32]

They claimed that 20-30% enhancement in the material removal rate.

2.2.3 Centrifugal force assisted AFM

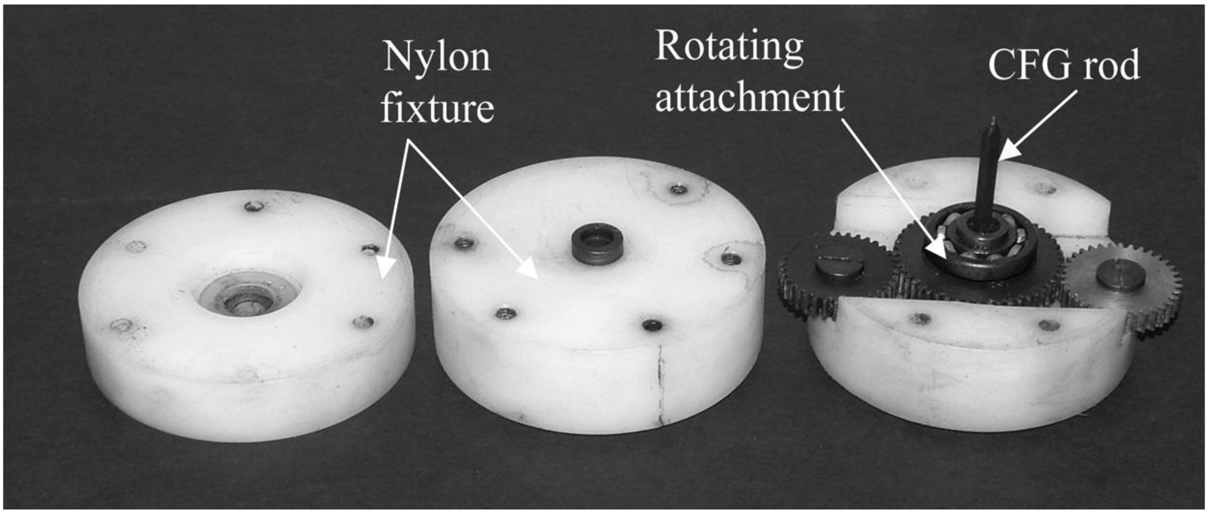
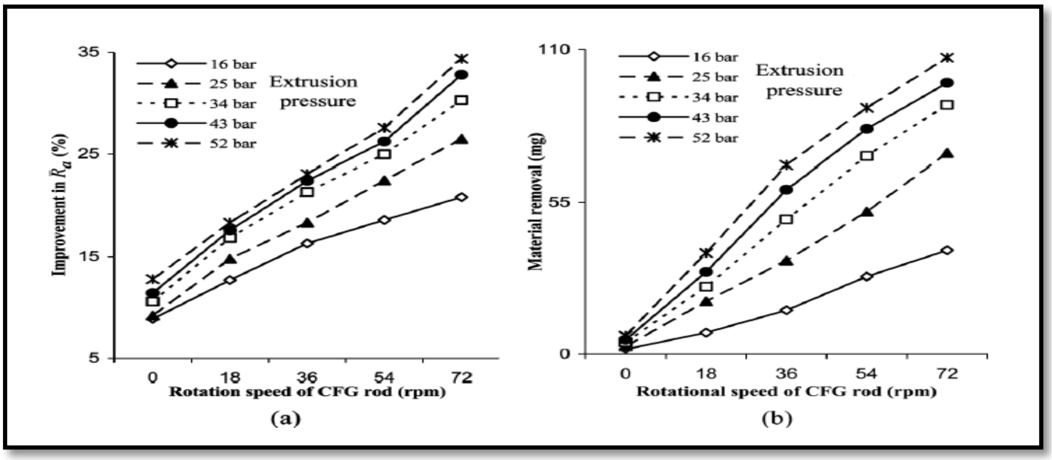


Figure 2.10: Fixture used for CFAAFM process experiment [33]

Walia et al. (2006) explored centrifugal force assisted abrasive flow machining (CFAAFM) process as a hybrid machining process with the aim of the performance improvement in AFM process by applying centrifugal force to the abrasive media with a rotating centrifugal force generating (CFG) rod introduced into the workpiece passage. CFG rod is made of the shape triangular, spline, square and rectangle. Out of this four type of CFG rod, rectangle shaped rod gives maximum material removal and better surface finish than other processes [33].

CFAFM holds good only for low viscous media only because in high viscous media, CFG rod isn't able to generate that much centrifugal force to throw the abrasive on the side wall of the workpiece and abraded action will taking place.

With CFAAFM, reduction in machining time by 70% - 80% is observed.



(a) (b)

Figure 2.11: Effect of CFG rod rotational speed and extrusion pressure on a) improvement in Ra, and material removal (mg) [33]

2.2.4 Rotational AFM

Sankar et al. (2000) developed a new set-up to rotate the workpiece so that the probability of active abrasive particles in the workpiece finishing region is high which improves both surfaces finishing rate and material removal rate [34].

Workpiece fixture is rotated externally by variable frequency drive, because of rotation of workpiece active abrasive grains moves in a helical path instead of the short straight path. Because of the helical path, more workpiece surface comes into contact with abrasives and hence more abraded action has been taking place.

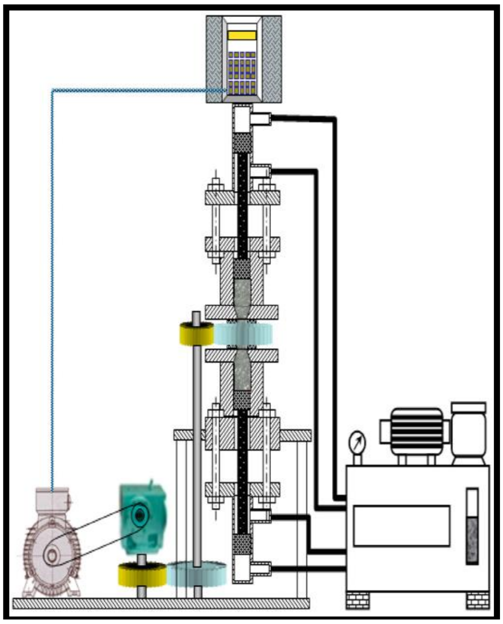


Figure 2.12: Schematic diagram of rotational AFM [34]

This study establishes that R-AFF can give 81.8% more MR and produce 44% better ΔRa compared to the AFF process.

2.2.5 Drill Bit Guided AFF

Sankar et al. (2009) tried to improve finishing rate, material removal, and surface texture by placing the freely rotatable drill bit in the media flow path at workpiece finishing region.

The inner part of the media flows along with the helical flutes of the drill bit, which creates random motion of the abrasives in the inner region of the media. This causes a reshuffling of abrasive particles to the outer region. Hence, comparatively more and fresh abrasive grains come in contact with the workpiece surface [35].

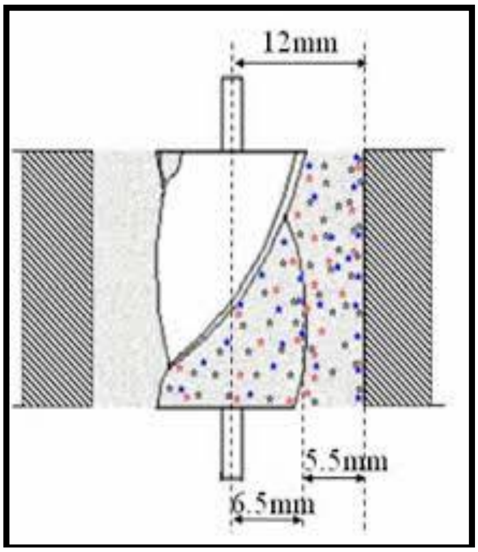


Figure 2.13: Schematic view of drill bit inside the workpiece finishing area of AFM [35]

From experimental results, it is found that the active abrasive takes a longer path in the DBG-AFM than the AFM in each cycle. It results in higher finishing rate in the former as compared to second. Material removal is found to decrease with a decrease in drill bit diameter.

2.2.6 AFM with movable/rotatable Mandrel

Kendra et al. (2014) suggest that the problem of non-uniform polished surface and non-uniform material removal can be solved by using a movable/rotatable mandrel. The innovative upgrade of AFM with the movable/rotatable mandrel (AFMmm) shows high potential in the improvement of their productivity. It provides higher polishing media speed at the site of polishing & therefore, higher process efficiency. It’s a sustainable polishing process [36].

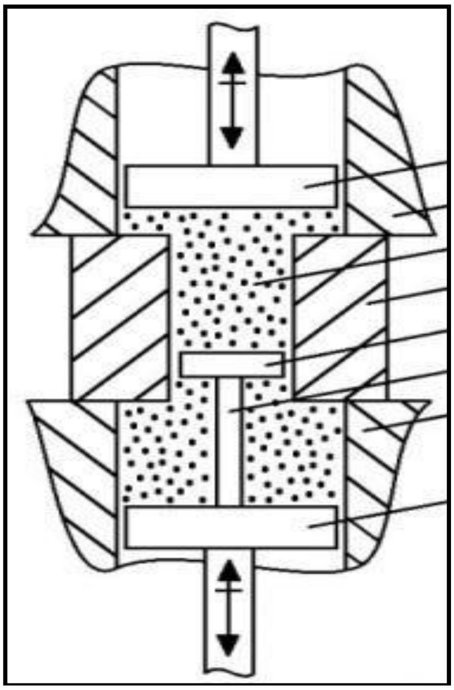


Figure 2.14: AFM with movable/ rotatable mandrel [36]

2.2.7 Ultrasonic Assisted Abrasive Flow Finishing (UAAFF)

Venkatesh et al. (2015) work on Ultrasonic Assisted Abrasive Flow Finishing to improve the surface roughness of bevel gear [37].

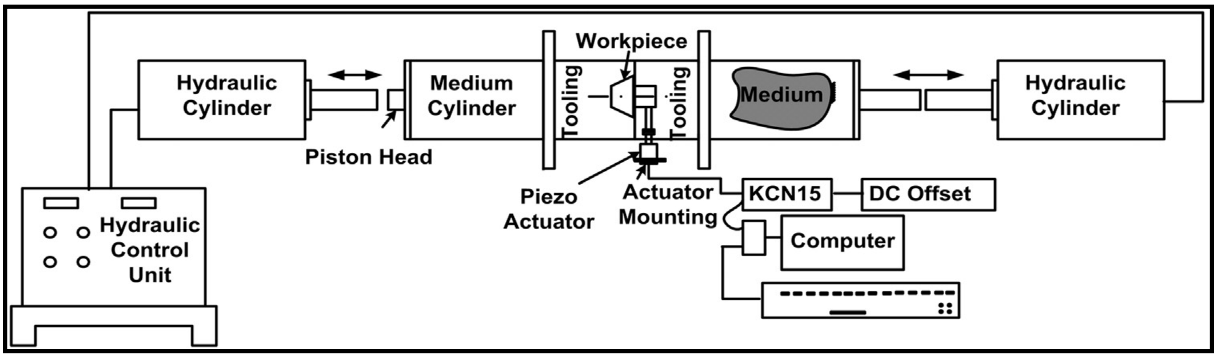


Figure 2.15: Schematic diagram of UAAFF setup [37]

In UAAFF, abrasive polymer mixture is pumped down the centre of the ultrasonically energized tool. The combination of media flows with vibration results in the effective abrasion of the workpiece surface. They take velocity, pressure and temperature as an input parameter to measure the surface finish and material removal of the bevel gear in AFM.

Blind holes can also be polished with Ultrasonic assisted AFM.UAAFF has the capacity to produce micro/nano level finish on closed cavity surfaces without generating much deterioration to its profile or dimensional accuracy. With this process blind hole can be also polished.

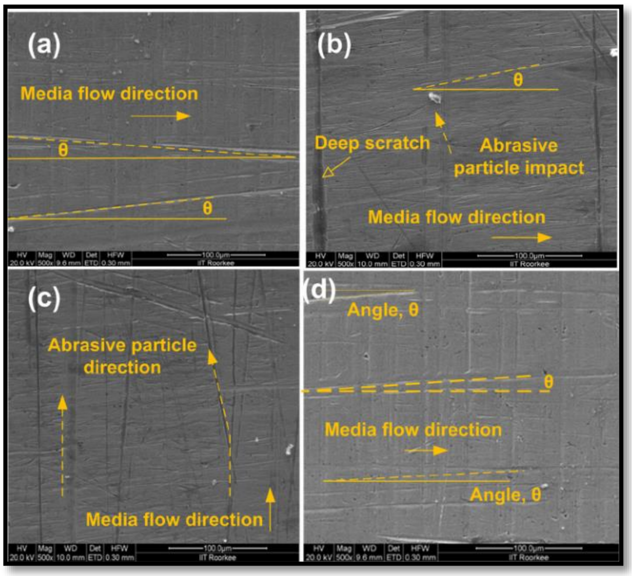


Figure 2.16: SEM images of bevel gear surface finished with UAAFF [37]

73% improvement rate will be seen with UAAFF while 55% rate of improvement for normal AFF for same time intervals. They concluded that ultrasonic assisted AFM can increase the velocity of abrasive; increase active grains hence improve in surface quality and MR rate.

2.3 Summary and Gaps of Literature Review

Any innovation related to process or product must be useful for the mankind and maximize quality without any compromise. From literature, it can be concluded that,

- Most of the work done by the researcher to obtain surface finish by abrasive flow machining is either related to internal finishing or external finishing of the workpiece.
- No attempts have been made for simultaneous finishing i.e. internal as well as external finishing of the workpiece with Abrasive Flow Machining.
- Most of the work done on the soft materials.
- More detailed experimental data is needed to study the effect of various process parameters on process performance at various locations.

2.4 Problem Formulation

Abrasive flow machining can be a high potential candidate in the simultaneous finishing of the workpiece, instead of finishing internal as well as external surfaces separately with conventional finishing processes.

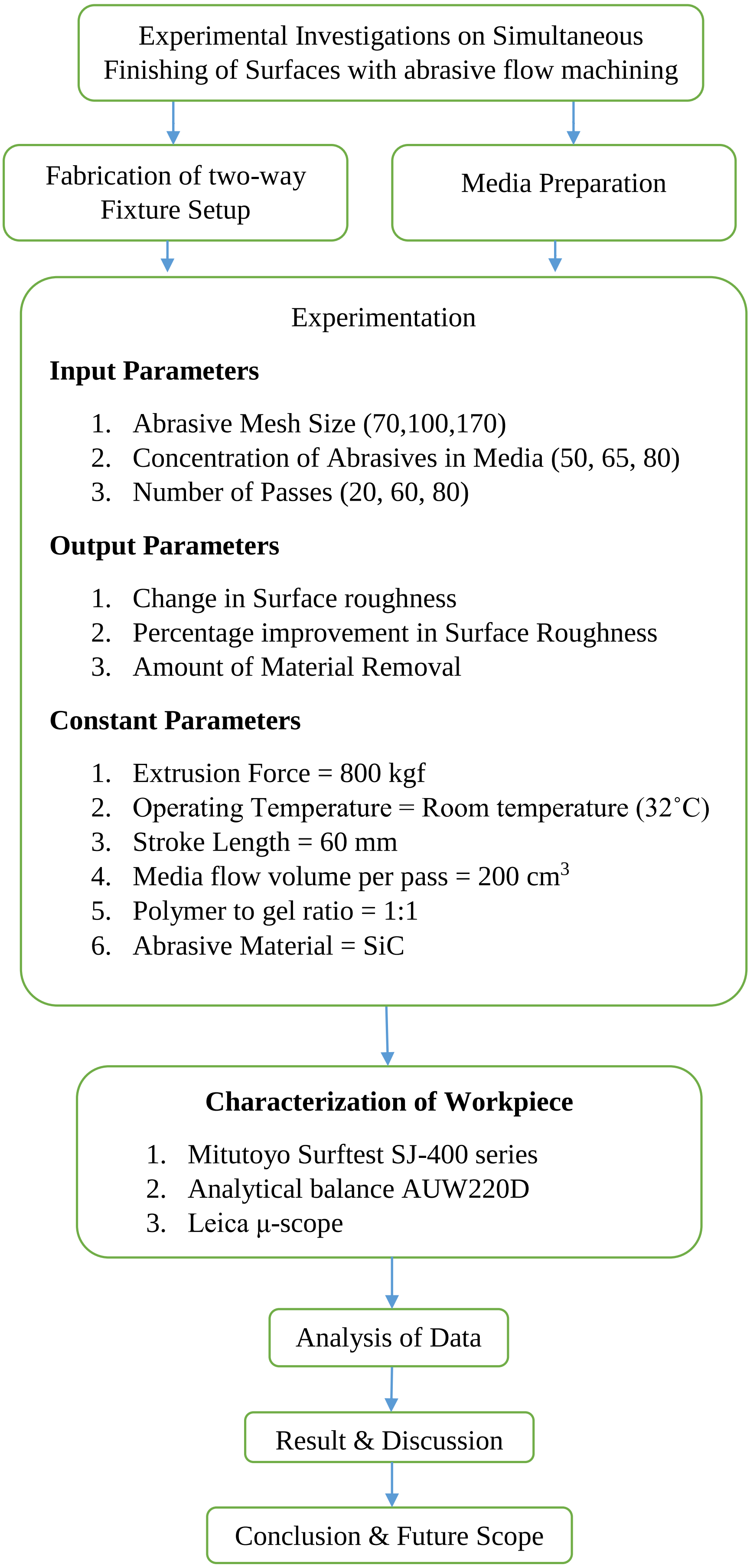
Therefore, an attempt have been made to investigate the surface topography of the ring-shaped workpiece finished simultaneously viz. internal as well external surface with the help of abrasive flow machining.

2.5 Objectives of Study

The main objectives of this study are,

- To fabricate an AFM fixture setup for simultaneous finishing of the workpiece.
- To fabricate the abrasive media.
- To investigate and analyse the influence of the various process parameters on performance characteristics of the AFM and process optimization.
- To characterize the surface achieved using different characterization techniques such as Surftest SJ-400 series, Leica μ-scope etc.

2.6 **Research Methodology:**



Chapter III - EXPERIMENTATION

Abrasive flow machining is a potential candidate in the finishing and/or deburring of the ring-shaped cylindrical workpiece. The experiments are carried out with the help of the fixture setup and conventional UTM. The abrasive media is prepared for this experimentation work. The change in surface roughness value and amount of material removed are measured to check the process capabilities. The brief detail of fabrication and experimentation are explained in this chapter.

The abrasive flow fixture setup is designed and fabricated in the Thapar University, Patiala to perform this study. The concept of two-way AFM is used. The present study focussed on the simultaneous finishing of internal as well as the external surface of the workpiece.

The AFM setup consists of fixture setup, abrasive media, and the hydraulic system. Fixture setup contains the nylon fixture, abrasive media cylinder, and piston arrangement etc. The media consists of the carrier medium and the abrasives. The hydraulic system is used to provide motion to the piston of the media cylinder. The hydraulic system of the Universal Testing Machine is used in the study. The standard UTM used for hydraulic actuation. The combined system is shown in figure 3.1.

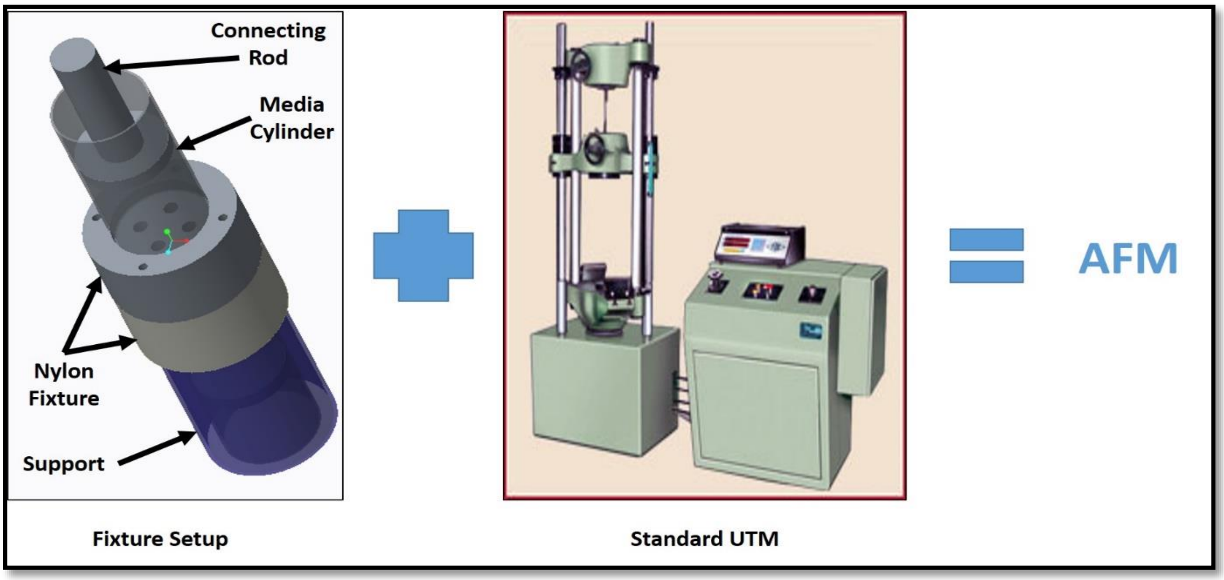


Figure 3.1: Abrasive flow machining setup overview

3.1 Selection of Workpiece:

The designing of a fixture is based on the workpiece shape. Hence, the material and shape of a workpiece are decided before designing the fixture. The detailed description of fixture fabrication is explained in section 3.2.

3.1.1 Selection of Workpiece Material:

With the previous literature, it can be drawn that AFM is best suitable for soft materials. Although, some attempts were made on certain hard materials. But in the present study, a soft material is chosen. The workpiece material chosen for this study is Aluminium alloy of grade 6061. This grade of the aluminium is chosen because of it is most commonly used in the household applications. Aluminium alloy 6061 is a precipitation-hardened aluminium alloy, containing the silicone (0.4% to 0.8% by weight) and magnesium (maximum 0.15% by weight) as its major alloying elements. It has good mechanical properties and reveals good weldability. It has a density of 2.70g/cm^3.

It is one of the most common aluminium alloys which is used in the general purpose uses, viz. aircraft fittings, couplings, camera lens mounts, marine fittings and hardware, hinge pins, electrical fittings and connectors, appliance fittings, decorative or misc. hardware, magneto parts, hydraulic pistons, brake pistons, bike frames, valves and valve parts, etc. In some of the applications such as valves, pistons etc. roughness plays a vital role.

3.1.2 Workpiece Design

The purpose of the study is to finish a workpiece internally as well as externally, with the same objective a ring-shaped cylindrical workpiece of Aluminium 6061 is machined for the present study as shown in figure 3.2.

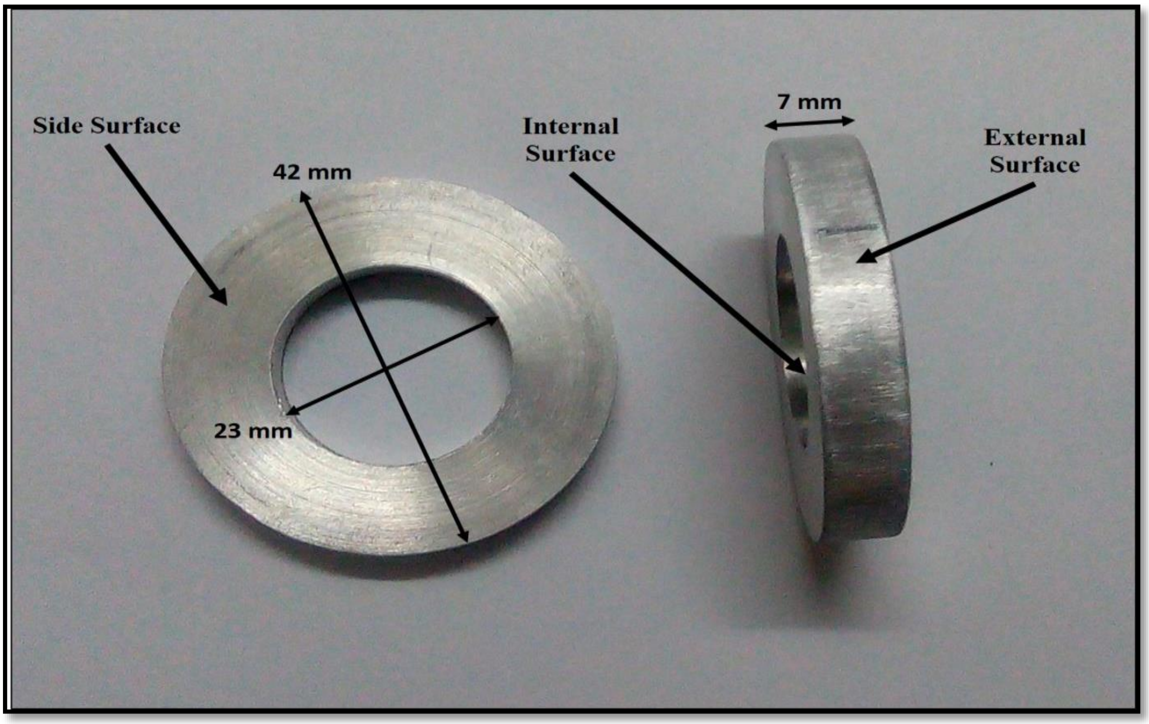


Figure 3.2: Dimension and shape of aluminium alloy workpiece

The present study is focussed on the finishing of surfaces at three locations as shown in figure 3.2.

1) Internal Surface
2) External Surface
3) Side Surface

The workpiece dimensions are described below,

a) Internal diameter (ID) = 23mm
b) Outer Diameter (OD) = 42mm
c) Thickness of Workpiece (T) = 7mm

The particular dimensions have been chosen for the workpiece to explore the facility of finishing of a standard bearing with the same dimensions.

3.2 Fabrication of AFM Fixture:

After selecting the workpiece material and design, the fixture is designed and fabricated according to the workpiece features.

3.2.1 Fixture Material Selection:

From literature review, it was found that there were mainly four types of materials used in fixture fabrication,

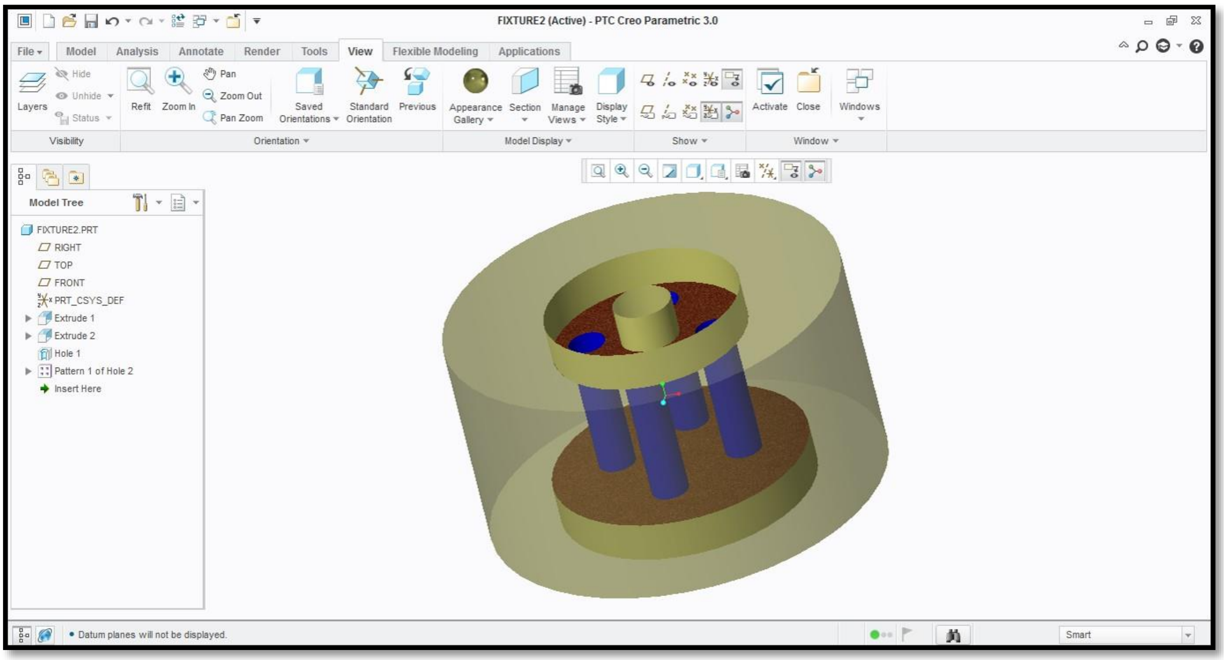
a) Steel (high production fixture but it was too costly),
b) Urethane (protects w/p from abrasive scratching or grooving but fails at high-temperature application),
c) Teflon (provides high strength but expensive),
d) Nylon (change dimension while absorbing water but inexpensive)

After evaluating the machining and financial constraints a nylon material was chosen for fixture fabrication. Nylon is a widely available material, easy to machine and comparatively cheaper than other materials. Therefore, after studying the behaviour of all the materials, nylon is chosen for the fixture material in this study.

3.2.2 Fixture Design

As soon as the design or shape of the workpiece is changed, the fixture design also has to change accordingly; this is the main disadvantages of the AFM process and makes its costly process too.

After deciding the dimension of the workpiece, the dimensions for the fixture are decided, with keeping in mind the main objective of the simultaneous finishing of the workpiece. The fixture is designed in such a way that media can pass through the whole of the workpiece to fulfil the desired objective. The workpiece must be surrounded by abrasive media from all the sides. Since the abrasive media for this study was too thick and viscous, the space between the workpiece surface and fixture surface, to allow media flow in-between was chosen as 4mm. The other dimensions were chosen to suit the easy and sufficient flow requirement of the media.



• Datum planes will not be displayed.

Figure 3.3: Fixture design in Creo 3.0

The dimensions of the nylon fixture are enlisted below,

Dimensions	Fixture 1	Fixture 2
Overall Height (H)	51.5 mm	55.5 mm
Overall Diameter (D)	102 mm	102 mm
Media Diameter (D_{m})	65.5 mm	65.5 mm
Media Depth (L_{m})	10 mm	10 mm
Internal Work Diameter (D_{wi})	15 mm	15 mm
Outer Work Diameter (D_{wo})	50 mm	50 mm
Work Depth (L_{w})	10 mm	15 mm
Media Hole Diameter (D_{mh})	9.5 mm	9.5 mm
Media Hole Circle Diameter (D_{mc})	33 mm	33 mm
Clamping Hole Diameter (D_{ch})	6 mm	6 mm

Clamping Hole Circle Diameter (D_{cc})	86 mm	86 mm

Table 3.1. Dimensions of nylon fixture

A CAD model of the fixture is shown in figure 3.3 and the actually fabricated fixture is shown in figure 3.4.

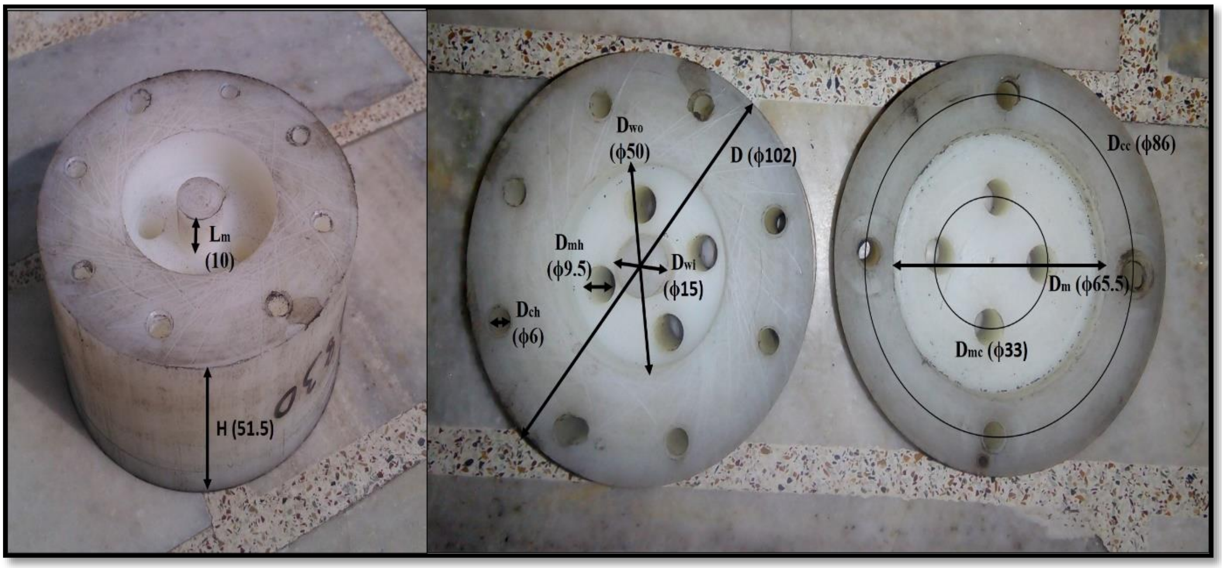


Figure 3.4. Shape and dimensions of manufactured nylon fixture

3.3 Fabrication of the Media Cylinder & Piston arrangement:

The media cylinder, tapered section, and the connecting rod is fabricated to fulfil the requirement of AFM setup. In this topic, the fabrication of the cylinder, tapered section and the connecting rod are discussed; shown in figure 3.4.

To hold the abrasive media in a sufficient quantity and to sustain a high working pressure, the standard engine sleeve of the rajdoot bike is used as media cylinder in this research work. The general dimensions of the engine sleeves and piston used in engine are enlisted below,

- Length of sleeve = 122mm
- Outer diameter of sleeve = 66mm
- Internal diameter of sleeve = 61.5mm
- Outer diameter of piston = 61.5mm
- Length of piston = 62mm

The boring and reaming of the cylinder are done for the smooth movement of the piston in the media cylinder. The piston cylinder used for the present study is shown in figure 3.5.

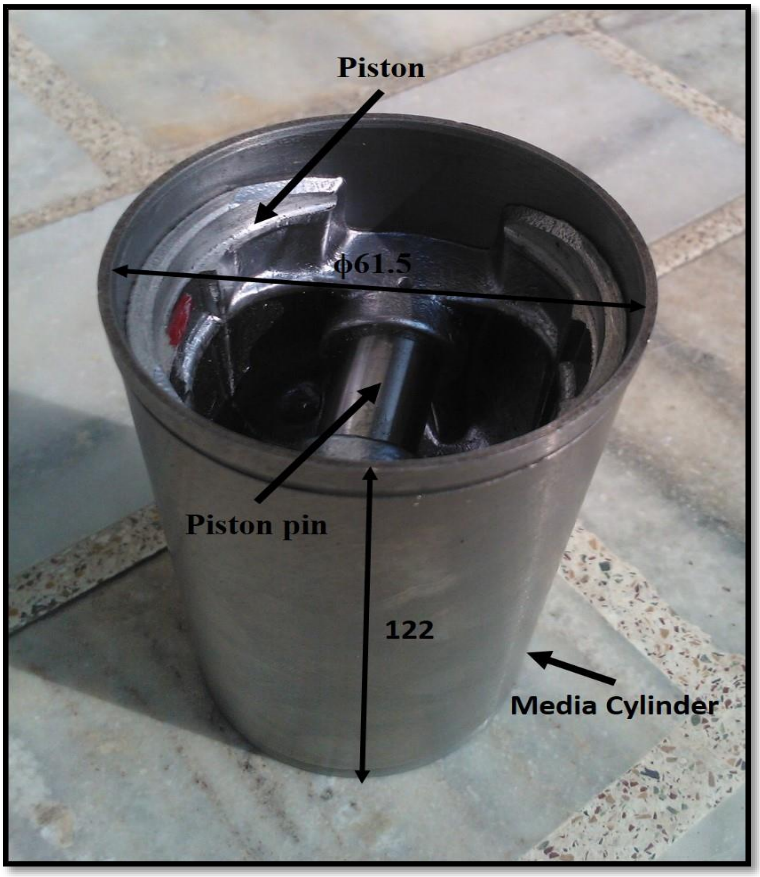


Figure 3.5: Media cylinder & piston arrangement

A tapered section is welded to the media cylinder to guide the abrasive media to the four media holes of the fixture. The tapered section used in study has enlisted dimensions,

- Large Diameter = 60.3mm
- Small Diameter = 42mm
- Height = 10.8mm
- Slope = 84 in 100 mm

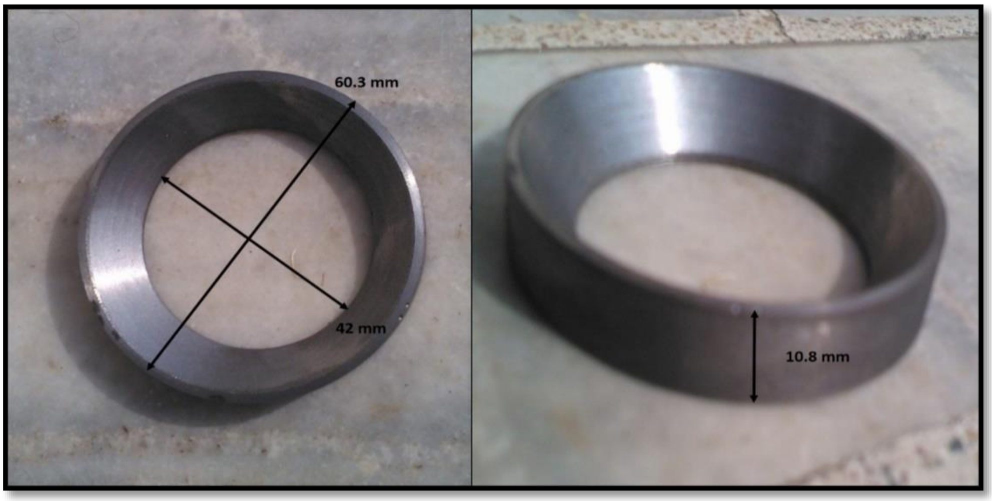


Figure 3.6. Schematic view of tapered section

The tapered section of mild steel was manufactured on the lathe machine. The schematic view of the tapered section is shown in figure 3.6. A connecting rod (as shown in figure 3.7.) is also fabricated to move the piston.

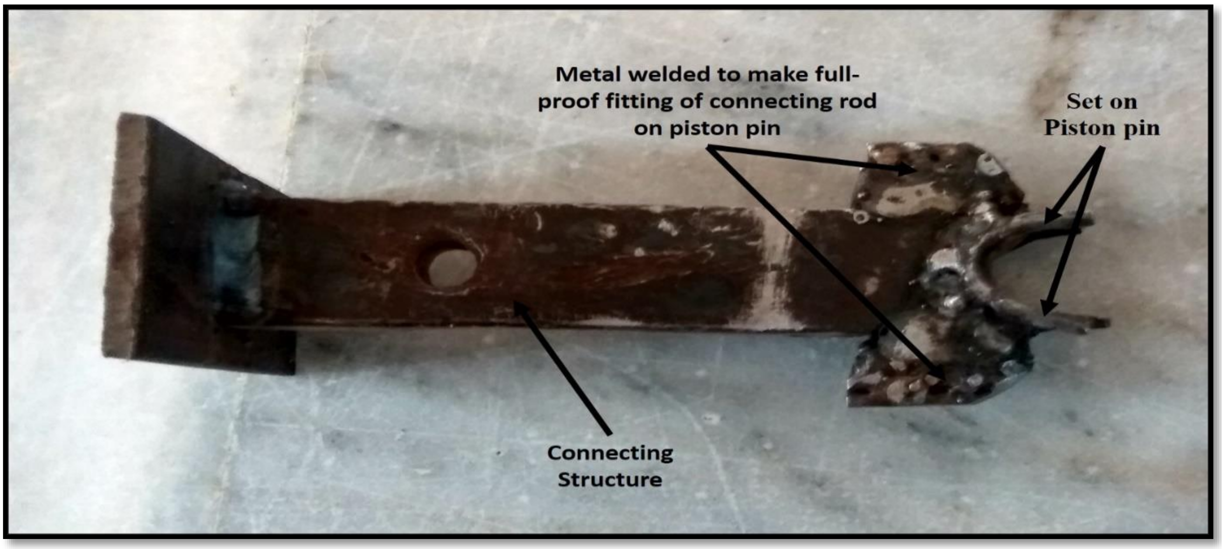


Figure 3.7. Schematic view of connecting rod

A fabricated fixture setup consists of nylon fixture, media cylinder piston arrangement, connecting rod, and mild steel cylindrical support is shown in figure 3.8.

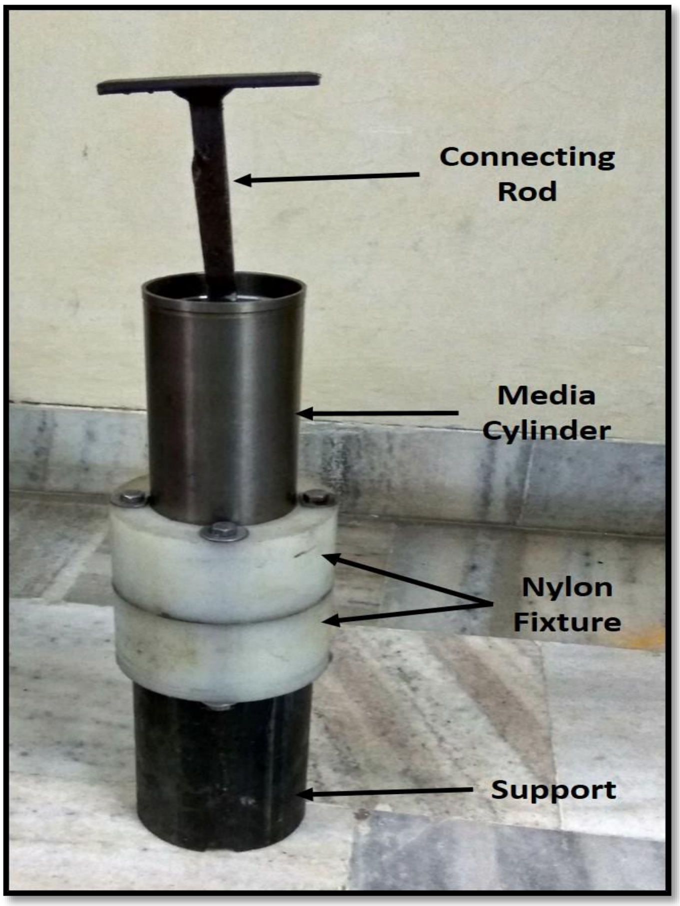


Figure 3.8 Fabricated Fixture setup

The Schematic diagram of media flow and cross-sectional view of fixture setup is shown in figure 3.9.

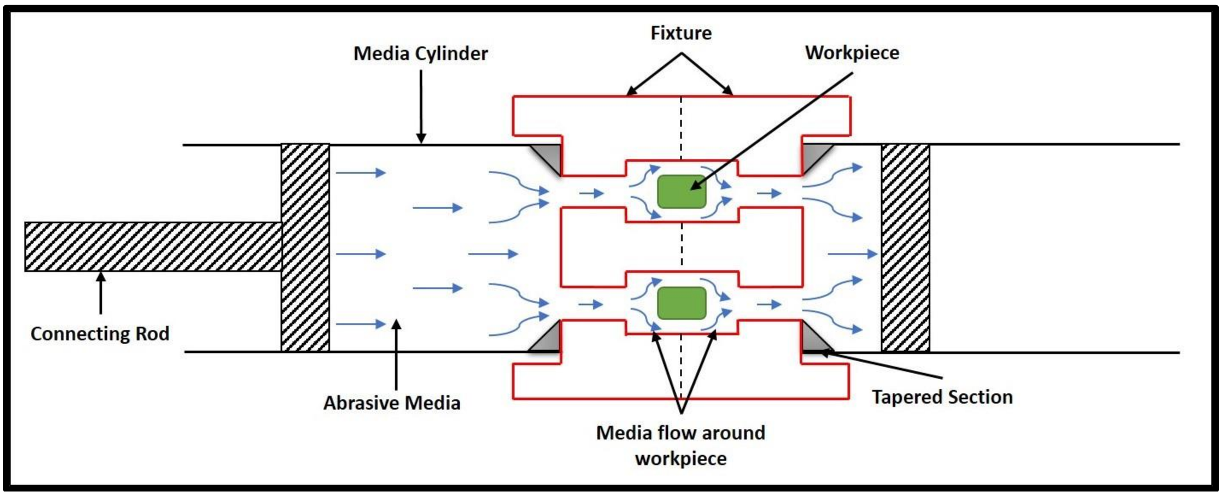


Figure 3.9: Cross-sectional view of fixture setup

3.4 Preparation of AFM Media

The abrasive laden media is the heart of the AFM research. The manufacturing of the media is most critical and vital part of the research on the abrasive flow machining.

3.4.1 Procedure of media preparation

The abrasive media are made up of the mixture of silicone based polymer, hydrocarbon gel, and the abrasive particles.

The silicone polymer is made by reacting the poly-dimethyl siloxane with a boron compound, e.g. boric acid, boric acid anhydride and others in the presence of the Lewis acid catalyst, with continuous heat and stirring. The catalyst is used to speed up the formation of the polymer. The ammonium carbonate or the ammonia is used to neutralise any acidic residue in the polymer. The silicone polymer alone loaded with the abrasive particles didn’t give satisfactory results for abrasive honing. But when it mixed with gel, formed from the hydrocarbon oil and metallic soap, it becomes readily flowable and has a consistency in between a paste and dough. The gel was manufactured by mixing the hydrocarbon oil and metallic soap at room temperature with stirring.

The mixture is then heated at elevated temperature to form a relatively thick gel. The silicone and gel are mixed and needed to obtain a homogeneous carrier. The amount of gel added to the polymer depended on the properties of the gel and the consistency required in the final composition. The ratio of the polymer with gel was used in this study is 1:1.This carrier is mixed with the abrasives in required percentage concentration of abrasives in media. The manufactured media is shown in figure 3.10.

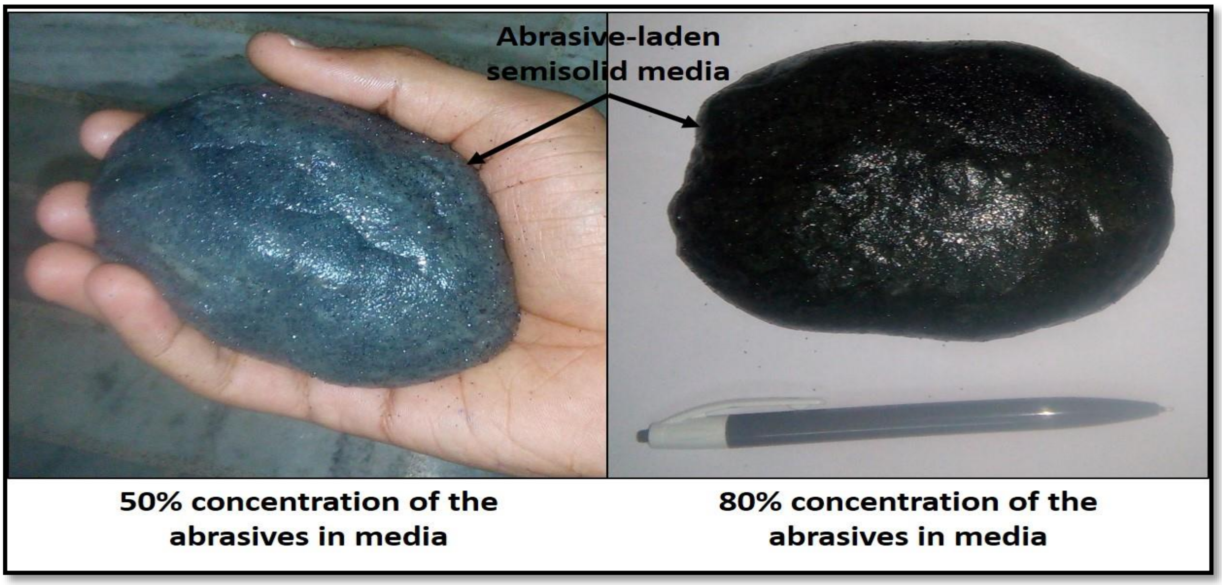


Figure 3.10.Different abrasive-laden semi-solid media used in experimentation

3.4.2 Bouncing Test of media

The bouncing test is carried out on media to check the rheological and viscous properties of it. The media used in this study is bouncing in nature. For testing, abrasive media are formed in the shape of the spherical ball are allowed to fallen on the hardened surface. The distance which is travelled by bounced media is recorded. If bounce of the media is more than 10cm when it is fallen from height 60cm to the hardened surface is considered as suitable for the abrasive flow machining.

3.4.3 Media Composition

The abrasive media contains the viscoelastic carrier medium to carry the abrasives and the abrasives to abraded and deburr the surface of the workpiece.

Different media compositions were selected for this study, i.e.

1. **Different size of abrasives used**

Silicon carbide abrasives are chosen among the different abrasives, viz. silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), diamond dust etc. Former two abrasives are cheapest and economical to use in general purpose; last two abrasives are comparatively costly but harder than former, hence generally used for the special applications only. Silicon carbide is harder and sharper than standard forms of the aluminium oxide; hence, silicon carbide is selected in this study.

The different sizes of abrasives selected for research work are,

Sr. No.	Abrasive	Mesh Size	Size in microns
1	Silicon Carbide (SiC)	70	210
2	Silicon Carbide (SiC)	100	149
3	Silicon Carbide (SiC)	170	88

Table 3.2: Different size of abrasives used in experimentation

2. Different concentration of abrasives in media:

For the present study, different concentration of abrasives by weight is chosen for media preparation.

Sr. No.	Media : Abrasive	Concentration type (by weight / by volume)
1	50:50	by weight
2	35:65	by weight
3	20:80	by weight

Table 3.3: Different concentration of abrasives used in experimentation

The concentration of abrasives in media is calculated as,

Concentration of Abrasive in media =

$$\frac{\boldsymbol{Weight\ of\ the\ Abrasives}}{\boldsymbol{Weight\ of\ the\ Abrasives + Weight\ of\ the\ Carrier\ Media}} \times \mathbf{100}$$

3.5 Hydraulic System for AFM

Since the hydraulic system for two-way abrasive flow machining was too costly and uneconomical for this study, an alternative hydraulic system is used.

From some trial experiments, it is clear that the average force required for the experimentation was nearly 800kgf. So, alternate mechanical or hydraulic systems are checked which fulfil the requirement of this study. The “Universal Testing Machine – 40 Tonne”, which is located at the mechanical department workshop of Maharishi Markandeshwar University, Mullana University Road, Mullana, Ambala was used in this study.

- The technical data for UTM – 40 are enlisted below,
- Maximum Capacity = 40 Ton or 40,000kgf
- Ram Stroke = 200mm
- Piston speeds (at no load) = 0-150 mm/min

Manufacturer = Enkay Enterprises, New Delhi.

The fixture setup is placed in the UTM machine and with the help of a hydraulic system of the UTM, the mechanical force is provided on the piston via connecting rod.

3.6 Selection of Machining Parameters:

Different machining parameters, their range, and its effect measures are selected for this study on the basis of trial experiments. Most of the machining parameters are discussed earlier, but till brief discussion are here as under,

3.6.1 Input Process Parameters

The various input process parameters are selected for this research work is enlisted below;

1) Size of abrasives (70,100,170 mesh sizes)
2) Concentration of abrasives (50,65,80% by weight)
3) Number of passes (20,40,60)

Here, the flow of media from upper media cylinder to lower media cylinder through workpiece fixture setup is known as one pass. The brief discussion regarding the size of abrasives and concentration of abrasives in media is discussed before in chapter 3.4.

3.6.2 Output Process Parameters

Three output parameters were selected for this study;

1) Change in Surface Roughness (ΔRa)

Since the initial surface roughness of each workpiece is different, hence, it is not advisable to take output parameter as surface roughness value. Hence, change in surface roughness will be more appropriate to use as output parameters as it does not depend on initial surface roughness.

Change in Surface Roughness (ΔRa) =

$$\boldsymbol{Initial\ Surface\ Roughness(Ra)i - Final\ Surface\ Roughness\ (Ra)f}$$

Here, change in surface roughness is calculated for the internal, external and side surface to measure the difference among them. The surface roughness tester of "MitutoyoSurftest SJ-400 series" is used for the measurement of change in surface roughness.

2) % improvement in Surface Finish

The percentage improvement in surface roughness for the internal surface and final surface have been analysed for this study.

% improvement in Surface Finish =

$$\boldsymbol{\frac{Initial\ Surface\ Roughness(Ra)i - Final\ Surface\ Roughness\ (Ra)f}{Initia\ Surface\ Roughness\ (Ra)i} \times 100}$$

In this study, percentage improvement can be measured with the initial surface roughness of the workpiece and final surface roughness of the workpiece after experimentation.The comparison between inner, outer and side surface based on the percentage improvement is also done in this study.

3) Amount of Material Removal (MR)

The amount of material removed can be measured by measuring the initial weight of the workpiece and final weight of the workpiece. The simple subtraction of final weight of workpiece with an initial weight of the workpiece gives the amount of material removal.

Amount of material removal =

Initial Weight of the Workpiece (W_i) – Final Weight of the Workpiece (W_f)

Analytical balance AUW220D of Shimadzu Analytical Pvt. Ltd. with least count of 0.1mg is used to measure the amount of material removal.

3.6.3 Constant Parameters

Some constant parameters which are selected in this study are,

Parameters	**Constant Value**
Extrusion force	800 kgf
Temperature	32˚C (Room Temperature)
Stroke length	60 mm
Media flow volume per pass	200 cm^3
Polymer to gel ratio	1:1
Abrasive material	SiC

Table 3.4: Constant parameters in present study

3.7 Design of Experiments (DOE)

Any experimental investigation contains mainly two parts, viz. experimentation and drawing interferences from results. Proper planning of experiments is important for deriving clear and accurate conclusions from the experimental observations. Hence, experimental design is considered as utmost important for accomplishing these tasks.

Hence, after deciding the input and output parameters, the design of experiments are decided. There are three input parameters viz. size of abrasives, the concentration of abrasives and number of passes with 3, 3 and 3 levels respectively and two output parameters viz. amount of material removal and change in surface roughness are decided for this study.

The design of an experiment is done on the Minitab 17.0 software. The general full factorial design of experiment is designed;

L27 Full Factorial Design

- Factors = 3
- Replicates = 1
- Number of levels = 3, 3, 3
- Base runs = 27.

Run Order	Abrasive Mesh Size	Concentration of Abrasives	Number of Passes
1	70	50	20
2	70	50	40
3	70	50	60
4	70	65	20
5	70	65	40
6	70	65	60
7	70	80	20
8	70	80	40
9	70	80	60
10	100	50	20
11	100	50	40
12	100	50	60
13	100	65	20
14	100	65	40
15	100	65	60
16	100	80	20
17	100	80	40
18	100	80	60
19	170	50	20
20	170	50	40
21	170	50	60
22	170	65	20
23	170	65	40
24	170	65	60
25	170	80	20
26	170	80	40
27	170	80	60

Table 3.5. L27 full factorial design

3.8 Experimentation

After deciding the process measures and design of experiments (DOE), the experiments are carried out. The experimentation is carried out at the workshop of the Maharishi Markandeshwar University, Mullana University Road, Mullana, Ambala.

The fixture setup consists of two fixtures, two media cylinder and piston arrangements, four nut and bolts, two ball bearing cages, connecting rod and a workpiece. The whole experimental procedure is shown in figure 3.11 and 3.12.

The main experimentation procedure includes the following steps;

A. Fix workpiece and ball bearing cages in fixtures

First of all the ring-shaped aluminium workpiece and the two ball bearing cages to foolproof the movement of the workpiece in between the fixtures are located and fixed.

B. Clamping of fixtures with the help of nut, bolts, and washer.

The nut and bolts of 4’’ length are used to clamp the fixtures to avoid any leakages.

C. Fill media in one of the two media cylinders

The abrasive media was filled in one of the two media cylinders, manually.

D. Fit media cylinder into the fixture setup

Fit media cylinder and piston arrangement on both side of the fixture setup and provide support to the fixture by support cylinder.

E. Place connecting rod above the piston of the upper media cylinder.

The connecting rod which is placed on the cylinder piston setup is used to transfer load from the UTM to the piston of the media cylinder.

F. Place whole fixture setup in the UTM.

The whole fixture setup with support cylinder is placed in between the universal testing machine for experimentation work

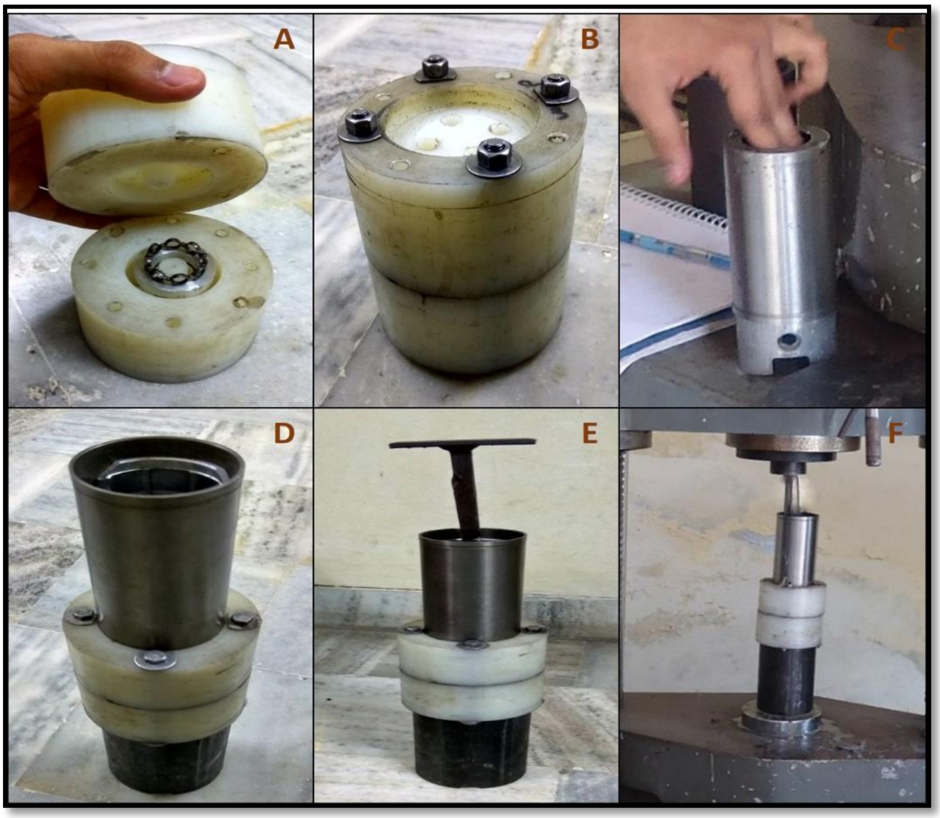


Figure 3.11: Schematic procedure of the experimentation

G. Experimentation:

After placing the fixture setup inside the UTM, the UTM is started and change it in compression testing mode. With the help of two rams for a compression test, instead of the workpiece on which testing are done, fixture setup was placed.

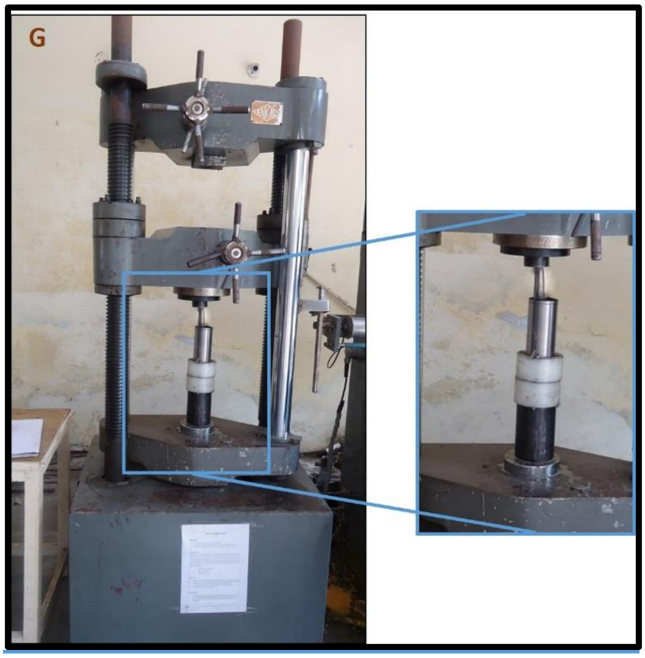


Figure 3.12: View of fixture setup in the UTM

While at experimentation it was found that average 800kgf load was required to pass the media through workpiece and fixture setup. Since, it was not possible to maintain constant load pressure by UTM, the concept of extrusion pressure as input parameter was leave off due to practical limitations.

The serious problem of media blockage by workpiece itself comes in the picture, while the trial experiment is carried out on the ring-shaped workpiece. As soon as the media passes through the fixture and apply force to the ring-shaped workpiece, the workpiece settled down on the four media holes of other fixture. Due to blockage of media, there was no relative motion of media with respect to the workpiece and hence, no abrasion of the workpiece was taking place.

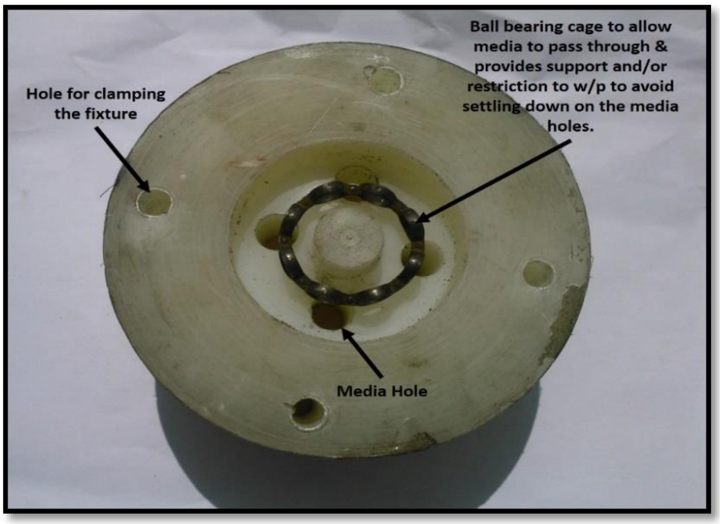


Figure 3.13: Use of ball bearing cage to avoid media blockage while experimentation

The problem of the media blockage can be overcome by the use of ball bearing cage on both sides of the workpiece. The cage allows media to easily pass through it and provides support and/or restriction to the workpiece to avoid settling down on the media holes. The schematic view of the ball bearing cage in the fixture to avoid the media blockage can be shown in figure 3.13.

One pass of media consists of the movement of media from upper media cylinder to lower cylinder through workpiece & fixture arrangement. After completion of the pass, the whole fixture setup is turned 180˚ to make lower media cylinder to upper media cylinder and vice versa for next pass as shown in figure 3.14. This was also a limitation of this study that after each pass there have to turn the fixture setup about 180˚ for next pass.

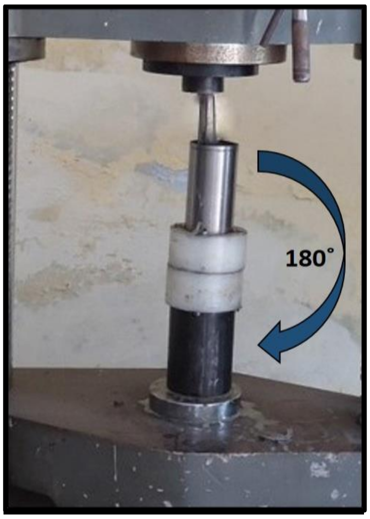


Figure 3.14: Fixture setup has to turn 180˚ after each pass

The problem of cracking of media cylinder are also seen while experimentation as shown in figure 3.15.


Media Cylinder break-up while experimentation

Figure 3.15. Media cylinder break-up while experimentation

The reason behind the media cylinder cracking may be given as while experimentation sometimes connecting rod tilts at some angle and because of it, the uneven force applies on the media cylinder surface and/or may be due to high extrusion pressure. Because of it, the media cylinder breaks down.

The media property also has been changed at the time of the experiment. The leakage of media, losing consistency of media after several passes etc. problems come in picture. Leakage and lack in consistency of media are avoided by adding hydrocarbon gel in media in appropriate quantity. The view of media after and before the experimentation is shown in figure 3.16.

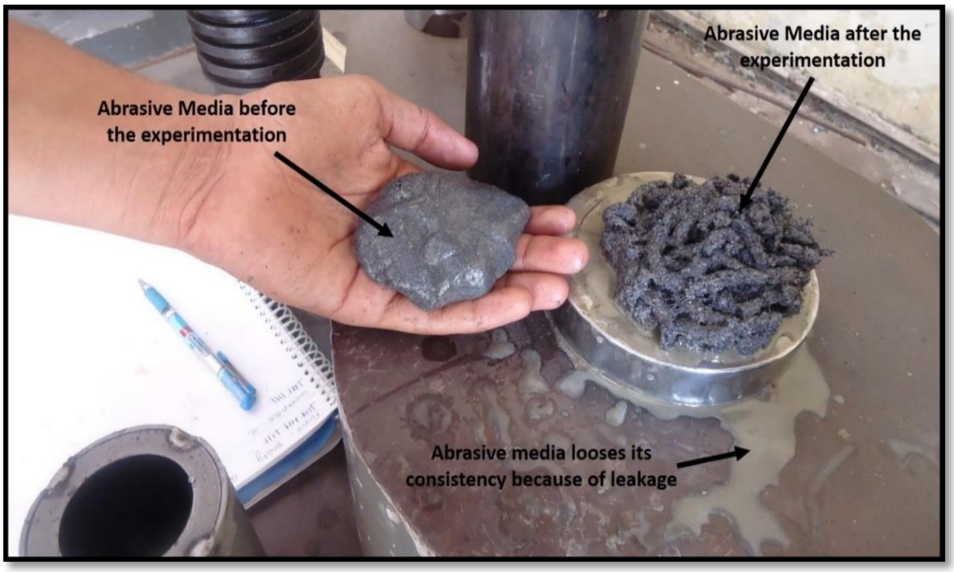


Figure 3.16: View of media before & after experimentation

The required number of passes is obtained with the help of UTM.The number of passes, surface roughness and amount of material removed etc. are noted down in the data sheet.

3.9 Data Collection:

The process measures are collected and noted down for the further analysis. The data collected in this study is explained listed below,

A. Change in Surface Roughness of inner surface of workpiece

Inner Surface									
Size of Abrasives	Concentration of Abrasives	Number of Passes							
		0	20		40		60		
		Ra (μm)	Ra (μm)	ΔRa (μm)	Ra (μm)	ΔRa (μm)	Ra (μm)	ΔRa (μm)	
70	**50**	0.82	0.68	**0.14**	0.62	**0.2**	0.58	**0.24**	**1**
	65	0.83	0.68	**0.15**	0.61	**0.22**	0.56	**0.27**	**2**
	80	0.98	0.78	**0.2**	0.69	**0.29**	0.63	**0.35**	**3**
100	**50**	0.84	0.73	**0.11**	0.68	**0.16**	0.65	**0.19**	**4**
	65	0.89	0.75	**0.14**	0.69	**0.2**	0.65	**0.24**	**5**
	80	0.99	0.82	**0.17**	0.74	**0.25**	0.68	**0.31**	**6**
170	**50**	0.93	0.83	**0.1**	0.78	**0.15**	0.75	**0.18**	**7**
	65	0.82	0.72	**0.1**	0.67	**0.15**	0.64	**0.18**	**8**
	80	0.93	0.8	**0.13**	0.73	**0.2**	0.68	**0.25**	**9**

Table 3.6: Data for change in surface roughness of the inner surface

B. Change in Surface Roughness of outer surface of workpiece

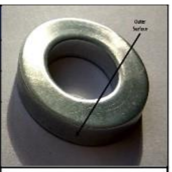
Outer Surface									
Size of Abrasives	Concentration of Abrasives	Number of Passes							
		0	20		40		60		
		Ra (μm)	Ra (μm)	ΔRa (μm)	Ra (μm)	ΔRa (μm)	Ra (μm)	ΔRa (μm)	
70	**50**	0.97	0.81	**0.16**	0.73	**0.24**	0.69	**0.28**	**1**
	65	0.91	0.75	**0.16**	0.67	**0.24**	0.62	**0.29**	**2**
	80	0.95	0.74	**0.21**	0.65	**0.3**	0.59	**0.36**	**3**
100	**50**	0.81	0.71	**0.1**	0.66	**0.15**	0.63	**0.18**	**4**
	65	0.88	0.76	**0.12**	0.69	**0.19**	0.64	**0.24**	**5**
	80	0.97	0.79	**0.18**	0.71	**0.26**	0.65	**0.32**	**6**
170	**50**	0.92	0.81	**0.11**	0.76	**0.16**	0.73	**0.19**	**7**
	65	0.96	0.84	**0.12**	0.78	**0.18**	0.74	**0.22**	**8**
	80	0.95	0.8	**0.15**	0.73	**0.22**	0.69	**0.26**	**9**

Table 3.7: Data for change in surface roughness of the outer surface

C. Change in Surface Roughness of side surface of workpiece

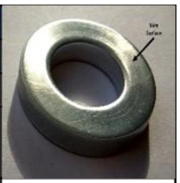
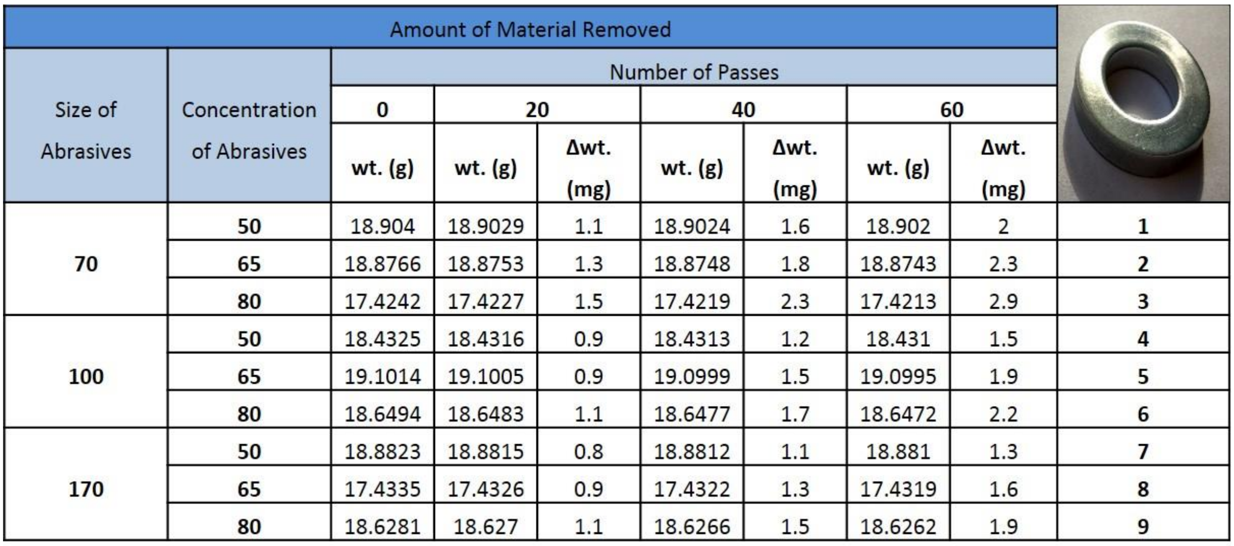
Side Surface									
Size of Abrasives	Concentration of Abrasives	Number of Passes							
		0	20		40		60		
		Ra (μm)	Ra (μm)	ΔRa (μm)	Ra (μm)	ΔRa (μm)	Ra (μm)	ΔRa (μm)	
70	**50**	0.86	0.75	**0.11**	0.71	**0.15**	0.68	**0.18**	**1**
	65	0.83	0.72	**0.11**	0.67	**0.16**	0.63	**0.2**	**2**
	80	0.81	0.69	**0.12**	0.63	**0.18**	0.59	**0.22**	**3**
100	**50**	0.84	0.76	**0.08**	0.72	**0.12**	0.69	**0.15**	**4**
	65	0.97	0.86	**0.11**	0.81	**0.16**	0.77	**0.2**	**5**
	80	0.91	0.8	**0.11**	0.75	**0.16**	0.71	**0.2**	**6**
170	**50**	0.85	0.79	**0.06**	0.76	**0.09**	0.74	**0.11**	**7**
	65	0.81	0.74	**0.07**	0.71	**0.1**	0.69	**0.12**	**8**
	80	0.9	0.81	**0.09**	0.76	**0.14**	0.72	**0.18**	**9**

Table 3.8: Data for change in surface roughness of the side surface

D. Amount of material removed of the workpiece



Amount of Material Removed									
Size of Abrasives	Concentration of Abrasives	Number of Passes							
		0	20		40		60		
		wt. (g)	wt. (g)	Δwt. (mg)	wt. (g)	Δwt. (mg)	wt. (g)	Δwt. (mg)	
70	50	18.904	18.9029	1.1	18.9024	1.6	18.902	2	1
	65	18.8766	18.8753	1.3	18.8748	1.8	18.8743	2.3	2
	80	17.4242	17.4227	1.5	17.4219	2.3	17.4213	2.9	3
100	50	18.4325	18.4316	0.9	18.4313	1.2	18.431	1.5	4
	65	19.1014	19.1005	0.9	19.0999	1.5	19.0995	1.9	5
	80	18.6494	18.6483	1.1	18.6477	1.7	18.6472	2.2	6
170	50	18.8823	18.8815	0.8	18.8812	1.1	18.881	1.3	7
	65	17.4335	17.4326	0.9	17.4322	1.3	17.4319	1.6	8
	80	18.6281	18.627	1.1	18.6266	1.5	18.6262	1.9	9

Table 3.9: Data for amount of material removal

All the data collected and analysed with the Minitab 17 software. The input parameters and output parameters are clearly defined and the corresponding value of output for each design of experiment can be entered carefully.

Experiment No.	Abrasive Mesh Size	Concentration of Abrasives	Number of Passes	ΔRa Inner (μm)	ΔRa Outer (μm)	ΔRa Side (μm)	Material Removal (mg)
1	70	50	20	0.14	0.16	0.11	1.1
2	70	50	40	0.2	0.24	0.15	1.6
3	70	50	60	0.24	0.28	0.18	2
4	70	65	20	0.15	0.16	0.11	1.3
5	70	65	40	0.22	0.24	0.16	1.8
6	70	65	60	0.27	0.29	0.2	2.3
7	70	80	20	0.2	0.21	0.12	1.5
8	70	80	40	0.29	0.3	0.18	2.3
9	70	80	60	0.35	0.36	0.22	2.9
10	100	50	20	0.11	0.1	0.08	0.9
11	100	50	40	0.16	0.15	0.12	1.2
12	100	50	60	0.19	0.18	0.15	1.5
13	100	65	20	0.14	0.12	0.11	0.9
14	100	65	40	0.2	0.19	0.16	1.5
15	100	65	60	0.24	0.24	0.2	1.9
16	100	80	20	0.17	0.18	0.11	1.1
17	100	80	40	0.25	0.26	0.16	1.7
18	100	80	60	0.31	0.32	0.2	2.2
19	170	50	20	0.1	0.11	0.06	0.8
20	170	50	40	0.15	0.16	0.09	1.1
21	170	50	60	0.18	0.19	0.11	1.3
22	170	65	20	0.1	0.12	0.07	0.9
23	170	65	40	0.15	0.18	0.1	1.3
24	170	65	60	0.18	0.22	0.12	1.6
25	170	80	20	0.13	0.15	0.09	1.1
26	170	80	40	0.2	0.22	0.14	1.5
27	170	80	60	0.25	0.26	0.18	1.9

Table 3.10: Collected data which are used in analysis

Chapter IV - RESULTS & DISCUSSION

After collecting the data from the experimentation, the results is examined and discussed in this chapter. The critical analysis is done to find the trend and effect of input parameters on the output parameters. The effect of each input parameters like the number of passes, abrasive mesh size and concentration of abrasives in media on the change in surface roughness of the internal, external and side surface of the workpiece followed by the amount of material removal with respect to input parameters is discussed.

4.1 Workpiece Before & After Experimentation

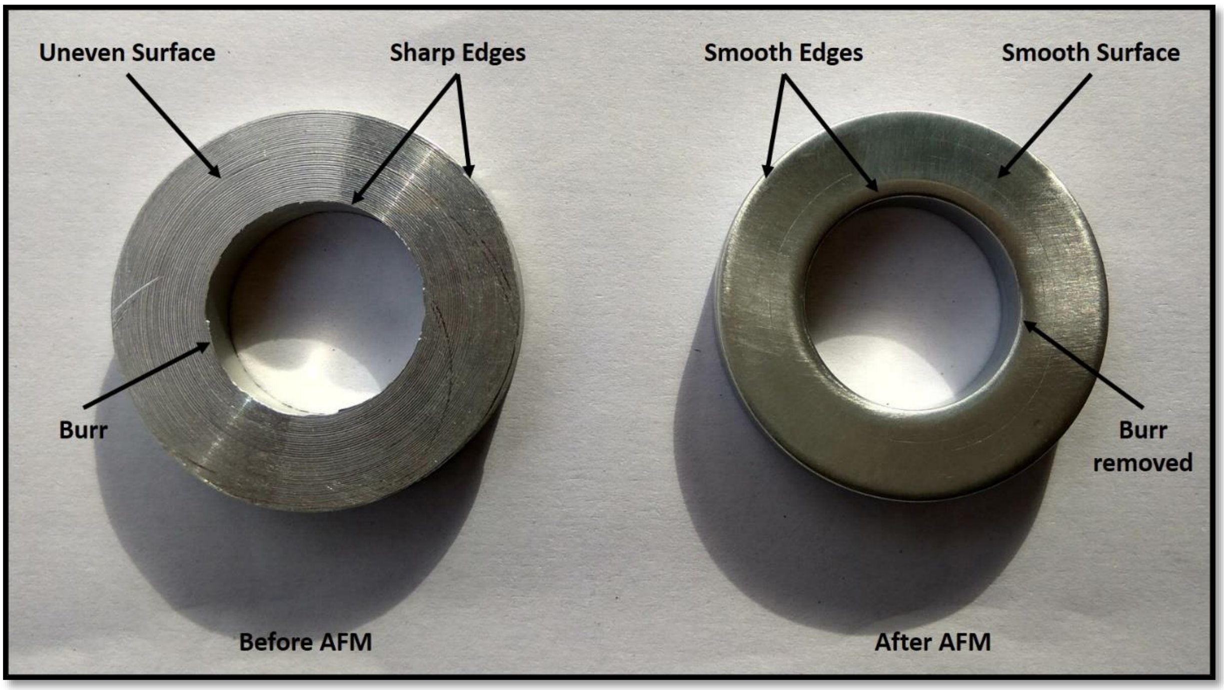


Figure 4.1: Workpiece before and after AFM

The ring-shaped aluminium workpiece is finished after the experimentation. From the figure 4.1, it's clearly depicted that unfinished workpiece before abrasive flow machining has burrs, sharp edges, and uneven surfaces. But, in the finished workpiece burrs are removed, sharp edges turn into smooth edges and the surfaces became smooth. Hence, with the help of abrasive flow machining the functionality and aesthetic appearance of the workpiece are increased.

4.2 Media Flow direction in Simultaneous Finishing

The media flow direction for the simultaneous finishing of the workpiece under this study is shown in below figure 4.2.

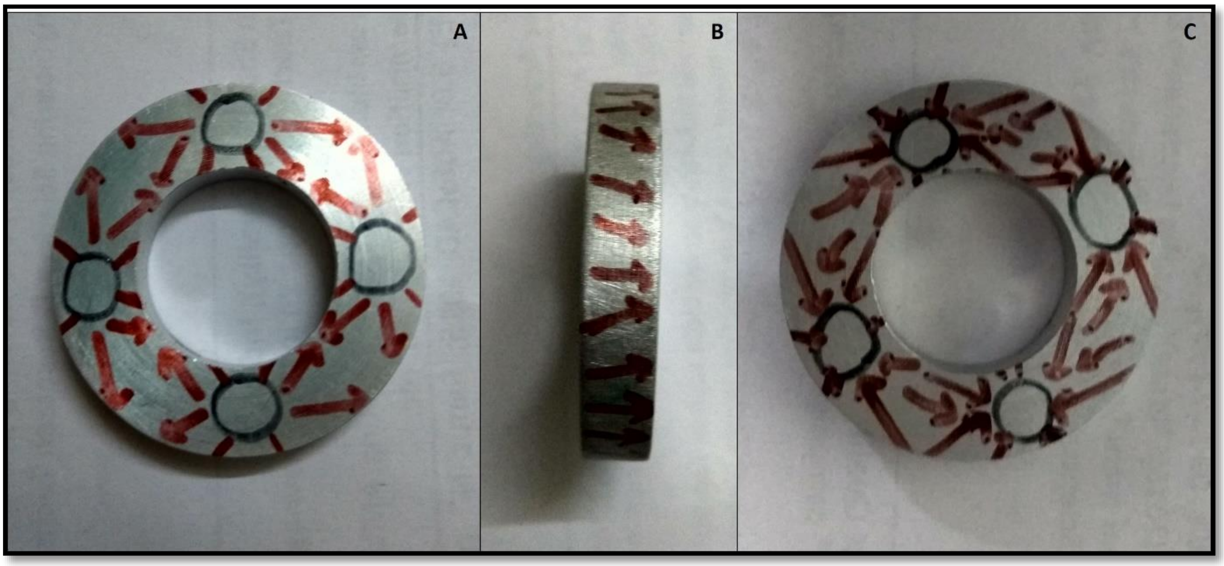


**Figure 4.2: Media flow direction for
a) Media supplied to side surface,
b) outer/inner surface, c) Media coming out from the fixture.**

The media is supplied to side surface of the workpiece through four media holes of the fixture. Since media is too viscous and semi-solid it fills the whole cavity of the fixture around the workpiece. The probable media flow direction in the workpiece surface is shown in figure 4.2. At a side surface, the media flows in all direction to fill the fixture cavity around the workpiece.

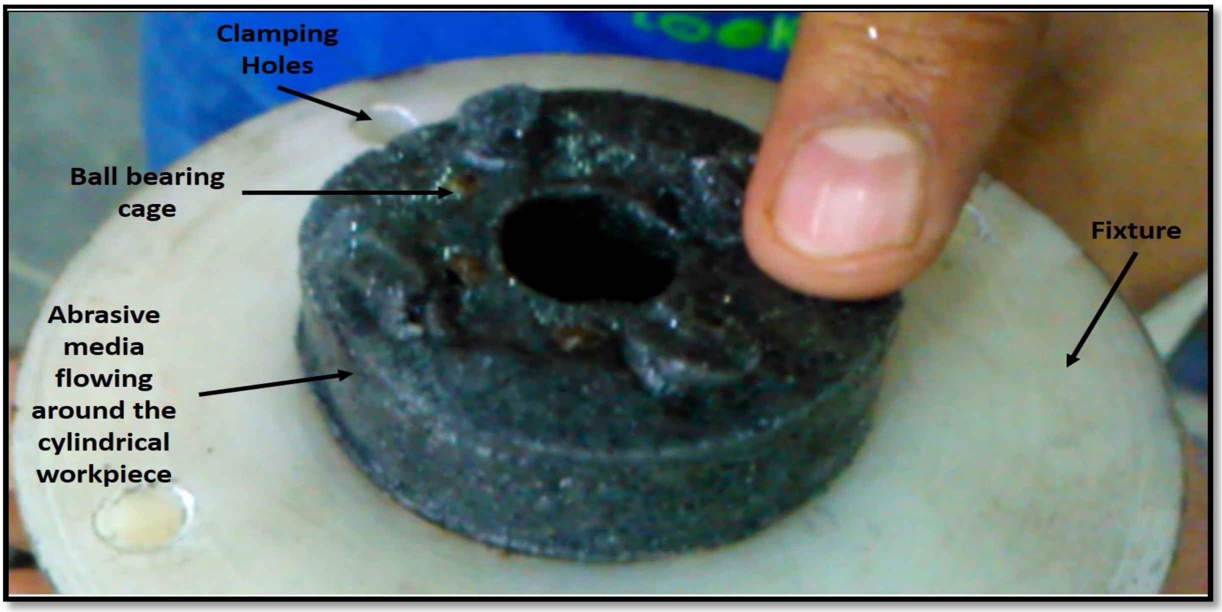


Figure 4.3: Abrasive media around the cylindrical workpiece while experimentation

At the internal and external surface, the media flows in a parallel direction to the workpiece surface and hence, more percentage increase in surface finish is observed at the inner and outer surface. After that media is coming out from the four media holes of the fixtures. The same pattern of media flow for supplied and coming out from the fixture is proposed.

From the figure 4.3, it is clearly depicted that abrasive media flows around the ring-shaped cylindrical workpiece. Because of relative motion between the abrasive media and the cylindrical workpiece, the workpiece surface is abraded and hence, surface finish is enhanced for all the surfaces i.e. inner, outer and side surfaces.

4.3 Change in Surface Roughness

Since initial surface roughness of each workpiece is different, therefore the result is discussed by considering the change in surface roughness value with respect to input parameters.

4.3.1 Inner Surface

In this section data is analysed to measure the effect of input parameters on the change in surface roughness of the inner surface of the workpiece.

A. Change in Surface Roughness v/s Number of Passes

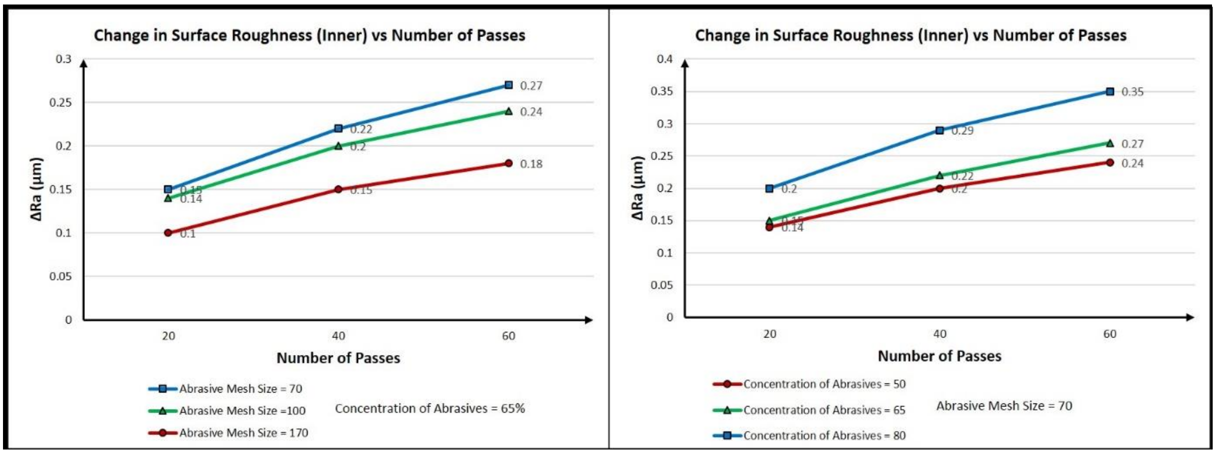


Figure 4.4: Change in surface roughness v/s number of passes for inner surface

As soon as the number of passes increases the change in the surface roughness is increased as shown in figure 4.4. In initial passes, change in the surface roughness per pass is high, but, after certain passes the trend is shallow. This is owing to high hills in the starting which are chipped off easily. After the cutting down of the hills, the amount of material plastically removed from the workpiece is decreased considerably.

B. Change in Surface Roughness v/s Concentration of Abrasives

If the concentration of abrasives in the media increases, the change in surface roughness is increased as shown in figure 4.5.

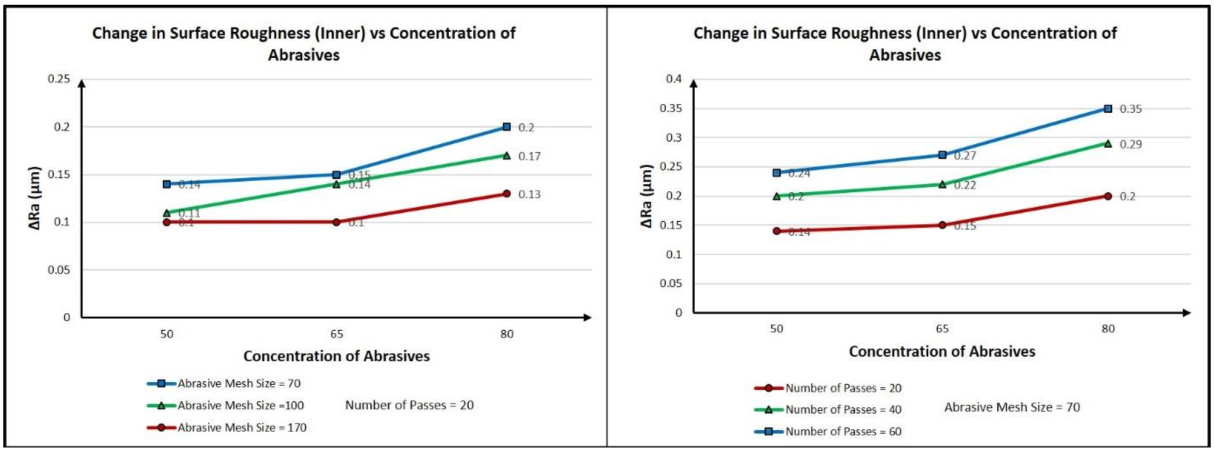


Figure 4.5: Change in surface roughness v/s Concentration of abrasives for inner surface

As soon as the concentration of abrasives in media increase, more active abrasives come in contact with the surface of the workpiece, hence more abrasion is taking place on the surface of the workpiece and more finished surface is obtained.

C. Change in Surface Roughness v/s Abrasive Mesh Size

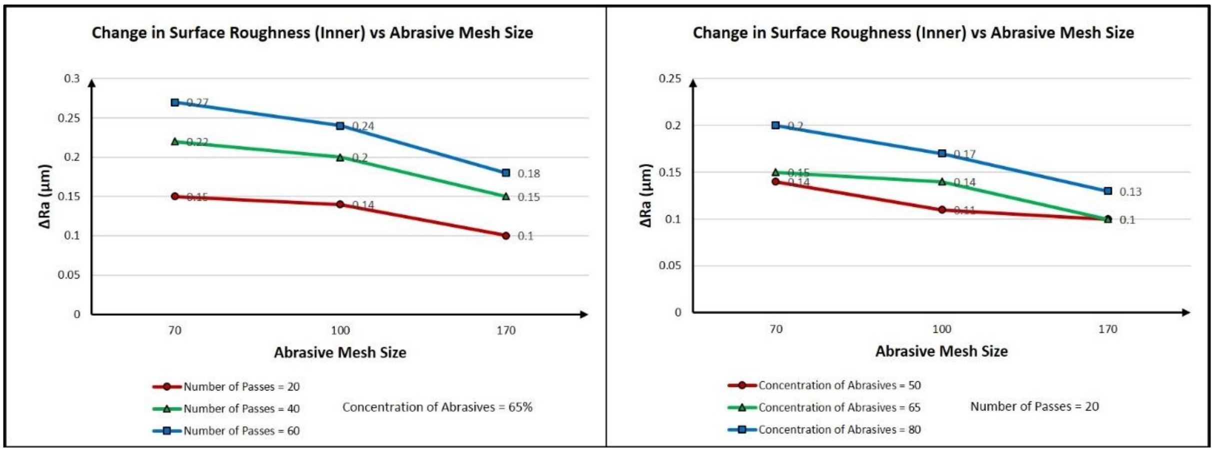


Figure 4.6: Change in surface roughness v/s abrasive mesh size for inner surfaces

With the increase in abrasive mesh size, the change in surface roughness of the surface of the workpiece is decreased as shown in figure 4.6. With the increase in the abrasive mesh size, the effective size of the abrasive is decreased. As soon as the size of abrasives decreases, a lesser amount of material is removed from the surface. Hence, change in surface roughness decreases with increase in the abrasive mesh size.

D. Main Effect Diagram for Inner Surface

From main effect diagram (figure 4.7), it is clearly depicted that with an increase in abrasive mesh size, the change in surface roughness is decreased. With the increase in the concentration of abrasives in media, the change in surface roughness is increased. It’s also clear from the graph that with an increase in the number of passes, the change in surface roughness is exponentially increased but the overall value of surface roughness is decreased.

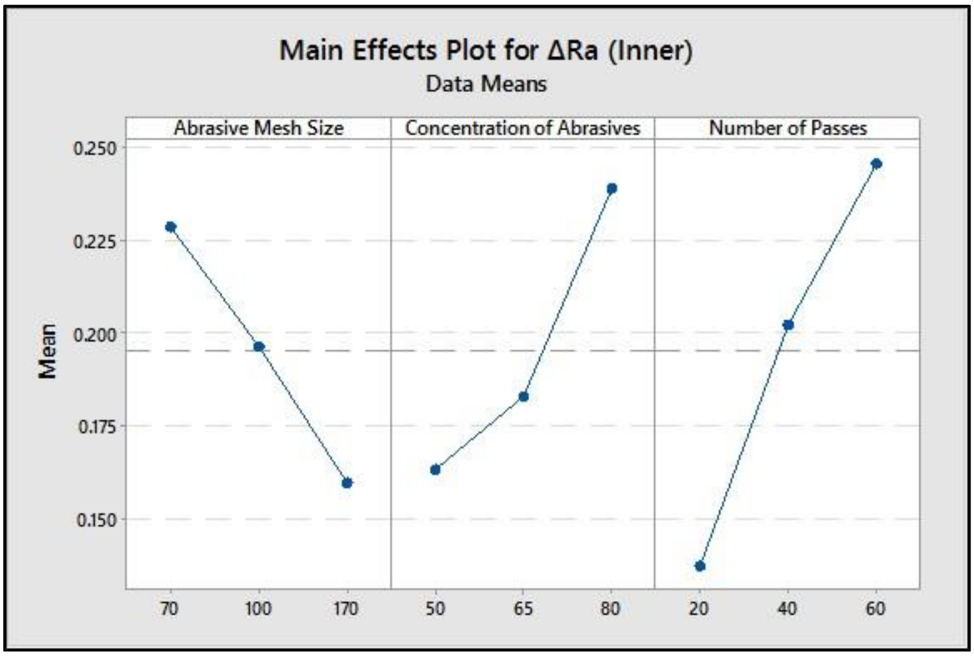
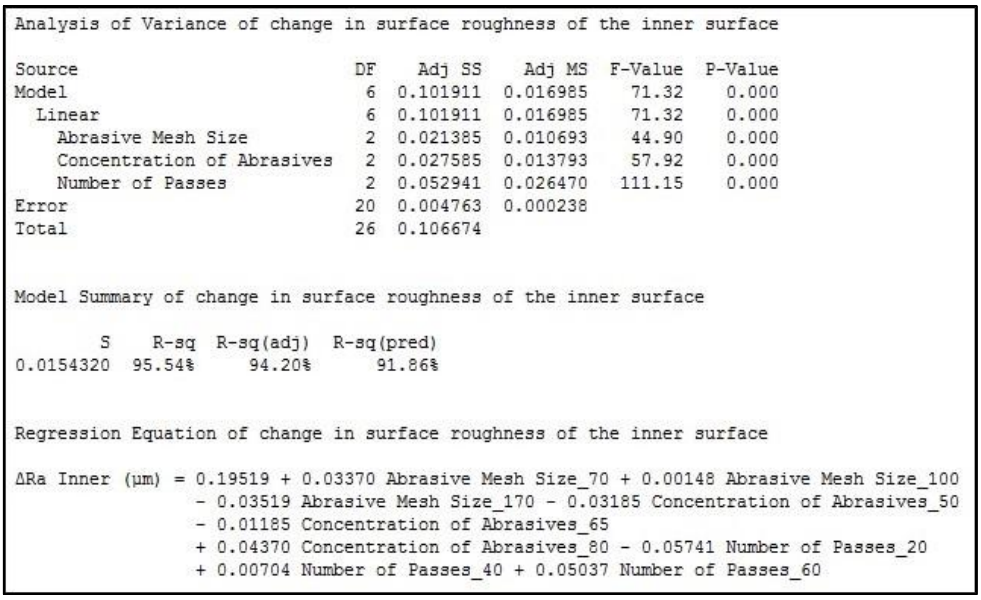


Figure 4.7: Main effect diagram of change in surface roughness for inner surface

E. Statistical analysis of change in surface roughness of inner surface



```
Analysis of Variance of change in surface roughness of the inner surface

Source                          DF    Adj SS    Adj MS  F-Value  P-Value
Model                            6  0.101911  0.016985    71.32    0.000
  Linear                         6  0.101911  0.016985    71.32    0.000
    Abrasive Mesh Size           2  0.021385  0.010693    44.90    0.000
    Concentration of Abrasives   2  0.027585  0.013793    57.92    0.000
    Number of Passes             2  0.052941  0.026470   111.15    0.000
Error                           20  0.004763  0.000238
Total                           26  0.106674


Model Summary of change in surface roughness of the inner surface

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0154320  95.54%     94.20%      91.86%


Regression Equation of change in surface roughness of the inner surface

ΔRa Inner (µm) = 0.19519 + 0.03370 Abrasive Mesh Size_70 + 0.00148 Abrasive Mesh Size_100
                 - 0.03519 Abrasive Mesh Size_170 - 0.03185 Concentration of Abrasives_50
                 - 0.01185 Concentration of Abrasives_65
                 + 0.04370 Concentration of Abrasives_80 - 0.05741 Number of Passes_20
                 + 0.00704 Number of Passes_40 + 0.05037 Number of Passes_60
```

Figure 4.8: Statistical analysis of change in surface roughness of the inner surface

For statistical analysis of the change in surface roughness of the inner surface, analysis of variance is applied on the result data. By examining the analysis of variance for change in surface roughness of the inner surface as shown in figure 4.8, it is observed that F_{obs} value (71.32) is greater than the F_{crit} value (2.60), so the obtained F-ratio is likely to occur by chance with probability less than the 0.05. Hence, all the input parameters have a significant effect on the change in surface roughness of the inner surface. Here, R-square value stands for the percentage of the response variable variation that is explained by the linear model. In this study, R-square value observed nearer to 95%, it means this model shows the variability of the response data around the mean. The regression equation for the change in surface roughness of the inner surface is shown in figure 4.8.

4.3.2 Outer Surface

In this section, the effect of the number of passes, concentration of abrasives and abrasive mesh size on the change in surface roughness is discussed. The same effect as inner surface is observed on the outer surface.

A. Change in Surface Roughness v/s Number of Passes

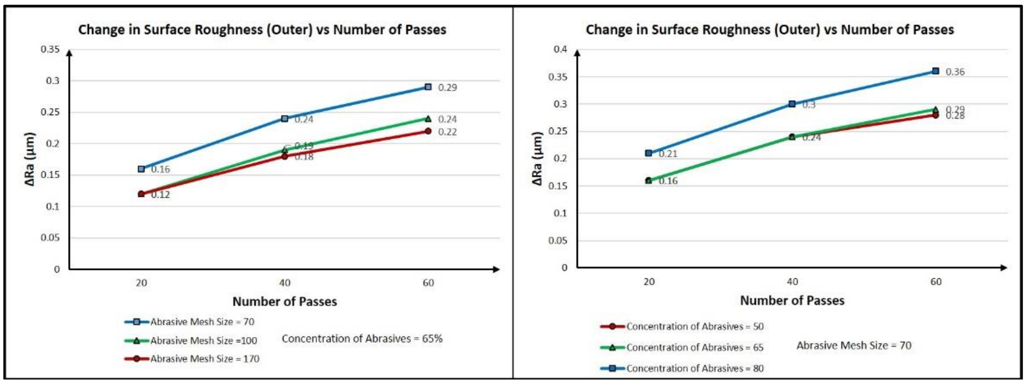


Figure 4.9: Change in surface roughness v/s Number of passes for outer surface

With the increase in the number of passes, the change in surface roughness is increased as depicted in figure 4.9. In initial passes the change in surface roughness is high, but with an increase in the number of passes, the change in surface roughness per pass is decreased.

B. Change in Surface Roughness v/s Concentration of Abrasives

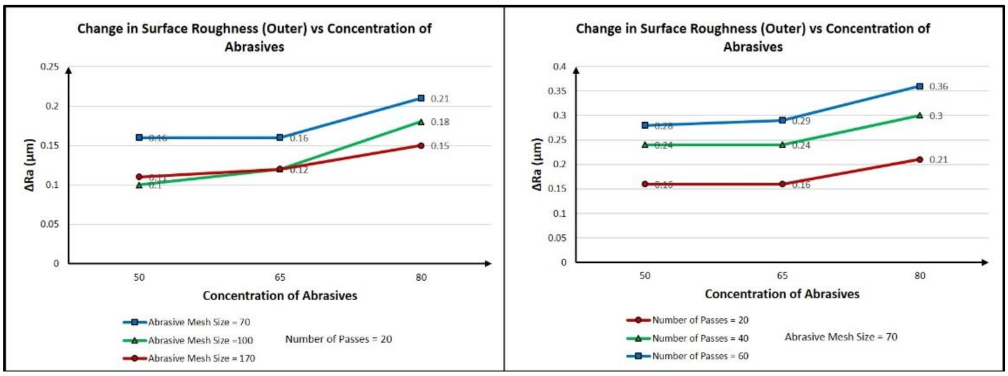


Figure 4.10: Change in surface roughness v/s concentration of abrasives for outer surface

As soon as the concentration of abrasives in the media increases, the change in surface roughness per pass is increased because of increase in active grain density as shown in figure 4.10.

C. Change in Surface Roughness v/s Abrasive Mesh Size

With the increase in the abrasive mesh size, the change in surface roughness of the workpiece is decreased as shown in figure 4.11, because a smaller amount of material is removed in the form of microchips as soon as the mesh size of the abrasive increased.

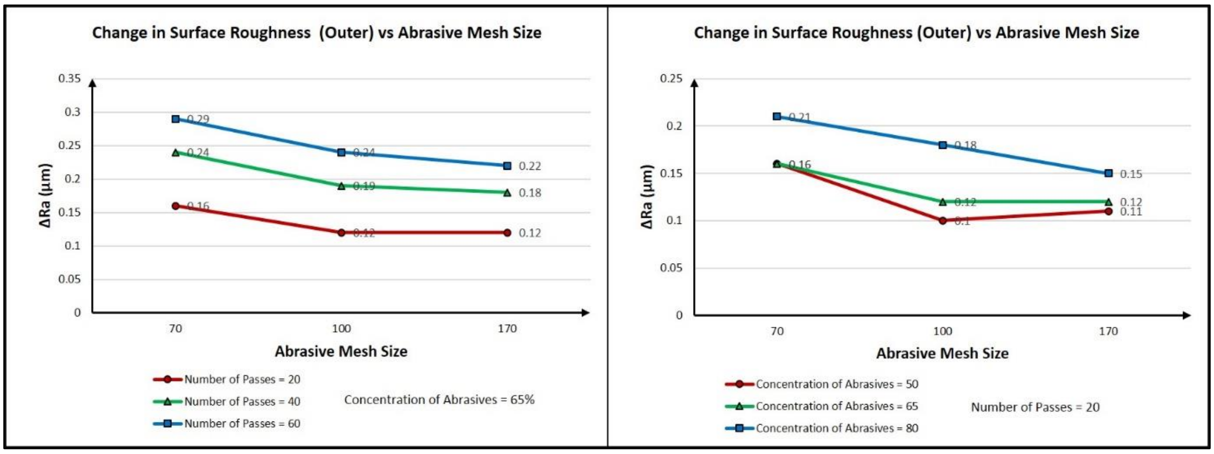


Figure 4.11: Change in surface roughness v/s abrasive mesh size for outer surface

D. Main Effect Diagram for Outer Surface

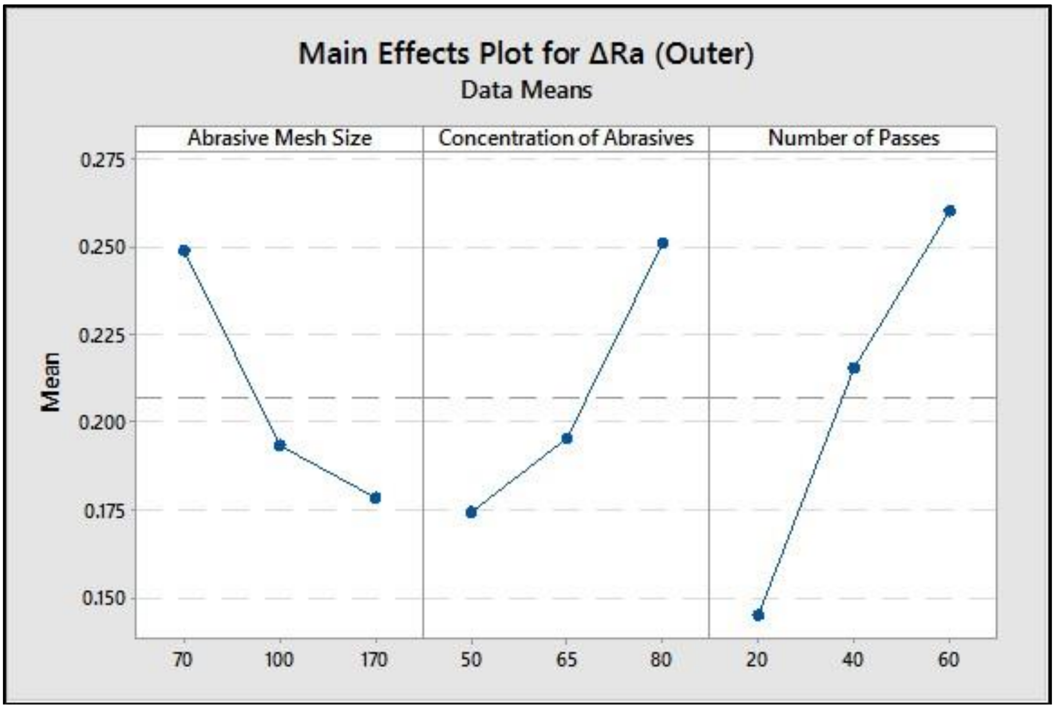
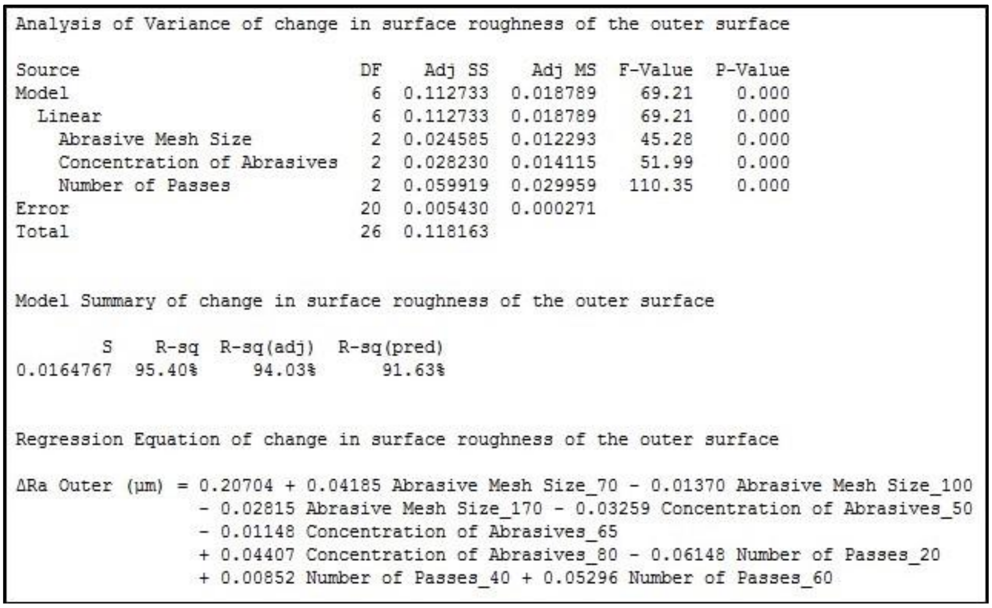


Figure 4.12: Main effect diagram of change in surface roughness for the outer surface

The same observation as inner surface is discovered for the outer surface. As soon as the abrasive size and the concentration of abrasives in media increases, the change in surface roughness increased. But, with an increase in a number of passes, the rate of improvement in surface roughness is decreased but the finishing of the surface is increased. The main effect diagram for the outer surface is shown in figure 4.12.

E. Statistical analysis of the change in surface roughness of the outer surface



```
Analysis of Variance of change in surface roughness of the outer surface

Source                        DF    Adj SS    Adj MS  F-Value  P-Value
Model                          6  0.112733  0.018789    69.21    0.000
  Linear                       6  0.112733  0.018789    69.21    0.000
    Abrasive Mesh Size         2  0.024585  0.012293    45.28    0.000
    Concentration of Abrasives  2  0.028230  0.014115    51.99    0.000
    Number of Passes           2  0.059919  0.029959   110.35    0.000
Error                         20  0.005430  0.000271
Total                         26  0.118163


Model Summary of change in surface roughness of the outer surface

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0164767  95.40%     94.03%      91.63%


Regression Equation of change in surface roughness of the outer surface

ΔRa Outer (µm) = 0.20704 + 0.04185 Abrasive Mesh Size_70 - 0.01370 Abrasive Mesh Size_100
                 - 0.02815 Abrasive Mesh Size_170 - 0.03259 Concentration of Abrasives_50
                 - 0.01148 Concentration of Abrasives_65
                 + 0.04407 Concentration of Abrasives_80 - 0.06148 Number of Passes_20
                 + 0.00852 Number of Passes_40 + 0.05296 Number of Passes_60
```

Figure 4.13: Statistical analysis of change in surface roughness of the outer surface

With the objective to maximize the change in surface roughness of the outer surface, the significance of the input parameters is analysed. The p-value of all the input parameters are less than the 0.05 and F_{crit} for (6,20) is less than the F_{obs}, which means all the input parameters has a significant effect on the change in surface roughness of the outer surface. R-square value for ΔRa of the outer surface is also greater than the 90%, hence all the response data variability around the means. The regression equation for the change in surface roughness of the outer surface is shown in figure 4.13.

4.3.3 Side Surface

The change in surface roughness of the workpiece with respect to the change in a number of passes, abrasive mesh size, and concentration of the abrasives in the media are discussed in this topic.

A. Change in Surface Roughness v/s Number of Passes

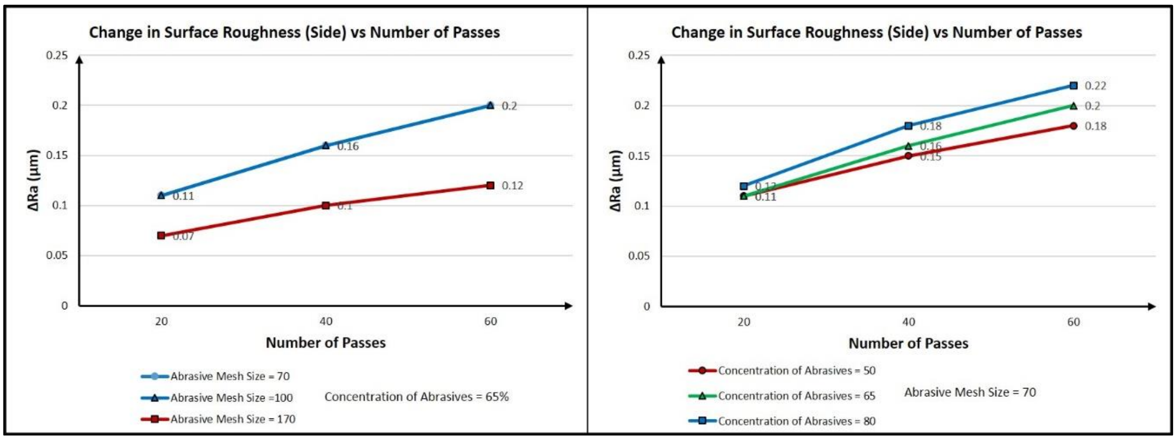


Figure 4.14: Change in surface roughness v/s number of passes for side surface

With the increase in the number of passes, the change in surface roughness is increased and surface roughness value is decreased as depicted in figure 4.14.

B. Change in Surface Roughness v/s Concentration of Abrasives

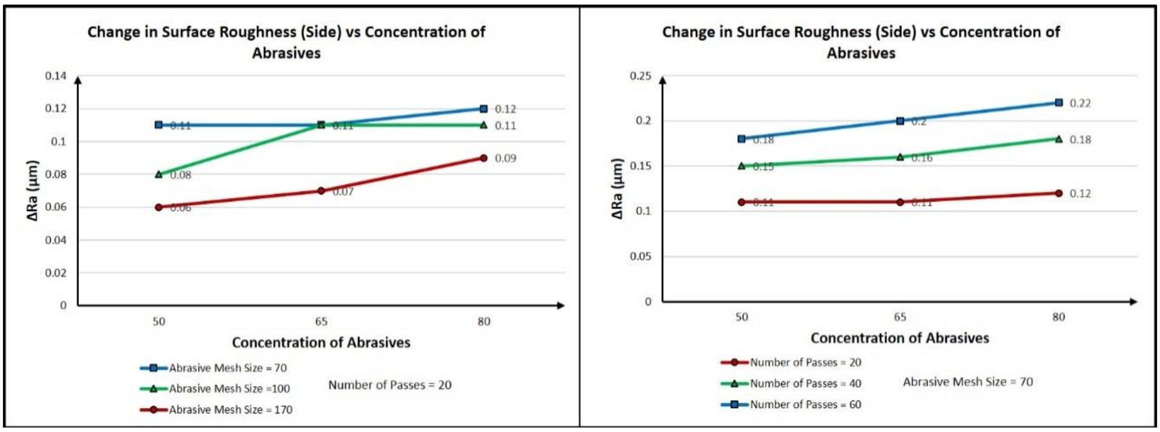


Figure 4.15: Change in surface roughness v/s concentration of abrasives for side surface

With the increase in the concentration of the abrasive in the media, more abrasives come in contact with the workpiece surface and hence, more change in surface roughness value is observed. The relation between the change in surface roughness and the concentration of abrasives for side surface are shown in figure 4.15.

C. Change in Surface Roughness v/s Abrasive Mesh Size

With the increase in abrasive mesh size, indentation of abrasive in workpiece surface is decreased; the change in surface roughness value is decreased as shown in figure 4.16.

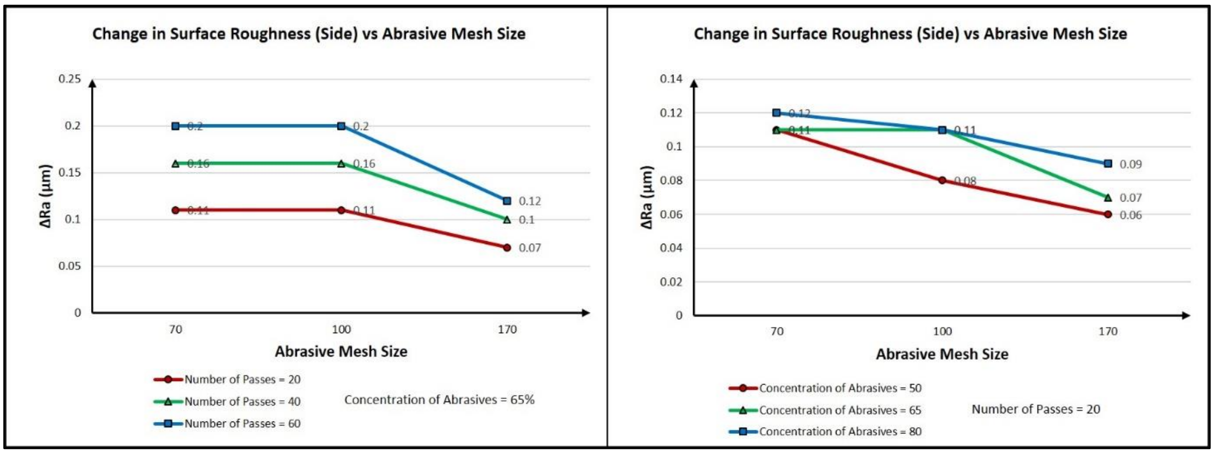


Figure 4.16: Change in surface roughness v/s abrasive mesh size for side surface

D. Main Effect Diagram for Side Surface

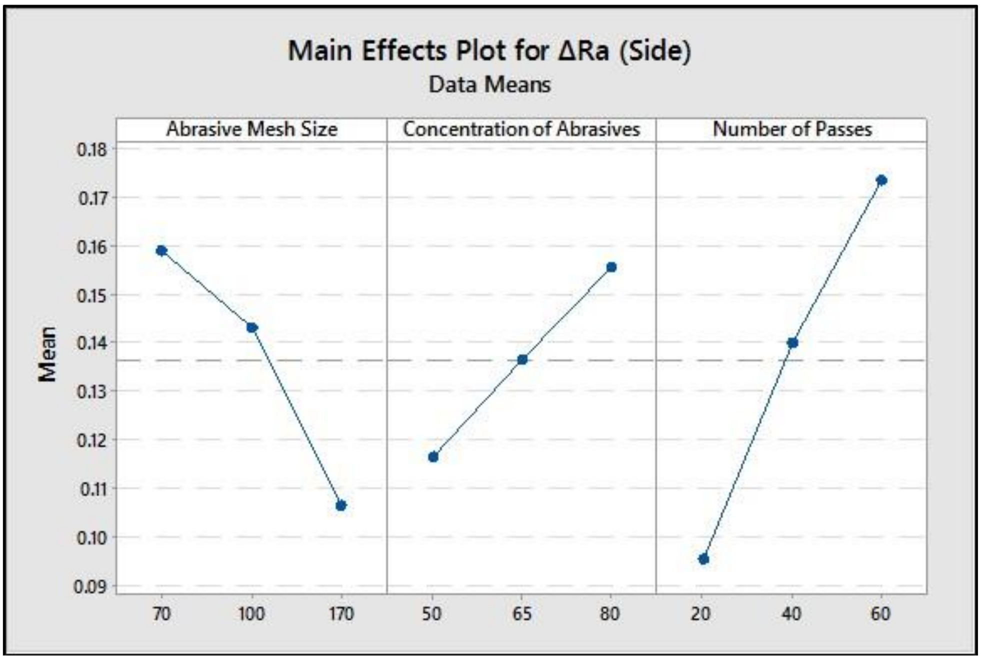
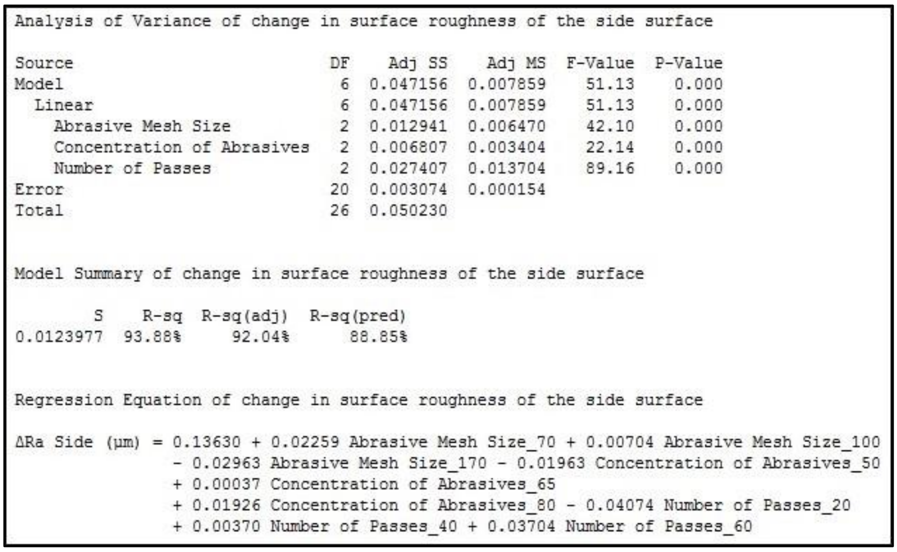


Figure 4.17: Main effect diagram of change in surface roughness for side surface

It is initially assumed that with abrasive flow machining, the surface roughness value of side surface won’t get change because abrasives come in contact normally with the workpiece surface. But, after experimentation, there is some improvement in surface roughness value of side surface is observed. The reason for this contradict may be given as media flow in the fixture is such a way that abrasives come in contact with workpiece surface in the tangential direction. Hence, there was some relative motion between abrasives and side surface is observed. Therefore, some improvement in surface roughness value of side surface is observed in this study.

E. Statistical analysis of change in surface roughness of the side surface

Since p-value for all the process variables is less than 0.05 and the F_{obs} (51.13) is greater than the F_{crit} (2.60), hence all the process variables have a significant effect on the change in surface roughness of the side surface. Also, R-square value is greater than 90%, it means that variability in response variables around the mean only. The regression equation for the ΔRa for side surface is shown in figure 4.18.



```
Analysis of Variance of change in surface roughness of the side surface

Source                        DF    Adj SS    Adj MS  F-Value  P-Value
Model                          6  0.047156  0.007859    51.13    0.000
  Linear                       6  0.047156  0.007859    51.13    0.000
    Abrasive Mesh Size         2  0.012941  0.006470    42.10    0.000
    Concentration of Abrasives 2  0.006807  0.003404    22.14    0.000
    Number of Passes           2  0.027407  0.013704    89.16    0.000
Error                         20  0.003074  0.000154
Total                         26  0.050230


Model Summary of change in surface roughness of the side surface

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0123977  93.88%     92.04%      88.85%


Regression Equation of change in surface roughness of the side surface

ΔRa Side (µm) = 0.13630 + 0.02259 Abrasive Mesh Size_70 + 0.00704 Abrasive Mesh Size_100
                - 0.02963 Abrasive Mesh Size_170 - 0.01963 Concentration of Abrasives_50
                + 0.00037 Concentration of Abrasives_65
                + 0.01926 Concentration of Abrasives_80 - 0.04074 Number of Passes_20
                + 0.00370 Number of Passes_40 + 0.03704 Number of Passes_60
```

Figure 4.18 Statistical analysis of change in surface roughness of the side surface

4.4 Percentage improvement in surface finishing

From the last graphical interpretation, it was clear that with an increase in the number of passes, concentration of abrasives in media and size of abrasives, the overall surface finish of the workpiece is improved with abrasive flow machining.

It can be speculated that surface finish achieved in the internal surface is more as compared to the external surface because the momentum of the fluid in the centre is high as compared to the momentum of the fluid near the outer wall of the ring/pipe. Since, with an increase in the momentum, more abrasive force come in contact with the work surface, a higher degree of finish at the internal surface is predicted.

But, in this study, it was found that percentage improvement of the surface finish of external surface is slightly more as compared to the percentage improvement of the internal surface. It contradicts our prediction because the design of fixture is made in such a way that there is no place for the change in media flow with respect to the surface. Hence, fixture design plays a vital role in achieving the objective of the simultaneous finishing of the workpiece.

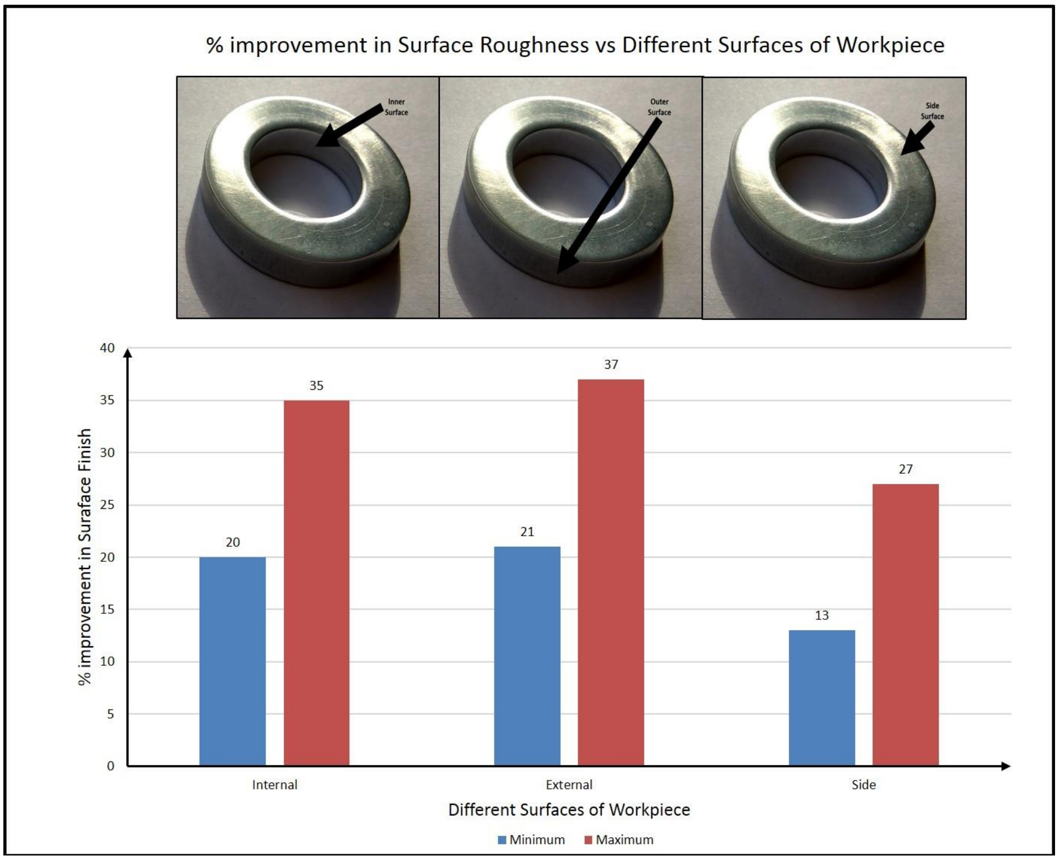


Figure 4.19: Percentage improvement in surface roughness v/s different surfaces of workpiece

In this study, it was found that the maximum percentage improvement in the surface finish of external and internal surfaces is nearly equal to 35%. It is generally observed that maximum percentage improvement in surface roughness of the workpiece is notice when the abrasive mesh size is 70 and concentrations of the abrasives are 80%. With the increase in abrasive grain size, the indentation of grain in the workpiece is increased and with an increase in the concentration of abrasive in media, the active grain increases and hence, percentage improvement in surface roughness is observed more in this condition for a same number of passes.

While the minimum percentage improvement in surface roughness of the external and internal surfaces are nearly 20%. The minimum surface roughness improvement is observed when the machining condition is set to abrasive mesh size as 170 and concentration of abrasive in media as 50%. The same reason is given for this type of observation, as soon as the abrasive size and concentration of the abrasive decreases, the amount of indentation of abrasives and the active grain density decreases, and hence lesser percentage of improvement is observed for this type of machining condition.

The percentage improvement in the surface roughness of the side surface is lesser than both external and an internal surface and is nearly equal to 27%. The reason behind this may be given as the internal and external surfaces come in contact with abrasives in parallel direction while the side surface comes in contact with the abrasives in more or less perpendicular direction to the workpiece surface.

Hence, it is concluded from above description that the surface finish improvement of the internal and external surfaces are nearly equal and the percentage improvement in a side surface is slightly lesser than both.

4.5 Amount of Material removal

The effects of the input parameters such as a number of passes, concentration of the abrasives in the media and abrasive mesh size present in media on the amount of material removed are discussed in this topic.

A. Amount of Material Removed v/s Number of Passes

As soon as the number of passes increases the amount of removed material is increased but the rate of material removal per passes is decreased as shown in figure 4.20.

This observation is notice because in some initial passes the peaks of the surface roughness are broken away in the form of the microchips. With the increase in the number of passes, the ploughing effect is also increased because the material is difficult to remove by abrasive edges. But, with an increase in a number of passes, the surface roughness value of the workpiece surface decreases.

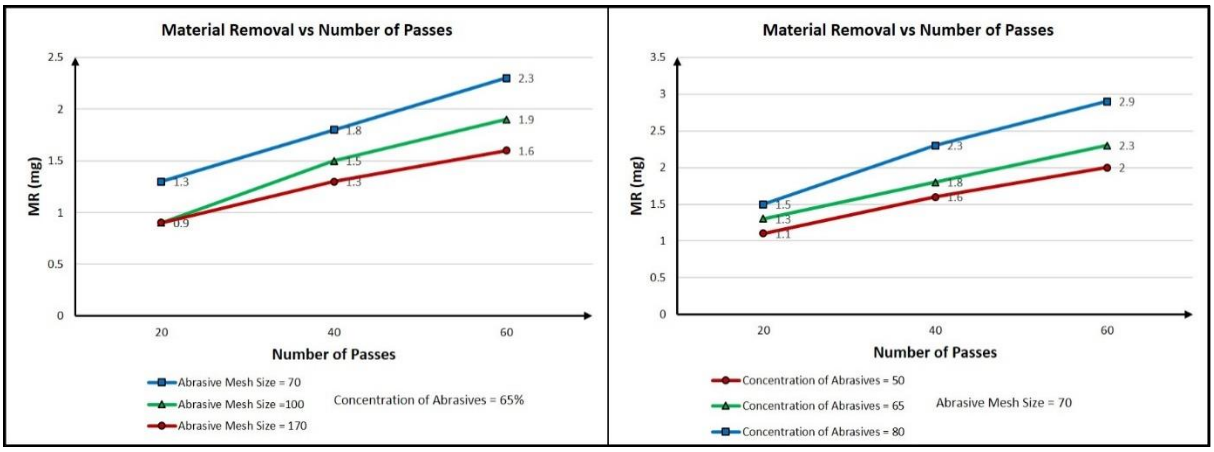


Figure 4.20: Material removal v/s number of passes for amount of material removal

B. Amount of Material Removed v/s Concentration of Abrasives

With the increase in the concentration of the abrasives in the media, the more abrasives come in contact with the workpiece surface and hence more surfaces are abraded and more amount of material is removed as shown in figure 4.21.

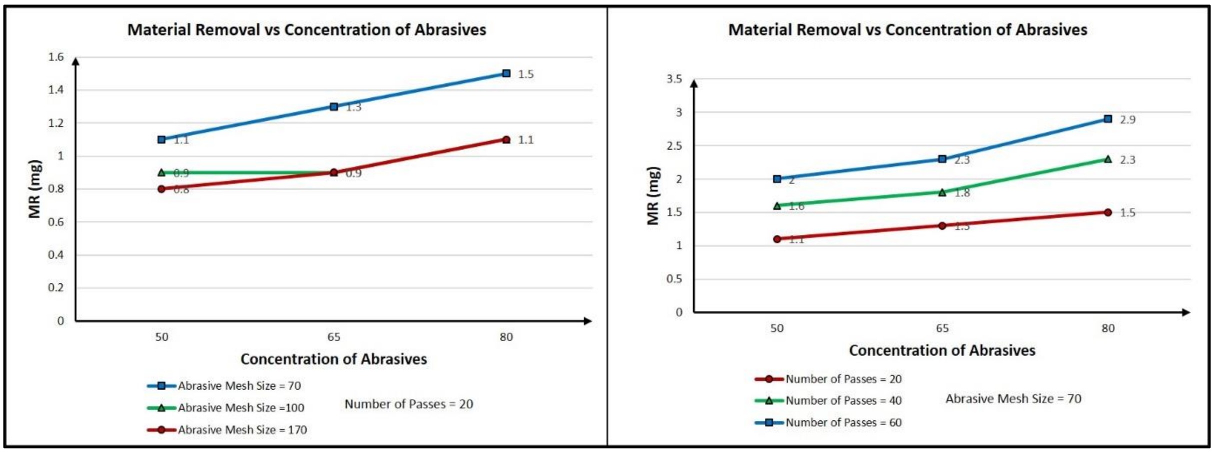


Figure 4.21: Material removal v/s concentration of abrasives for amount of material removal

Hence, with an increase in the concentration of the abrasives in the media, the amount of material removal is increased considerably.

C. Amount of Material Removed v/s Abrasive Mesh Size

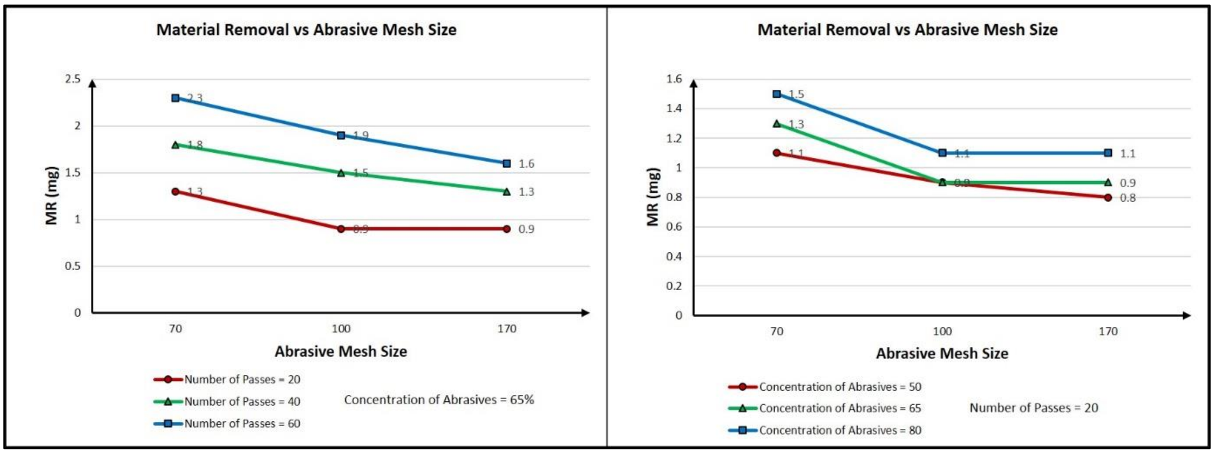


Figure 4.22: Material removal v/s abrasive mesh size for amount of material removal

As soon as the size of abrasive decreases, the lesser material of workpiece is come in contact with the abrasive surface, hence lesser the material removal from the workpiece. Hence, it is clear that with an increase in abrasive mesh size, the amount of material removal is decreased as shown in figure 4.22.

D. Main Effect Diagram for Material Removal

In this study, it was observed that, with an increase in abrasive size, concentration of abrasives in media and number of passes, the amount of material removal increased. But, it was also observed that with an increase in a number of passes, the rate of material removal per pass from workpiece surface is decreased. Hence, it is concluded that there was a high improvement in some initial passes of the media and the thereafter the quantity of material removal decrease. The main effect diagram between the inputs measures on the amount of material removed is shown in figure 4.23.

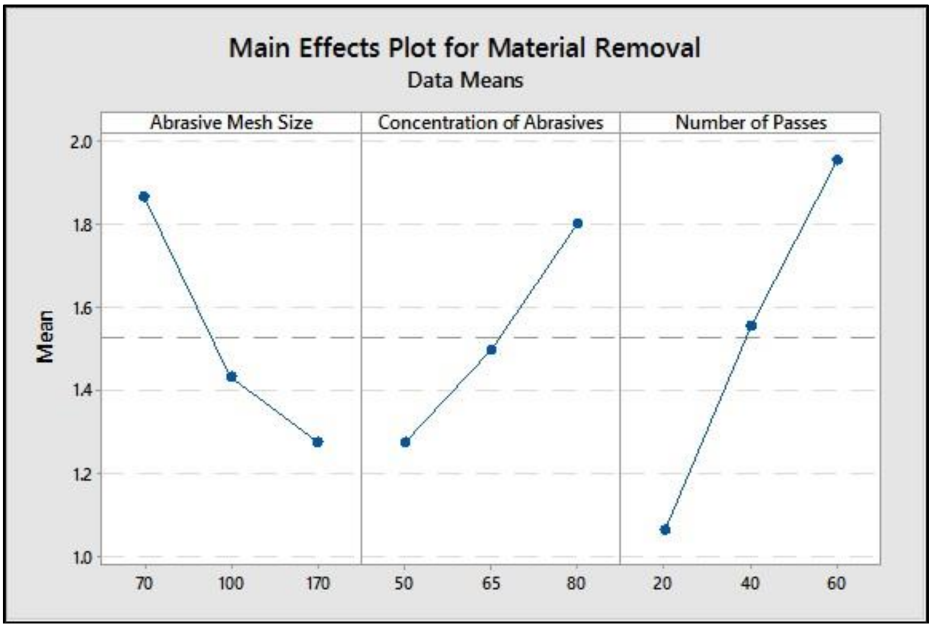


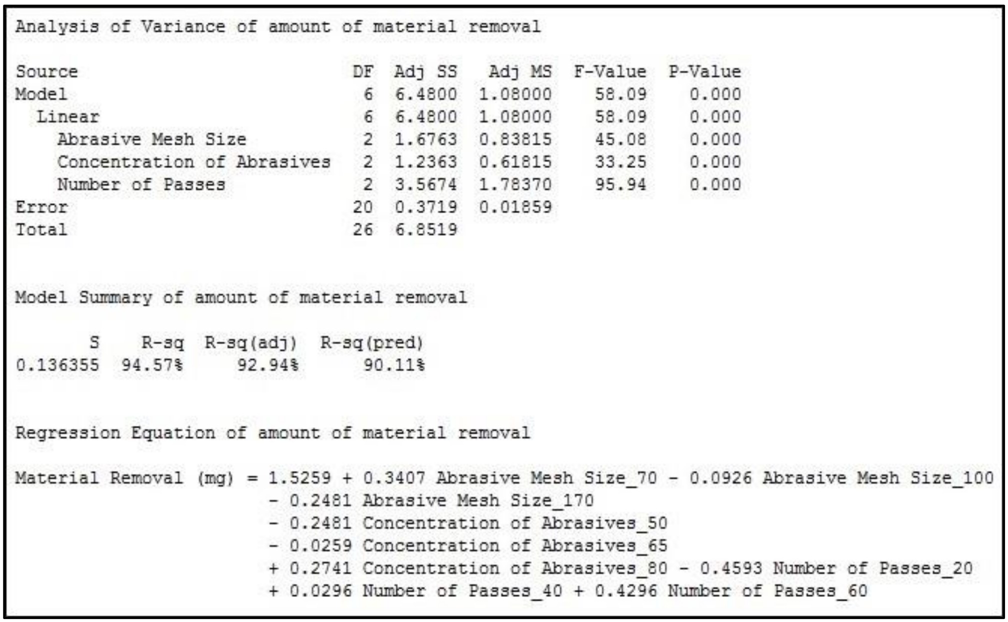
Figure 4.23: Main effect diagram for the amount of material removal

It is also assumed that with an increase in material removal, the surface finish may be worse because of possible ploughing in workpiece because of high indentation of abrasive. Literature indicates that ploughing effect of abrasives in the workpiece is observed after the applying extrusion pressure is more than the 5 to 6Mpa. But, in this study, applied extrusion pressure doesn’t exceed 2Mpa in any way. So, material removal from the workpiece increases the surface finishing of the workpiece.

E. Statistical analysis of amount of material removal

To examine the effect of process variables on the output variables, analysis of variance is applied to the collected data of the amount of material removal as shown in figure 4.24.

Since F_{crit} value (2.60) is less than the F_{obs} value (58.09), and a p-value of each variable is less than the 0.05, all the process variables have a significant effect on the amount of material removal from the workpiece. The R-square value is nearly equal to 94%, which means that much percentage of response variability are around the means only. The regression equation for the same is shown in figure 4.24.



```
Analysis of Variance of amount of material removal

Source                          DF  Adj SS   Adj MS  F-Value  P-Value
Model                            6  6.4800  1.08000    58.09    0.000
  Linear                         6  6.4800  1.08000    58.09    0.000
    Abrasive Mesh Size           2  1.6763  0.83815    45.08    0.000
    Concentration of Abrasives   2  1.2363  0.61815    33.25    0.000
    Number of Passes             2  3.5674  1.78370    95.94    0.000
Error                           20  0.3719  0.01859
Total                           26  6.8519


Model Summary of amount of material removal

       S    R-sq  R-sq(adj)  R-sq(pred)
0.136355  94.57%     92.94%      90.11%


Regression Equation of amount of material removal

Material Removal (mg) = 1.5259 + 0.3407 Abrasive Mesh Size_70 - 0.0926 Abrasive Mesh Size_100
                        - 0.2481 Abrasive Mesh Size_170
                        - 0.2481 Concentration of Abrasives_50
                        - 0.0259 Concentration of Abrasives_65
                        + 0.2741 Concentration of Abrasives_80 - 0.4593 Number of Passes_20
                        + 0.0296 Number of Passes_40 + 0.4296 Number of Passes_60
```

Figure 4.24: Statistical analysis of amount of material removal

4.6 Surface Characterization

Leica microscope which is located at the advanced measurement lab in Thapar University, Patiala has been used to view the surface topography of unfinished and finished workpiece as shown in figure 4.25. The workpiece surface has been zoomed to 10×.

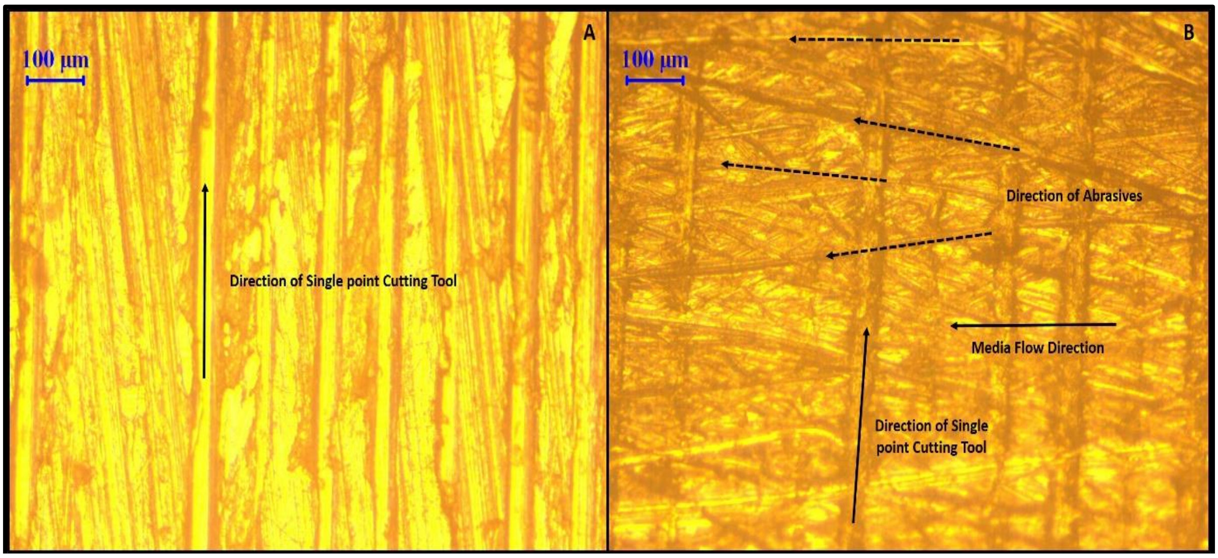


Figure 4.25: Leica microscopic images for side surface of (a) Unfinished workpiece, and (b) Finished workpiece at 10× zoom

For the unfinished surface, the vertical lay pattern for single point cutting tools has been observed. But, in the finished surface, the cross-hatched lay pattern of single point cutting tool with indentation of abrasives are also detected as shown in figure 4.25. For, side surface the workpiece, there should be a relative perpendicular direction of the media flow to the cuts of the single point cutting tools is predicated. But, while observation under the microscope, the cuts of abrasives are observed at some random angle with the flow of the media.

The probable reason for such type of abrasive cuts are may be given as media can supply in fixture through four media holes and come out from the other four media holes, hence, abrasive media has to travel at some angle with respect to the straight media flow direction to coming from the media holes. Therefore, abrasive indentation cuts are observed at a random angle under the Leica microscopic images.

The more random pattern of the abrasive flow is observed at side surface than the outer surface as shown in figure 4.26. The probable reason for this scenario may be given as at side surface media come in contact with workpiece through four media holes only. The media from four holes are moves surrounding to fill the fixture cavity. Hence, abrasive have to travel in a random direction instead of straight direction. But, at the outer surface, mostly less randomness in abrasive flow is observed because media fills cavity at side surface and now it has to move in a single direction to pass through workpiece surface and fill the fixture cavity.

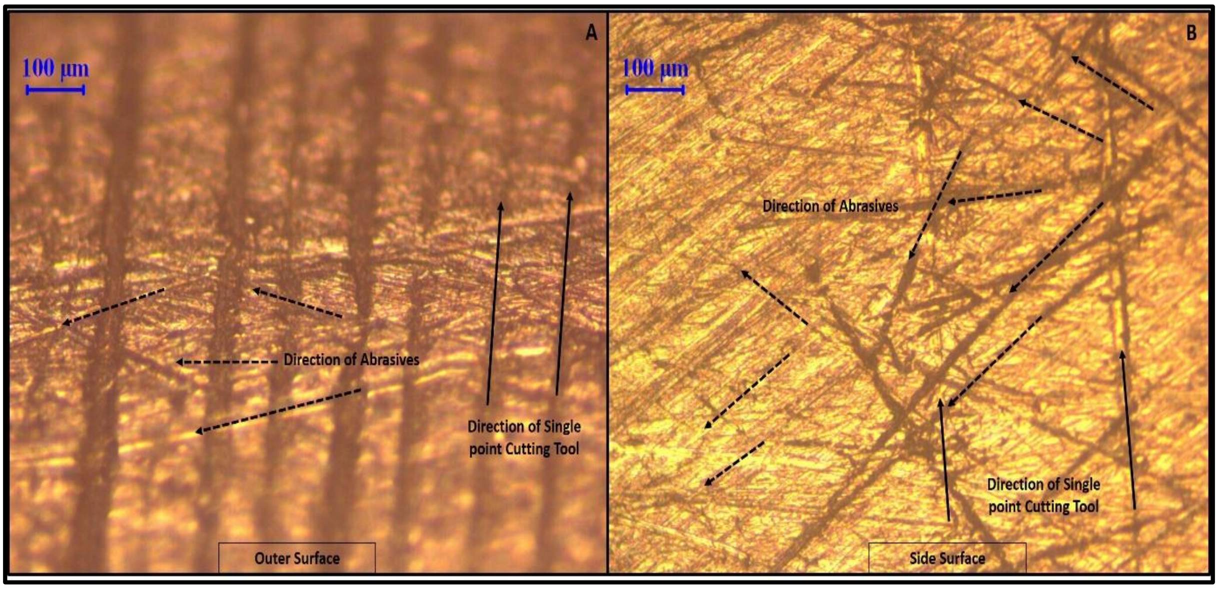


Figure 4.26: Leica microscopic images of finished workpiece at (a) Outer Surface, and (b) Side Surface at 10× zoom

The Leica microscopic images of outer surface at different zoom suggests that there is some ploughing effect due to the high indentation of abrasives present in this study as shown in figure 4.27.

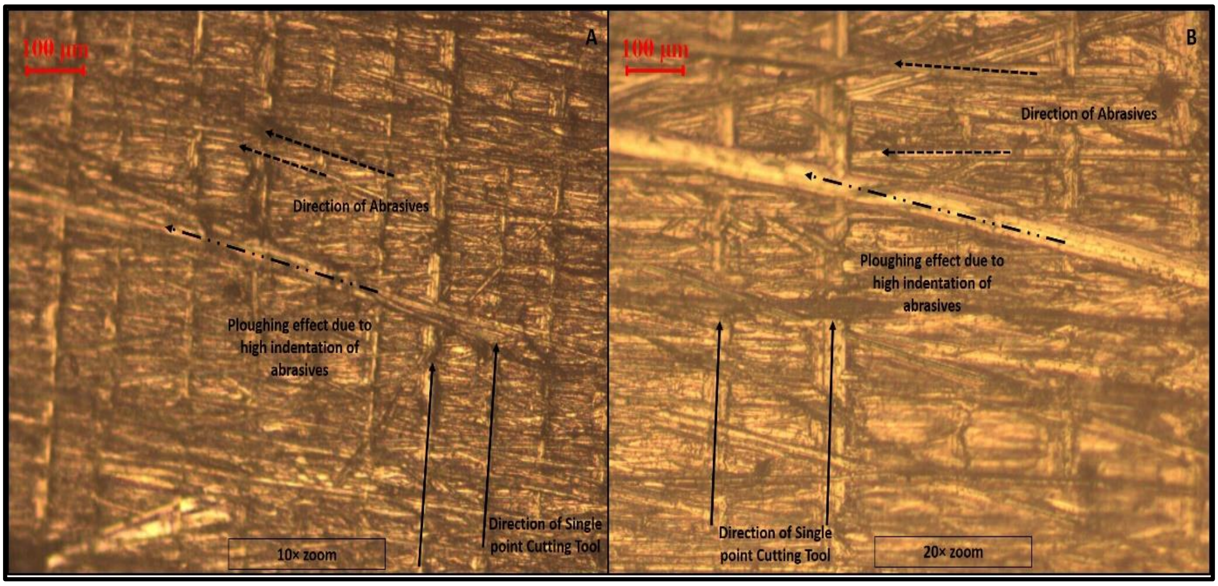


Figure 4.27: Leica microscopic images of finished workpiece at (a) Outer Surface at 10× zoom, and (b) Outer Surface at 20× zoom

At the time of experiments, there was a possibility that the high abrasive indentation occurs on the workpiece surface. Mostly, this type of ploughing effect due to the high indentation of the workpiece has worsened the surface instead of finishing it. The pressure also plays a vital role in producing high indentation of the abrasives on the surfaces. After the 5 to 6 Mpa, the surface of workpiece worsens instead of finishing because of presence indentations as depicted in figure 4.27. But, in this study, this type of indentation is negligible and they didn’t worsen the surface finish of the workpiece.

Chapter V - CONCLUSION & FUTURE SCOPE

5.1 CONCLUSION

After studying the effect of the input parameters such as number of passes, abrasive mesh size and concentration of abrasives in the media on output parameters such as change in surface roughness and amount of material removed with abrasive flow machining process, the following conclusions are made;

(1) The simultaneous finishing i.e. internal and external surface finishing of the ring-shaped cylindrical workpiece is possible with the abrasive flow machining.

(2) The objective of simultaneous finishing of the workpiece can be easily achieved by the change and/or improvement in fixture design.

(3) The change in surface roughness of the external and internal surfaces is comparatively more than the change in surface roughness of the side surface of the ring-shaped aluminium workpiece.

(4) The initial surface roughness range of the inner surface is 0.82-0.99 μm; after experiments obtained surface roughness range is 0.56-0.75 μm. The initial and final surface roughness range of the outer surface of the workpiece are 0.81-0.97 μm and 0.59-0.74 μm respectively. For side surface, the initial and final surface roughness ranges are 0.81-0.98 μm and 0.59-0.74 μm respectively.

(5) The percentage improvement in surface roughness of the internal, external and side surface of the ring-shaped workpiece are observed in this study are 35, 37 and 27% respectively.

(6) The maximum percentage improvement in surface roughness of the internal and external surface is nearly equal to 35%, while the maximum percentage improvement for the side surface is 27% only.

(7) With the increase in the number of passes, the size of abrasives and concentration of abrasives in media, the change in surface roughness is increased and the smoother surface is obtained with abrasive flow machining.

(8) The change in surface roughness increases with increase in the concentration of abrasive in the media and decrease in abrasive mesh size.

(9) The improvement in surface finish per pass is decreased with increase in a number of passes because more peaks are present in initial passes and are removed easily. After some passes, the rate of material removal per pass is decreased.

(10) With the increase in the number of passes, abrasive size, and concentration of abrasives, the more abraded action is taking place and more material is removed in the form of microchips, hence, more amount of material is removed.

(11) With abrasive mesh size 70, the concentration of abrasives in media is 80%, and the number of passes is 60; the maximum change in surface roughness and the material removal is observed for the same machining condition.

(12) With abrasive mesh size 170, and concentration of abrasives in media is 50%, the minimum change in surface roughness and material removal is observed for same machining condition.

5.2 FUTURE SCOPE

Although the present study, considers simultaneous finishing of ring-shaped aluminium workpiece but still there is a scope for further investigation considering the vast potential of this technique. The following suggestion is useful for future work:

(1) Simultaneous finishing may be useful sometimes for functional and aesthetic purposes. Hence, some applications related to stated purposes can be addressed in future work, such as deep groove ball bearing can be finished in one go with abrasive flow machining instead of separately finishing of the outer race, inner race and the ceramic balls with traditional processes.

(2) Some work parameters such as hydraulic pressure, media viscosity, working temperature etc. and their effect on change in surface roughness and material removal rate can be postulated.

(3) Media properties can be analysed with varying input parameters.

(4) The more hard material may be machined and different effects can be analysed.

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