PARAMETRIC OPTIMIZATION OF CNTs PARTICLE BASED ABRASIVE MEDIA USED IN ABRASIVE FLOW MACHINING PROCESS FOR FINISHING OF CAST IRON WORKPIECE

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CERTIFICATE

This is to certify that the thesis entitled ***'PARAMETRIC OPTIMIZATION OF CNTs PARTICLE BASED ABRASIVE MEDIA USED IN ABRASIVE FLOW MACHINING PROCESS FOR FINISHING OF CAST IRON WORKPIECE'*** is a bonafied work carried out by **Sonu Kumar** (Roll Number 2K12/PIE/22) in partial fulfilment for the award of the degree of Master of Technology in Production Engineering from **Delhi Technological University**, is an authentic work carried out by him under my guidance. The matter embodied in this thesis has not been submitted earlier for the award of any degree or diploma to the best of my knowledge and belief.

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ABSTRACT

Over recent years a significant amount of research has been undertaken to develop a process which can machine the component with higher MR and surface finish (Ra value). AFM is a relatively new process in the field of modern machining/finishing. It offers brilliant surface finish, economy and dimensional accuracy of the machined parts. Its applications have rapidly diversified into the automobile, pharmaceutical, chemical, production, defence, space and aeronautics industry.

In this report, a thorough study of present developments in the field of AFM was carried out. The indigenous new vertical double acting AFM setup is designed and developed with varying ranges of process parameters. Nano particles have extraordinary properties over available abrasives, so to enhance MR and surface finish nano particles can be used. Nanotubes find applications as additives to various structural materials so an attempt is made to CNTs as abrasive with the carrier and Al_2O_3 to machine the cast iron workpiece.

Study and synthesis of iron filled CNTs is discussed and it is characterized through Transmission Electron Microscope (TEM) images. In this study an endeavour was carried out to develop media (carrier+Al_2O_3+CNTs) as an alternative to the exiting available media. Experiments have been conducted using the Taguchi L_9 OA method and the relevant dependencies have been found out by carrying out ANOVA analysis It is found that the developed media is flexible to be used in AFM process and performance study reveals that the developed media yields a good surface finish and material removal (MR).

DEDICATIONS

This research is dedicated

to my parents; who have supported

me all the way since the beginning of my studies.

Also I dedicate this work to Neetu my loving wife who

has been a great source of moral Support, Strength,

Motivation and Inspiration.

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S.No. Symbol

S.No.	Symbol	Description
1.	S/N	Signal to Noise Ratio
2.	LN	OA designation
3.	f LN	Total degree of freedom of an OA
4.	R	Number of repetitions
5.	$\bar{T}$	Overall mean of the responses
6.	$\bar{A}2$,$\bar{B}2$	Average values of responses at the second level of parameters A&B
7.	CICE	Confidence Interval of confirmation experiments
8.	CIPOP	Confidence Interval of Population
9.	F α	The F-Ratio at the confidence level of (1- α) against DOF 1
10.	f_e	Error DOF
11.	V_e	Error Variance

CHAPTER 1
INTRODUCTION

1.0 Introduction

Technology is emerging and advancing day by day with the demand for highly accurate, precise and highly efficient machining process for advanced industries from critical aerospace and medical components to mass production automobile parts. This process has capability of finishing even the most areas which are not accessible, processing multiple, slots or edges , holes in one operation[1]. The development of materials having higher strength, hardness, toughness and other desired properties. This also needs to develop the advanced cutting tools material which can ease the process and are economical without compromising productivity.

The application of advanced abrasive finishing technique are increasing so as to get the highly accurate and highly efficient machining of complex shaped 3D components with nano level surface finish.

Abrasive finishing can be employed to finish most mechanical parts with shape limitations. Initial surface roughness of 0.25μm R_a can be improved easily to 0.05 μm within a few minutes. In addition AFM process has many attractive advantages, such as self sharpening, self adoptability, controllability and finishing tool requires neither compensation nor dressing.

There are various abrasive particles like Al_2O_3,SiC, CBN, diamond powder etc. are available which are being used for abrasive finishing process. To increase the MR and surface roughness, the abrasive are made magnetic in nature with ferromagnetic material by various techniques like sintering, mechanical mixing using ball mill etc.

The CNTs filled with ferromagnetic particle is synthesized with Chemical Vapor Deposition(CVD) technique and it is characterized through Scanning electron microscope (SEM) and Transmission Electron Microscope(TEM) images to observe different characteristics behaviour and feasibility to machine.

1.1 Non-traditional manufacturing processes

Since beginning of the life on earth, people have evolved energy sources and tools to power these tools to meet the requirements for making the life easier. In the early stage of human beings, tools were made of stone for fabrication of products. When tools were invented, desirable metals and more sophisticated articles were produced. Earlier products were made from durable and consequently, unmachinable materials. In an effort to meet the fabrication challenges created by these materials, tools have now developed to include materials such as steel alloy, carbide, ceramics and diamond. A similar evolution has taken place with the methods used to power our tools. Initially, tools were powered by muscles; either human or animal. However as the powers of water, wind, steam and electricity were harnessed, human beings were able to further extend manufacturing capabilities with new machines, accuracy and faster machining rates. The traditional manufacturing processes in use today for material removal basically based on electric motors and hard tool materials to perform tasks such as drilling, boaring, milling and broaching. Conventional forming operations are performed with the energy from pneumatics, hydraulics, electric motors and gravity. Likewise, material joining is conventionally achieved with thermal energy sources such as burning gases and electric arcs. In contrast, non-traditional manufacturing processes harness energy sources considered unconventional by yesterday’s standards. Material removal could be achieved with electro-chemical reaction, plasmas and high velocity jets of liquids and abrasives particles. Materials those were in the past have been extremely difficult to form, are now formed with explosives and the shock waves from strong electric sparks and magnetic fields. Material-joining capabilities have been expanded with the use of high-frequency sound waves and beams of electrons and coherent light. During the last 50 years, over more than 20 different non-traditional manufacturing processes have been invented and successfully implemented into production. The non-conventional manufacturing processes are not affected by toughness or brittleness, hardness of material and can produce any intricate shape on any work piece material by suitable control over the various physical parameters of the processes. The non-traditional manufacturing processes may be classified on the basis of type of energy namely, electrical, chemical, mechanical, thermal or magnetic, apply to the work piece directly and have the desired shape transformation or material removal from the work surface by using different scientific mechanism. Thus, these non-conventional processes can be classified into various groups according to the basic requirements which are as follows:

(i) Type of energy required, namely electrical, mechanical, chemical etc.

(ii) Basic mechanism involved in the processes, like ionic dissolution, erosion, Vaporization etc.

(iii) Source of immediate energy required for material removal, namely, hydrostatic Pressure, high voltage, high current density, ionized material, etc.

(iv) Medium for transfer of those energies, like high velocity particles and electrolyte, Electron, hot gases, etc. On the basis of above requirements

(a) Ultrasonic Machining-Ultrasonic Machining is a non-traditional process, in which abrasives contained in slurry are driven against the work by a tool oscillating at low amplitude (25-100 µm) and high frequency (15-30 KHz). The process was first developed in 1950s and was originally used for finishing EDM surfaces. The basic process is that a ductile and tough tool is pushed against the work with a constant force. A stream of abrasive slurry passes between the tool and the work (gap is 25-40 µm) to provide abrasives and carry away chips. The majority of the cutting action comes from an ultrasonic (cyclic) force applied. The basic components to the cutting action are believed to be, brittle fracture caused by impact of abrasive grains due to the tool vibration; cavitations induced erosion; chemical erosion caused by slurry.

(b) Jet Machining In jet machining, high-velocity stream of water (Water Jet Cutting) or water mixed with abrasive materials (Abrasive Water Jet Cutting) is directed to the work piece to cut the material. If a mixture of gas and abrasive particles is used, process is termed as Abrasive Jet Machining and is used not to cut the work but for finishing operations like cleaning, polishing ,deburring.

(c) Water Jet Cutting Water Jet Cutting (WJC) uses a fine, high-pressure, high velocity (faster than speed of sound) stream of water directed at the work surface to cause slotting of the material: Water is the most common fluid used, but additives such as oil products and viscous glycerol are added when they can be dissolved in water to improve the fluid characteristics. The fluid is pressurized at 150-1000 MPa to produce jet velocities of 550-1400 m/s. The fluid flow rate is typically from 0.5 to 2.5 l/min. The jet has a well behaved central region surrounded by a fine mist.

(d) Abrasive Water Jet Cutting (AWJC) In Abrasive Water Jet Cutting, a narrow, water jet is mixed with abrasive particles is impacted with very high pressures resulting in high velocities that cut through all materials. The presence of abrasive particles in the water jet reduces cutting forces and enables cutting of thick and hard materials (steel plates over 80-mm thick can be cut). The stream velocity is up to 90 m/s, about 2.5 times the speed of sound Abrasive Water Jet Cutting process was developed in 1960s to cut materials that cannot withstand high temperatures for stress distortion or metallurgical reasons such as wood and composites, and materials which were difficult-to-cut traditionally. e.g. glass, stones, ceramics and titanium alloys. The common types of abrasive materials used are quartz sand, silicon carbide, and corundum , at grit sizes ranging between 60 and 120

(e) Abrasive Jet Machining (AJM) In Abrasive Jet Machining, fine abrasive particles (typically ~0.025mm) are accelerated in a gas stream (commonly air) towards the work piece surface. As the particles impact the work piece surface, they cause small fractures, and the gas stream carries both the abrasive particles and the fractured (wear) particles away. The jet velocity is in the range of 150-300 m/s and pressure is from two to ten times atmospheric pressure. The preferred abrasive materials involve aluminum oxide (corundum) and silicon carbide at small grit sizes. The grains should have sharp edges and should not be reused as the sharp edges are worn down and smaller particles can clog nozzle. Abrasive Jet Machining is used for debarring, etching, and cleaning of hard and brittle metals, alloys, and non-metallic materials (e.g., silicon, glass, ceramics and germanium).

(f) Electric Discharge Machining-this is one of the most widely used non-traditional processes. A formed electrode tool produces the shape of the finished work surface. The sparks occur across a small gap between tool and work surface. The machining must take place with dielectric fluid, which makes a path for each discharge as the fluid becomes ionized in the gap. The fluid, quite often kerosene-based oil is also used to flush the debris. The arc is generated by a pulsating direct-current power supply connected to the work and the tool. Electrode materials are high temperature, but easy to machine, thus allowing easy manufacture of intricate shapes. Typical electrode materials include graphite, copper and tungsten. The process is based on melting temperature, not hardness, so very hard materials can be machined this way

(g) Wire Electric Discharge Machining-Wire EDM is a special form of EDM that uses a small diameter wire as the electrode to cut narrow kerfs in the work. The work piece is fed continuously and slowly past the wire in order to achieve the desired cutting path. Numerical control is used to control the work-part motions during cutting. As it cuts, the wire is continuously advanced between a supply spool and a take-up spool to present a fresh electrode of constant diameter to the work. This helps to maintain a constant kerfs width during cutting. Wire EDM must be carried out with dielectric fluid. This is applied by nozzles directed at the tool-work interface as in the figure, or the work part is submerged in a dielectric bath. Wire diameters range from 0.08 to 0.30 mm, depending on required kerfs width. Materials used for the wire include copper, brass, tungsten, and molybdenum. Dielectric fluids include demonized water or oil. As in electric discharge machining, an overcut in the range from 0.02 to 0.05 mm exists in wire EDM that makes the kerfs larger than the wire diameter.

(h) Laser beam machining (LBM) - Laser beam machining (LBM) uses the light energy from a laser to remove material by vaporization and ablation. The types of lasers used in LBM are basically the carbon dioxide (CO2) gas lasers. Lasers produce collimated monochromatic light with constant wavelength. In LBM all of the light rays are parallel, which allows the light not to diffuse like normal light. The light produced through the laser has significantly less power than a normal white light, but it would be highly focused, thus delivering a significantly higher light intensity and respectively temperature in a very localized area. Lasers are being used for a variety of industrial applications like heat treatment, welding, and measurement, as well as a number of cutting operations such as drilling, slitting, slot cutting, and marking operations. Drilling micro-diameter holes is possible, down to 25 µm. For larger holes, the laser is controlled to cut the outline of the hole. The range of work materials that can be machined by Laser Beam is virtually unlimited including metals with high hardness and strength, ceramics, soft metals, glass, plastics, rubber, wood and wood. LBM can be used for 2-Dimensional or 3-Dimensional workspace. The LBM machines typically have a laser mounted, and the laser beam is directed to the end of the arm using mirrors. Mirrors are often cooled (water is common) because of high laser powers.

(i) Electron beam machining (EBM) - Electron beam machining (EBM) is one of several industrial processes that use electron beams. Electron beam machining uses a high-velocity stream of electrons focused on the work piece surface to remove material by melting and vaporization an electron beam gun generates a continuous stream of electrons that are focused through an electromagnetic lens on the work piece surface. The electrons are accelerated with voltages of approx. 150,000 V to create velocities over 200000 km/sec. The lens is capable of reducing the area of the beam to a diameter as small as 25 micron. On impinging the surface, the K.E of the electrons is converted into thermal energy of extremely high density, which vaporizes the material in a much localized area. EBM must be carried out in a vacuum chamber to eliminate collision of the electrons with gas molecules. Electron beam machining is used for a variety of high-precision cutting applications on any known material. Applications include drilling of extremely small diameter holes, down to 50 µm diameters, drilling of holes with very high depth-to-dia ratios, more than 100:1, and cutting of slots that are only about 25 µm wide. Besides machining, heat treatment and welding are other significant applications of the technology. The process is generally limited to very thin parts in the range from 0.2 to 6 mm thick. Other limitations of EBM are the need to perform the process in a vacuum which require the high energy and the expensive equipment.

(j) **Abrasive Flow Machining (AFM) -** In abrasive flow machining, the viscous elastic media flows through the workpiece, performing erosion. Abrasive particles in the slurry contact raised features on the intricate surface of the workpiece and flush them. The slurry is forced through the workpiece by means of hydraulic ram to the shape of the workpiece. The maximum amount of material removal occured in areas where the flow of the slurry is restricted; according to Bernoulli's Principle, pressure and flow speed of the fluid increase in these areas, facilitating a higher material removal rate.The pressure exerted by the fluid on all contacting surfaces also results in a very uniform finish. The detailed process and its classification is discussed in this report.

1.2 Basic principle of AFM

In abrasive flow machining, the abrasive fluid flows through the work piece, effectively performing erosion. Abrasive particles in slurry contact raised features on the surface of the work piece and flush them. The fluid is forced through the work piece by a Hydraulic ram where it acts as a flexible file, moulding itself precisely to the shape of the work piece surface. The highest amount of material removal occurs in areas where the flow of the fluid is restricted; according to Bernoulli's principle, the speed and pressure of the fluid increase in these areas, facilitating a higher MMR. The pressure exerted by the fluid on all contacting surfaces also results in a very uniform finish. AFM may be performed once, as a one-way flow process, or repeatedly as a two-way flow process (double acting). In the two-way flow process, a reservoir of medium exists at either end of the work piece, and the medium flows back and forth through the work piece from reservoir to reservoir.

1.3 Classification of AFM

1.3.1 One way AFM process

In one way [2] AFM process the media is extruded inside the work piece only in one direction. For this purpose the setup has a hydraulically actuated reciprocating piston and an extrusion medium chamber adapted to receive and extrude medium unidirectional across the internal surface of the work piece having internal passage formed therein. Piston direct the media through the internal passage of the work piece while a medium collector collects the media as it is extruded out through the work piece. The extrusion media chamber is provided with an access port to periodically receive medium from the collector into extrusion medium chamber. The hydraulically actuated piston intermittently withdraws from its extruding position to open the extrusion media chamber access port to collect the medium in the extrusion media chamber. When the extrusion medium chamber is charged with the working media, the operation is resumed.

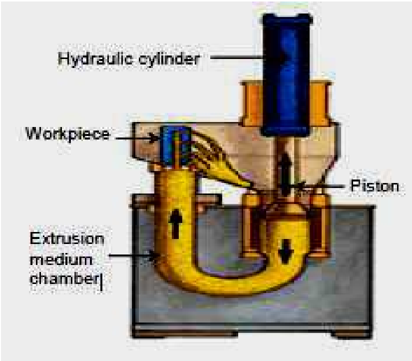


Figure 1. Schematic of One –way AFM[3]

1.3.2 Two-way AFM process

Two ways AFM machine [4] has two hydraulic cylinders and two medium cylinders. The media is extruded, hydraulically or mechanically, from the filled chamber to the empty chamber via the restricted passageway through or past the work piece surface mounted in fixture to be abraded (Figure 2). Typically, the medium is extruded back and forth between the chambers for the predetermined fixed number of cycles. Counter bores, recessed areas and even inaccessible cavities can be finished by using restrictors or mandrels to direct the medium flow along the surfaces to be finished.

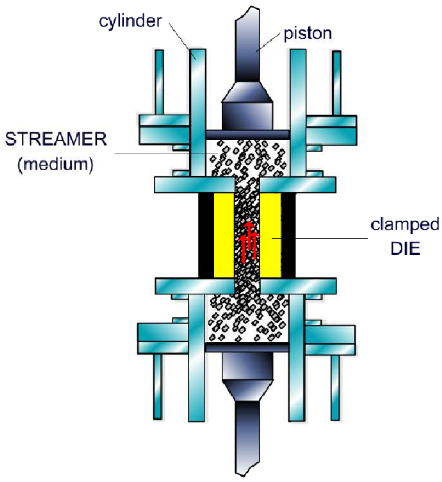


Figure 2. Schematic of two way AFM[5]

1.3.3 Orbital AFM

In this process good surface finishing is obtained by producing low-amplitude oscillations of the work piece [6].The tool consists a layer of abrasive-laden elastic plastic medium (i.e. same as used in two way abrasive flow finishing), and has a higher viscosity and more elastic in nature.

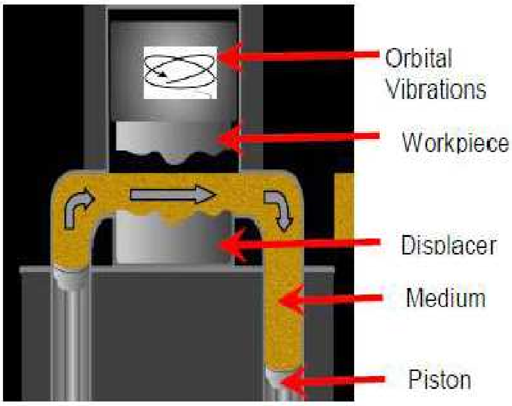
+ 

Figure 3. Operational set up of Orbital AFM [6]

1.4 Elements of abrasive flow machining

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

1.4.1Fixture

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

Fixture design is often a very important factor in achieving the desired effects from the AFM process as the design of fixture depends on the shape of work piece. In this project the work piece is cylindrical so a proper design of fixture is used which can hold a cylindrical work piece. Basic functions of fixture [7] include:

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

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

Figure 4. (a),(b) Nylon Fixtures used in AFM setup

1.4.2 Abrasive media

This technique uses a non-Newtonian liquid polymer containing abrasive particles of Al_2O_3, SiC, boron carbide or diamond as the grinding medium and additives [8]. The viscosity and the concentration of the abrasives can be varied Most widely used carrier is a high viscosity fluid. The base materials have enough degree of cohesion and tenacity to drag the abrasive grains along with it through various passages. AL_2O_3 and SiC are most suitable abrasives for many applications but Cubic boron nitride (CBN) and diamond are specifically used for special applications. Abrasive particles to base material ratio can be varying from 2 to 12.Abrasive are available in different mesh sizes. The abrasive have limited life. AS a thumb rule, when the media has machined an amount equal to 10% of its weight, it must be discarded. Machined parts should be properly cleaned before use, by acetone. The additives are used to enhance the base carrier to get the desired flowability and rheological characteristic of the media.

The newly developed media which having AL_2O_3 (180 mesh size), polymer and hydrocarbon gel is mixed properly in predetermined proportion to get the viscous elastic media which can machine effectively. Hydrocarbon gels are commonly used lubricants in the media. All additives are carefully blended in predetermined quantities to obtain consistent formulation.

Figure 5. Abrasive laden Media (carrier+Al_2O_3+CNT) used for trials

1.4.3 Machine setup

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

Figure 6. Vertical double acting AFM machine setup

1.5 AFM applications

(A) INTERNAL EDGE CONTROL

The Abrasive Flow Machining (AFM) process provides a controlled and repeatable method for burr removal and surface finish enhancement at hole intersection(s) and difficult to reach surfaces. Irregular shapes, holes and intersecting surfaces can be deburred or even polished with precision and predictable results in places that are impossible to reach by virtually any other method.**AFM** removes the burrs and enhances the adjacent surfaces by flowing the selected abrasive material on the target surface/edge and is typically limited ONLY by hole size coupled with the particulate size of the chosen abrasive.

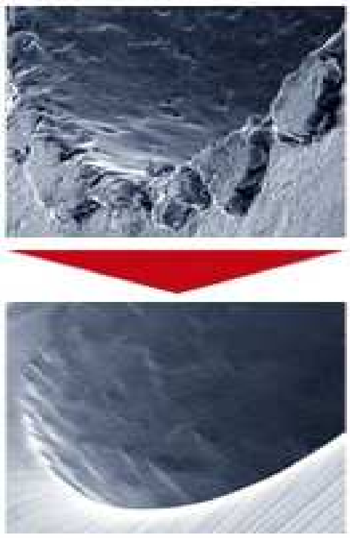


Figure 7. Internal Edge finished component [9]

(B) MOLDS AND DIES

- Metal forming
- Glass forming
- Plastic applications

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

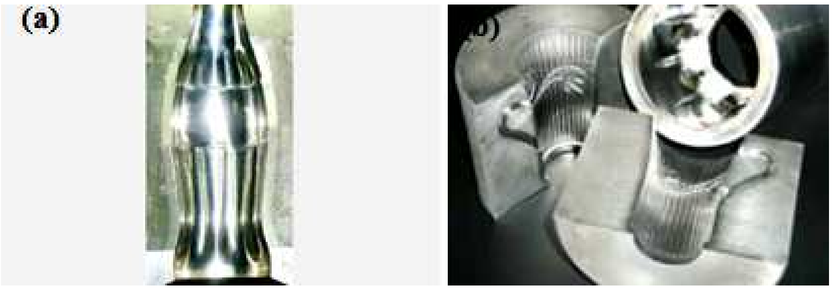


Figure 8.(a),(b) New glass moulds (dies and moulds)[9]

(C) AERONAUTICAL COMPONENET MANUFACTURING

- Increased fatigue strength
- Higher performance and efficiency

Abrasive Flow Machining will precisely remove the “recast layers” of material resulting from the thermal characteristics of laser and EDM cutting techniques in many high-strength applications. Improved surface integrity with enhanced eddy current readings results in more reliable components. Accurate and repeatable edge control, regardless of configuration, typically equates to less flow resistance and enhanced cycle fatigue strength.

Figure 9.Critical aircraft hydraulic and fuel system components [9]

(D) ULTRA CLEAN

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

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

AFM allows for extreme fine finishes on intricate geometry and difficult-to-reach surface configurations often found in prosthetic applications and in a broad range of materials.

(E) INTERNAL COMBUSTION ENGINE

- Diesel engines
- Automotive

A high-pressure fuel injection system’s life cycle can be extended through Abrasive Flow Machining by reducing surface cracks and more uniform surface finishes in critical areas of fatigue failure. Reduction of resistance in fuel and exhaust passages enhances performance and efficiency while maintaining critical tolerance parameters. Smoother intake passages allow for effective mixing of air/gas, higher efficiency and a more powerful engine.

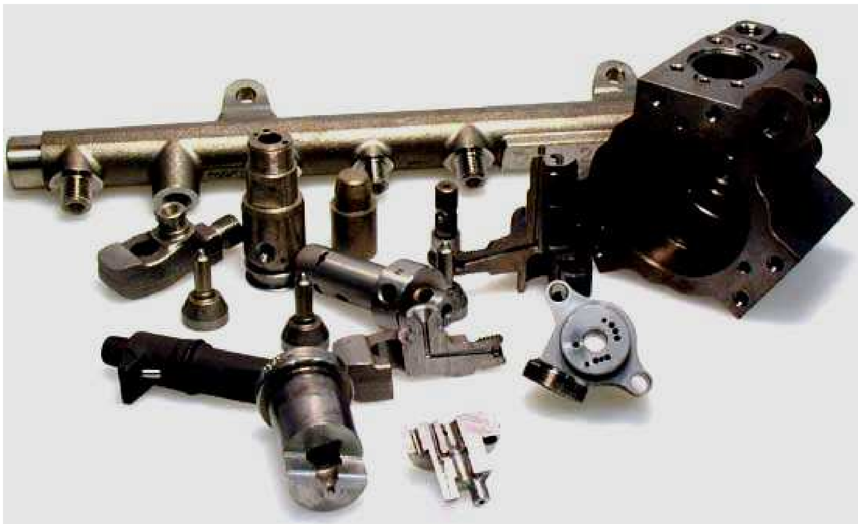


Figure 10. Automotive components [9]

CHAPTER 2

LITERATURE REVIEW AND PROBLEM FORMULATION

Finishing process is a very necessary process for any manufacturing industries. Finishing operation is not only time consuming but also very costly process. In some cases finishing operation is done manually. Some time manual handling causes serious health problem. Some time the mechanical parts are very complex and it is very difficult to finish such part manually by conventional methods. AFM is such process which is the right answer of above problems. This AFM process replaces a lot of manual finishing process leading to more standardization of manufactured part. Further the effectiveness of AFM can be increased by changing the concentration of abrasive in media.

2.1 Major areas of AFM research

A lot of work has been done to study the effects of important AFM process parameters. Some the work has been reported as under:

2.1.1 Extrusion Pressure

It has been found that cutting is faster at an increased extrusion pressure, with all other parameters remaining constant. A part of total pressure is lost within the media due to its internal resistance to flow and rest is imparted to abrasion particles contacting the work piece surface [10]. Jain and Jain [11] reported that at higher pressure the improvement in material removal just tends to stabilize probably due to localized rolling of abrasion particles

2.1.2 Number of Process Cycles

A number of cycles are required to achieve the desired surface finish and material removal. It has been reported in a number of studies that abrasion is more pronounced in some initial cycles after which improvement in the surface finish stabilize or reduce in some cases [10, 12, and 13]. Total number of process cycles range from one to several hundred [14]. Within 1 to 8 cycles, a linear dependence between material removal and surface roughness versus number of cycles was indicated. In AFM the forward and backward extrusion back to the initial stage completes a cycle.

2.1.3 Media Flow Volume

Media flow volume is a very prominent parameter which controls the material removal and surface finish. It has been found that if media flow volume is increased than material removal increases. Theoretically it can be understand that as media flow volume is increased more no of abrasive particles come in contact with work piece and more abrasion takes place.

2.1.4 Media Flow Rate

Media viscosity, extrusion pressure, and passage dimension determine the media flow rate (the speed of the abrasive slug passing through the restrictive passage) which affects the uniformity of the material removal and the formation of edge radius. Rhoades [15] has reported that media flow rate is less influential parameter in respect to material removal. Slower slug flow rates are best for uniform material removal and high slug flow rates produce large edge radii [Rhoades 8]. It has been noted by Williams et.al. [10] that if volume of flow is constant. The media flow rate is insignificant with regard to material removal. On the other hand, it has been claimed by Singh [16] and Jain and Jain [11] the media flow rate influences both of the material removal and surface roughness.

2.1.5 Media Viscosity

Williams and Rajurkar [17], and Williams et. al. [10] have reported that viscosity of the media is one of the significant parameters of the AFM process. Keeping all other parameter constant, an increase in viscosity improves both material removal and surface roughness. Przyklenk [18] has observed that the material removal capacity of the least viscous media differs from the most viscous one.

2.1.6 Media Temperature

From the experimental results reported by Weller [19], it can be interpreted that an increase in temperature during processing results in faster cutting of the material, under otherwise constant cutting conditions. Jain and Jain [20] analyzed the heat flow to the work piece and the medium in AFM process. In their study Hull et.al [21] reported the effect of temperature (within the range 30-70 °c) on rheology of media used and stated that the media may sometimes undergo a permanent change in physical properties with increase in temperature.

2.1.7 Abrasive Particle Size

Sizes of abrasive particles used in AFM process range from #8 grit (roughing and stock removal application) to 500 grit (small hole application). Smaller size abrasive gives better surface finish and can reach into complex and narrow passages, while larger one cut faster. According to one thumb rule [22] finer abrasives should be used when the initial roughness of the work surface is less. The reason for a decrease in material removal is that with an increase in mesh size (or decrease in grain size in mm) the depth of penetration as well as width of penetration, decreases.

2.1.8 Abrasives Concentration

McCarty [23] mentions the possibility of using a large range of concentration of abrasive in the media (2 to 12 times weight of carrier media). However, Siwert [24] suggested that abrasive particle to base material ratio (by weight) should vary from 4:1 to 1:4 with 1:1 as the most appropriate ratio. As the concentration of abrasive in the media increase, material removal increases while the surface roughness value decrease. However, its effect is visible only up to a certain percentage of abrasive concentration, beyond which it becomes insignificant. At higher concentration of abrasive particles viscosity of the media increases leading to more material removal [25]. Further, a higher concentration of abrasive particles permits the media to sustain a larger cutting force.

2.2 Latest development in AFM

2.2.1 Centrifugal force assisted Abrasive Flow Machining (CFAAFM)

Walia and Shan [26] have shown by their experiments that if a centrifugal force is provided in machining zone than the parameters can be effected positively. They showed that if centrifugal action is provided by rotating the work piece than both material removal and surface finish increases. It can be seen that addition of centrifugal force with help of external guided arrangements in media increase improvement in surface finish and material removal rate. A rotating Centrifugal Force Generating (CFG) rod was used inside the cylindrical work piece, which provides the centrifugal force to the abrasive particles normal to the axis of work piece.

2.2.2 Magnetic field assisted Abrasive Flow Machining (MFAFM)

Jha and Jain [27] analyzed that if the magnetic field is created around the work piece than the force acting on the work piece can be controlled. Magnetic field can be applied around the work piece by using electromagnetic coil or by simply using permanent magnet piece. By varying D.C. electric current flowing in the electromagnet coil or by changing the working gap while using a permanent magnet forces around the work piece can be controlled. A change in the electric current changes magnetic flux density in the working zone due to which the normal force exerted by an abrasive particle on the work piece changes. This change in normal force changes finishing rate ire critical surface finish that can be achieved by the process under the given finishing conditions. This class of processes is capable to produce surface roughness value of 8 nm or lower**.**

2.2.3 Rotational Abrasive Flow Finishing (RAFF)

Rotational abrasive flow finishing process works on the same principle as CFAAFM, the only difference being that instead of the use of a rod to generate the centrifugal force; the work piece itself is rotated using a suitable setup. The rotation of the work piece along with the extrusion pressure on the medium causes abrasive action and hence material removal.

2.2.4 Drill Bit-Guided Abrasive Flow Finishing (DBG-AFF)

Ravi and Mondal[29] have given a new concept to increase the material removal and to increase the surface finish. They found that if a drill bit is used which passes through work piece than material removal can be increased and also surface finish can be improved. If a drill bit is used it provides a strict passage for the flow of media and hence increases the pressure in the finishing zone which positively effect the material removal and surface finish. Beside this the shape of the drill bit also effect the material removal and surface finishing. In case if helical drill bit is used than three kind of motion of media takes place which are straight reciprocating motion, scooping motion, and helical motion. The overlapping of different kind of motion increases the material removal rate and surface finish.

2.3 Problem Formulation

Abrasive flow machining (AFM) is a non traditional finishing process used for finishing parts with predominant irregular geometry. In this process abrasive laden media is a dominating factor in which the different abrasives like CBN, SiC, Al_2O_3 etc. are being used with carrier traditionally. Nano particles have extraordinary properties over available abrasives. In this study an attempt is made to enhance MR and surface finish using CNTs along with Al_2O_3 abrasive particles to machine the cast iron workpiece.

2.4 Objective

The present investigation aims to explore the following objective:

1. Development of vertical double acting abrasive flow machining setup
2. Use of “Fe-filled CNT” with Al_2O_3 to check the capability to machine cast iron work piece.
3. Experiments have been conducted using the Taguchi L_9 OA method and the relevant dependencies have been found using ANOVA analysis.
4. The characterisation of new media is conducted through Scanning Electron Microscope (SEM).

CHAPTER 3

CARBON NANO TUBES (CNTs) SYNTHESIS

Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure; It is a tube-shaped material, made of carbon, having a diameter measuring on the nanometre scale. A nanometre is one-billionth of a meter, or about one ten-thousandth of the thickness of a human hair. The graphite layer appears somewhat like a rolled-up chicken wire with a continuous unbroken hexagonal mesh and carbon molecules at the apexes of the hexagons. Carbon nanotubes typically have diameters ranging from 1 nm up to 50 nm. Their lengths are typically several microns.

There are various techniques to synthesis the CNT, commonly used techniques are:-

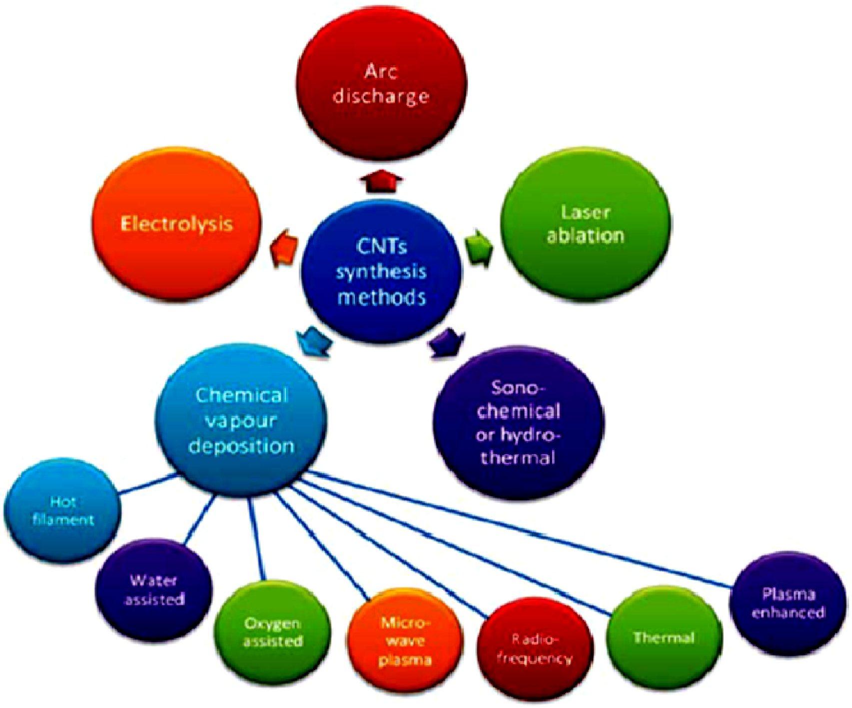


Figure 11. Currently used methods for CNTs synthesis [28]

3.1 Chemical Vapor Deposition (CVD)

In this several gases such as methane (CH_4), carbon monoxide (CO) and acetylene (C_2H_2) heated substrate which is coated with catalyst like Ni, Al_2O_3, and SiO_2, inert gas such as nitrogen and hydrogen. The energy source decomposes the molecule into active carbon atoms which then will be diffused on the substrate and CNTs begin to grow upto the temperature 800 °C which is quite high. The diameter of each nanoparticle defines the diameter of grow. It is possible to have control over the diameter and length of grown CNT.CVD process has mostly two main steps, first prepare substrate by sputtering and then to use thermal annealing to have catalyst nanoparticles on the substrate

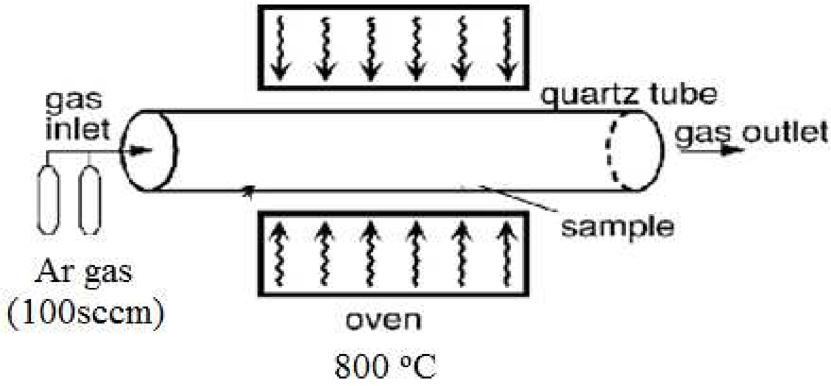


Figure 12. Schematic showing CVD method to develop CNT

3.1.1Advantage of CVD Method

- Large scale production and high yield production
- Low cost
- Continuous production instead of batch production
- Control of the quality and CNT
- Ability to manipulate
- No separation of unwanted by-products

CVD process is extremely sensitive to the condition parameters.

Table 1. Mechanical Properties of Engineering Fibers

Fiber Material	Specific Density	E (TPa)	Strenght (GPa)	Strain at Break (%)
Carbon Nanotube	1.3 – 2	1	10 - 60	10
HSS	7.8	0.2	4.1	< 10
Carbon Fiber - PAN	1.7 – 2	0.2 - 0.6	1.7 - 5	0.3 - 2.4
Carbon Fiber - Pitch	2 - 2.2	0.4 - 0.96	2.2 - 3.3	0.27 - 0.6

3.2 Experimental Procedure

Chemical Vapour Deposition technique is used to synthesze Fe-filled CNT by heating the solution of Ferrocene(5gm) and Toluene(25ml) in the oven, maintaining the oven temperature around 800^{o}C and argon gas(100 sccm) is passed to get inert atmosphere, then 800^{o}C temperature is maintained to completly vaporise the solution of Fererocene and Toluene. As solution vaporise completley the oven temperature is lowered by 25^{o}C

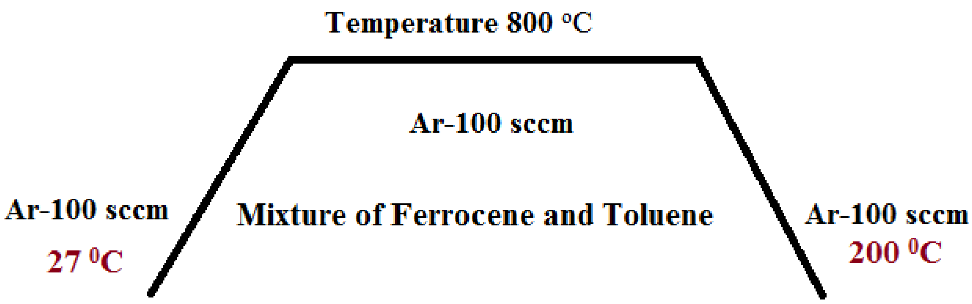


Figure 13. Optimised condition to synthesize Fe-filled CNTs

As oven reached 775^{o}C - 875^{o}C carbon start dissociating and carbon layers get stick on quartz tube with sp_2 bond. Then cooling is done slowly which takes aproximately 3hrs.

Figure 14. Thermal CVD Setup

After this the developed CNT layers is brushed and collected.The collected sample is tested for its magnetic nature by bar magnet, N & S north and south pole respectively showing the deposited film having pole characterisitic means the botoom layer of film having N Pole while top layer of deposited film having S Pole. The collected sample is charecterize through TEM hence different properties, characteristics and morphology of Fe-filled CNTs is observed.

Figure 15 (a), (b) and (c) are the TEM micrographs of Fe filled CNTs at different locations and it shows that the growth of CNTs is uniform and there is very less amount of other carbon impurities such as amorphous carbon, soot or carbon particles. The deep black parts shown in the image are iron particles encapsulated inside the nanotube which is confirmed from the lattice image in figure 15 (d) of filled CNTs in which walls of CNTs having lattice planes can be clearly seen with respect to lattice plane of iron particles encapsulated inside the CNTs.

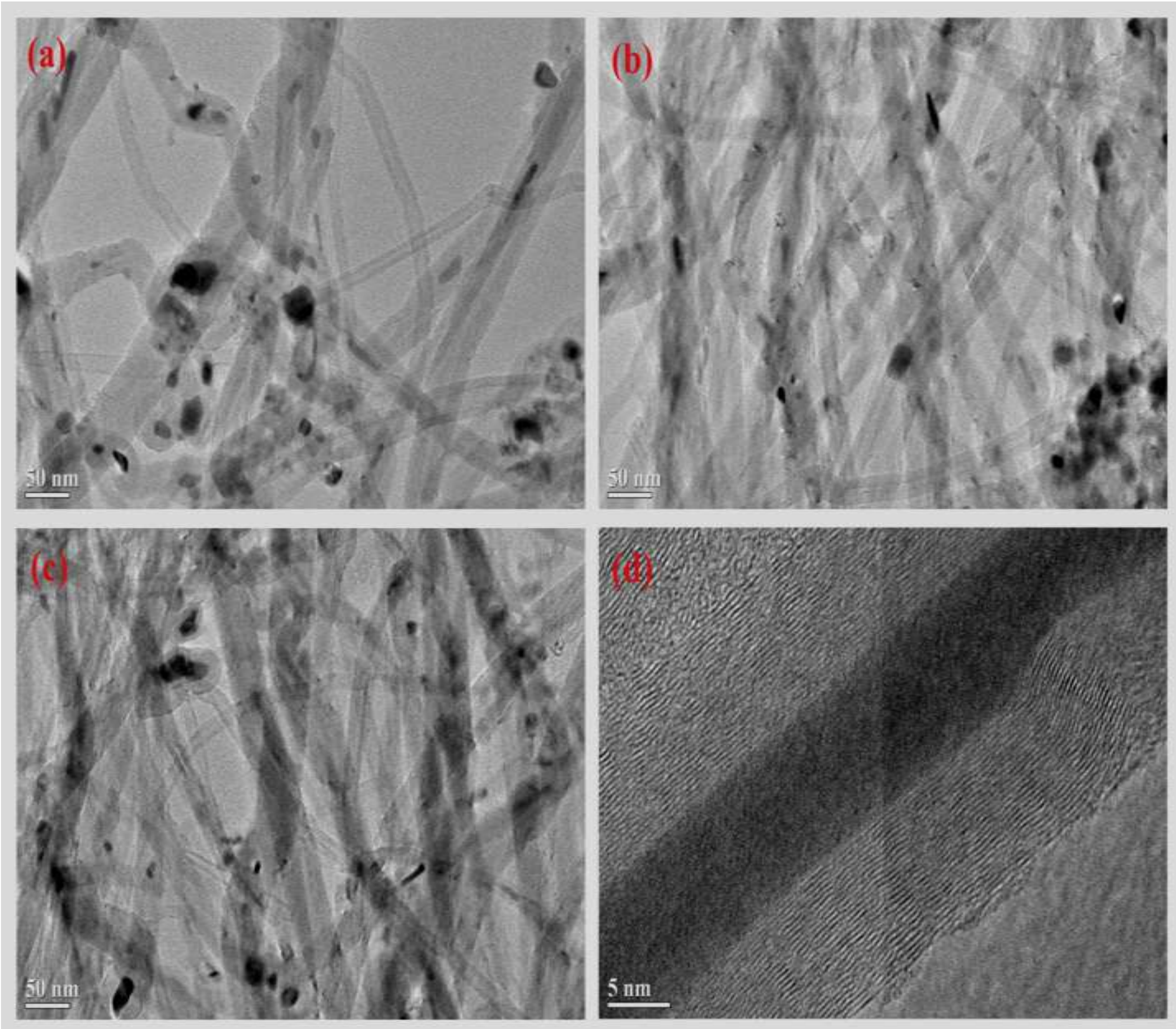


Figure 15. (a), (b) and (c) are TEM images of CNTs at different locations and (d) shows lattice images of CNT walls and Iron.

CHAPTER 4

EXPERIMENTAL DESIGN AND ANALYSIS

Design of experiments (DOE) or experimental design is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics, these terms are usually used for controlled. A properly planned and executed experiment is of the utmost importance for deriving clear and accurate conclusions from the experimental observations. Design of experiment is considered to be a very useful strategy for accomplishing these tasks. The science of statistical experimental design originated with the work of Sir Ronald Fisher in England in 1920s. Fisher founded the basic principle of experimental design and the associated data-analysis technique called Analysis of Variance (ANOVA) during his efforts to improve the yield of agricultural crops. The theory and applications of experimental design and the related technique of response surface methodology have been advanced by many statistical researchers as Box and Hunter, Box and Draper, Hicks. Various types of matrices are used for planning experiments to study several decision variables. Among them, Taguchi's Method makes heavy use of orthogonal arrays.

4.1 Taguchi's experimental design and analysis

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The Taguchi method was developed by Dr. Genichi Taguchi of Japan who maintained that variation. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. The Taguchi method is best used when there are an intermediate number of variables (3 to 50), few interactions between variables, and when only a few variables contribute significantly.

4.2 Philosophy of Taguchi method

1. Quality should be designed into a product, not inspected into it. Quality is designed into a process through system design, parameter design, and tolerance design. Parameter design, which will be the focus of this article, is performed by determining which process parameters most affect the product and then designing them to give a specified target quality of product. Quality "inspected into" a product means that the product is produced at random quality levels and those too far from the mean are simply thrown out.
2. Quality is best achieved by minimizing the deviation from a target. The product should be designed so that it is immune to uncontrollable environmental factors. In other words, the signal (product quality) to noise (uncontrollable factors) ratio should be high.
3. The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system wide. This is the concept of the loss function, or the overall loss incurred upon the customer and society from a product of poor quality. Because the producer is also a member of society and because customer dissatisfaction will discourage future patronage, this cost to customer and society will come back to the producer.

4.3 Taguchi Method Design of Experiments

The general steps involved in the Taguchi Method are as follows:
1. Define the process objective, or more specifically, a target value for a performance measure of the process. This may be a flow rate, temperature, etc. The target of a process may also be a minimum or maximum; for example, the goal may be to maximize the output flow rate. The deviation in the performance characteristic from the target value is used to define the loss function for the process.
2. Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure such as temperatures, pressures, etc. that can be easily controlled. The number of levels that the parameters should be varied at

must be specified. For example, a temperature might be varied to a low and high value of 40^{o}C and 80 ^{o}C. Increasing the number of levels to vary a parameter at increases the number of experiments to be conducted.

3. Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter, and will be explained below.

4. Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure.

5. Complete data analysis to determine the effect of the different parameters on the performance measure.

4.4 Experimental Design Strategy

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

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

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

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

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

4.5 Loss Function and S/N Ratio

The heart of Taguchi method is his definition of nebulous and elusive term ‘quality’ as the characteristic that avoids loss to the society from the time the product is shipped [50]. Loss is measured in terms of monetary units and is related to quantifiable product characteristics. Taguchi defines quality loss via his ‘loss-function’. He unites the financial loss with the functional specification through a quadratic relationship that comes from Taylor series expansion .

$$L(y) = k(y-m)^2$$

Where, L = loss in monetary unit

m = value at which the characteristic should be set

y = actual value of the characteristic

k = constant depending on the magnitude of the characteristic and the monetary unit involved.

The following two observations can be made

- The further the product's characteristic varies from the target value, the greater is the loss. The loss is zero when the quality characteristic of the product meets its target value.
- The loss is a continuous function and not a sudden step as in the case of traditional approach.

This consequence of the continuous loss function illustrates the point that merely making a product within the specification limits does not necessarily mean that product is of good quality.

In a mass production process the average loss per unit is expressed as:

$$L\ (y) = \{k\ (y_1-m)^2 + k\ (y_2-m)^2 + ... + k\ (y_n - m)^2\ \}$$

Where

y 1, y2 .... y_n = values of characteristics for units 1, 2,........n respectively

n = number of units in a given sample

k = constant depending upon the magnitude of characteristic and the monitory unit involve

m= Target value at which characteristic should be set.

Equation can be written as:

$$L(y) = k\ (MSD)$$

Where MSD denotes mean square deviation, which presents the average squares of all deviations from the target value rather than around the average value.

Taguchi transformed the loss function into a concurrent statistic called S/N ratio, which combines both the mean level of the quality characteristic and variance around this mean into a single metric .The S/N ratio consolidates several repetitions (at least two data points are required) into one value. A high value of S/N ratio indicates optimum value of quality with minimum variation. Depending upon the type of response, the following three types of S/N ratio are employed in practice.

1.Larger the better :

$$(S/N)_{HB} = -10 \log (MSD_{HB})$$

Where

$MSD_{HB} = \frac{1}{2}\sum_{j=1}^{R}(\frac{12}{yj})$

2.Lower the better :

$$(S/N)_{LB} = -10 \log (MSD_{LB})$$

Where

$MSD_{LB} = 1/R \quad \sum_{j=1}^{R}(y21)$

Nominal the best :

$$(S/N)_{LB} = -10 \log (MSD_{NB})$$

Where

$MSD_{NB} = \frac{1}{R}\sum_{j=1}^{R}\left(y_j - y_0\right)^2$

R = Number of repetitions

It is to be mentioned that for nominal the best type of characteristic, the standard definition of MSD has been used. For smaller the better type the target value is zero. For larger the better type, the inverse of each large value becomes a small value and again the target value is zero. Therefore, for all the three expressions the smallest magnitude of MSD is being sought. The constant 10 has been purposely used to magnify S/N number for each analysis and negative sign is used to set S/N ratio of larger the better relative to the square deviation of smaller the better.

4.6 Taguchi Procedure for Experimental Design and Analysis

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

(A). Selection of OA

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

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

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

•Brainstorming

•Flow charting

•Cause-effect diagrams

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

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

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

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

f_{LN} = N-1

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

L_N = OA designation N = number of trials

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

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

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

(B). Assignment of parameters and interactions to OA

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

(C). Selection of outer array

Taguchi separates factors (parameters) into two main groups:

- •Controllable factors
- •Noise factors

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

(D). Experimentation and data collection

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

(E). Data analysis

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

- •Plot of average response curves
- •ANOVA for raw data
- •ANOVA for S/N data

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of a parameter on the response. Typically, ANOVA for OA's are conducted in the same manner as other structured experiments . The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise tors are present. A standard ANOVA is conducted on S/N ratio, which identified the significant parameters.

(F). Parameter design strategy

Parameter classification and selection of optimal levels

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

Group I : Parameters, which affect both average and variation

Group II : Parameters, which affect variation only

Group III : Parameters, which affect average only

Group IV : Parameters, which affect nothing

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

(G).Prediction of mean

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

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

$$= A_2 + B_2 - T$$

T= overall mean of the response

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

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

(H). Determination of confidence intervals

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

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

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

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

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

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

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

Where

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

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

(I). Confirmation experiment

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

CHAPTER 5

PROCESS PARAMETER SELECTION AND EXPERIMENTATION

The main process parameters, which may affect the machining characteristics such as material removal and surface finish, are selected. The scheme of experiments is also discussed in this chapter. The experiments were conducted within the ranges of selected process parameters which includes amount of CNTs with AL_2O_3, no. of cycle, and different extrusion pressure. Material removal and surface finish were measured. The measured data are also tabulated in this chapter.

5.1 Selection of workpiece

Cast Iron work piece were prepared by drilling, maintaining its initial surface roughness in the range of 2.6-3.6µm and dimension 10 mm OD x 8 mm ID x 16 mm length. Few workpiece ready for machining is shown in figure-16.The length to diameter (L/D) of the workpiece was decided on the basis of the recommendation given by Kohut [15].Workpiece are cleaned by acetone and subsequently measurements of initial surface roughness and weight were taken. The surface roughness was measured in five different locations using Taylor Hobson. The internal cylindrical surface was finished by AFM process. Each workpiece was machined for a predetermined number of cycles. The workpiece was taken out from nylon fixture and cleaned with acetone before the subsequent measurement.

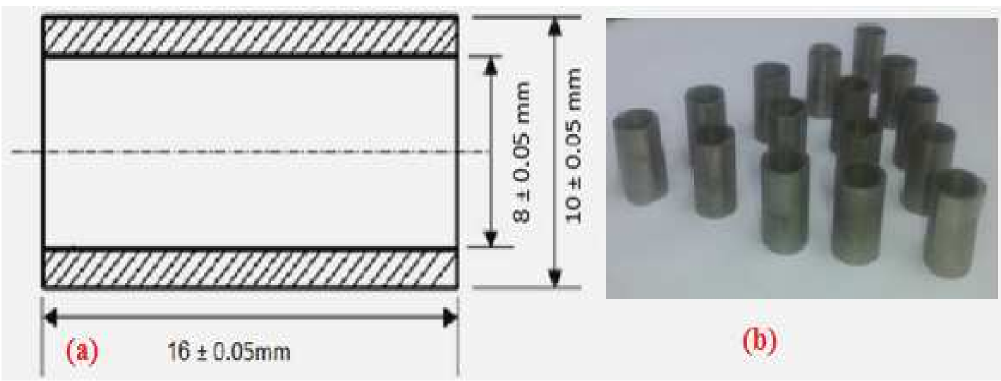


Figure 16.(a),(b) Cast Iron work pieces used in trials and its dimensional details

5.2 Selection of process parameter and their ranges

Table2. Process parameter and their ranges

S. No.	Process Parameter	Range	Unit
1	Extrusion Pressure	5-35	MPa
2	No. of Cycle	1-9	Number
3	Temperature	32± 2	°C
4	Media Flow volume	290	cm^3
5	Capacity	25 + 25	Ton
6	Stroke length	96	mm
7	Hydraulic cylinder Bore diameter-2 No.	130	mm
8	Hydraulic cylinder Stroke	90	mm
9	Working Pressure	210	kg/cm^2
10	Maximum Pressure in the Cylinder	35	MPa
11	Stroke Length of Piston	300	mm

5.3 Response characteristics

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

5.3.1 Percentage improvement in surface finishing

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

$$\Delta R_a = \frac{(\text{Initial Ra} - \text{final Ra})}{\text{Initial Ra}} \times 100$$

5.3.2 Material removal (MR)

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

MR= (Initial weight – final weight)

5.4 Scheme of experiments

The experiments were designed to study the effect of some of the AFM parameters on response characteristics of AFM process is shown in table 3. Taguchi parametric design methodology was adopted. The experiments were conducted using appropriate orthogonal array (OA). An L_9 (a standard 3-level OA) having 8= (9-1) degree of freedom was selected for the present analysis. The selected number of process parameters and their levels are given in the table 3 and L_9 OA designed is given in table 4.

Table 3. Process Parameters and their values at different levels

Symbol	Process Parameters	Unit	Level 1	Level 2	Level 3
N	No. Of Cycle	Numbers	4	6	8
P	Extrusion Pressure	Bar	13	23	33
C	Amount of CNT	Grams	Without CNT	5	10

Polymer to Gel ratio :1:1, Workpiece Material- Cast Iron ,Abrasive type Al2O3 & CNT, Mesh Size:180,
Extrusion Pressure: 5 MPa, Media Flow Volume :290cm^3,Temperature:32 ± 2 °C, Initial surface roughness : 2.6 - 3.6 µm.

Table 4. The L_9 (3^4) OA (Parameters Assigned) with Response

Exp. No.	Run Order	Parameters Trial Conditions				Response (Raw Data)			S/N Ratio (db)
		N	P	C	---------	R1	R2	R3	
		1	2	3	4				
1	1	1(4)	1(13)	1(0)	1	Y11	Y12	Y13	S/N(1)
2	4	1(4)	2(23)	2(5)	2	Y21	Y22	Y23	S/N(2)
3	7	1(4)	3(33)	3(10)	3	Y31	Y32	Y33	S/N(3)
4	5	2(6)	1(13)	2(5)	3	Y41	Y42	Y43	S/N(4)
5	8	2(6)	2(23)	3(10)	1	Y51	Y52	Y53	S/N(5)
6	2	2(6)	3(33)	1(0)	2	Y61	Y62	Y63	S/N(6)
7	9	3(8)	1(13)	3(10)	2	Y71	Y72	Y73	S/N(7)
8	3	3(8)	2(23)	1(0)	3	Y81	Y82	Y83	S/N(8)
9	6	3(8)	3(33)	2(5)	1	Y91	Y92	Y93	S/N((9)
Total					Σ		Σ	Σ	

R1, R2, R3 represents response value for three repetitions of each trial. The 1's,2's, and 3's represents levels 1,2,3 of the parameters, which appear at the top of the column.(---) represents no assignment in the column. Yij are the measured values of the quality characteristics (response)

5.5 Precautions taken during experimentation

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

1. Each experiment is repeated three times to avoid experimental error.
2. The experiments repeated randomly in order to avoid bias, if any, in the results.
3. As the experiments were proceeds the cutting edges of abrasive particles wear off and become dull which result in less favorable results are produced in later experiments secondly the particles of work piece material were mixed with the media and as the time proceeds the volume of work piece material inside the media increases which deteriorate the finishing action. To avoid this large volume of the media is prepared and after each experiment the used media is taken out from the cylinder and mixed throughout with the fresh media contained in large container. The media for next trial is taken from this mixture. For the limited number of experiments conducted, this would ensure with reasonable reliability that the media used for each of the experiment run contain approximately equal amount of fresh grains(grain with sharp edges)
4. Each set of experiments was performed at room temperature in a narrow range (32 ± 2°C).
5. Before any measurement was taken, the work-piece was cleaned with acetone.
6. The surface roughness was measured in the direction of flow of media and at several random points all over the cavity of the work-piece.

5.6 Experimentation

The three process parameters no. of cycle, extrusion pressure, amount of CNT, were selected as in table 3. The process parameters were varied according to the values as shown in table 3. Experiments were conducted according to the test condition specified by the L_9 OA (Table 4). Each experiment was repeated three times in each of the trial conditions. Thus twenty seven work-pieces were selected having initial surface in close range of (2.6 – 3.6 micron). In each of the trial conditions and for every replication, the percentage improvement in surface roughness and material removal were measured. The data is recorded in Table 5.

Table 5. Experimental results of various response characteristics

Exp No.	Run Order	% Improvement in Ra			S/N ratio (db)	Material Removal (MR) (mg)			S/N ratio (db)
		R1	R2	R3		R1	R2	R3	
1	1	9.37	9.67	10.45	19.82	2.7	2.57	2.8	8.59
2	4	7.99	7.56	6.64	17.30	5.5	5	5.8	14.65
3	7	24.74	22.65	21.04	27.10	6.1	6.3	6.8	16.10
4	2	12.23	11.76	10.14	21.03	7.1	2.91	2.99	10.80
5	5	13.54	14.65	14.32	23.01	8.9	8.7	8.5	18.79
6	8	17.01	17.25	17.2	24.68	5.5	5.4	5.7	14.85
7	3	29.98	29.25	29.68	29.44	3.7	2.95	3.1	10.12
8	6	16.039	15.834	15.53	23.97	4.0	4.15	4.9	12.67
9	9	23.19	24.56	24.68	27.65	4.5	4.73	4.9	13.44
Total		154.09	153.18	149.68		48.0	42.71	45.49	
		$T_{\Delta Ra}$ = Overall mean of ΔRa=16.92%				T_{MR} =Overall mean of MR =5.04mg			

CHAPTER 6

RESULTS AND DISCUSSION

Detailed analysis and discussion of results of experiments.

6.1 Analysis and discussion of results

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

6.2 Effect on material removal

The average values of material removal (MR) and S/N ratio for each parameter at levels L1, L2 and L3 are calculated and given in table 6.

Table6.Average values and Main effects: Material Removal, MR (in mg)

Process Parameter	Level	No. of Cycle (N)		Extrusion Pressure(P)		Amount of CNT(C)	
Type of Data		Raw Data	S/N Ratio	Raw Data	S/N Ratio	Raw Data	S/N Ratio
Average Values(%Ra)	L1	4.84	13.11	3.42	9.83	4.19	12.03
	L2	6.19	14.81	6.16	15.37	4.82	12.96
	L3	4.10	12.08	5.55	14.80	6.11	14.99
Main Effects(%Ra)	L2-L1	1.35	1.7	2.74	5.54	0.63	0.93
	L3-L2	-2.09	-2.73	-0.61	-0.57	1.29	2.03
Difference (L3-L2)–(L2-L1)		-3.44	-4.43	-3.35	-6.11	0.66	1.1
L1,L2,L3 represent levels 1,2 and 3 respectively of parameters. (L2-L1) is the average main effect when the corresponding parameter changes from Level 1 to Level 2. (L3-L2)is the main effect when the corresponding parameter changes from Level 2 to Level 3							

It can be seen from the figure17 that as the number of cycle is increased initially the material removal increases but after level 2 as the number of cycle increased material removal decreases. This is because abrasive particles became dull after level 2 and material removal was low.

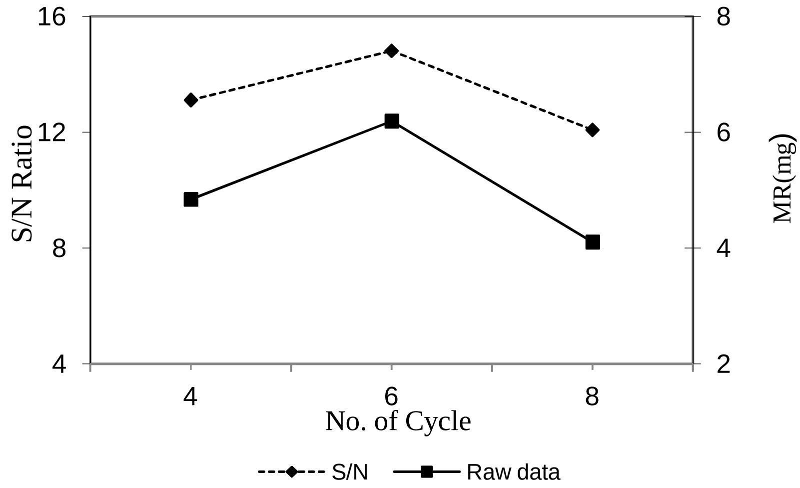


Figure 17. Effect of No. of Cycle on the S/N Ratio and MR

It can be seen from the figure 18 that up to level 2 as pressure increases material removal increases and after level 2 the material removal decreases because initially abrasives cut the peaks of surface hence material removal is more. But when surface gets smooth, after that it will cause low material removal.

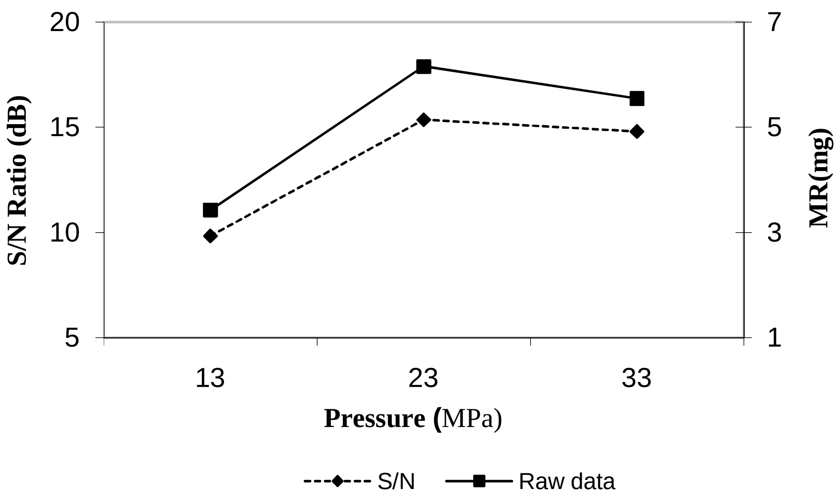


Figure 18.Effect of Pressure on the S/N Ratio and MR

From figure19 it was found that as the amount of CNT particles increased material removal also increased. CNT particles are harder as compare to the aluminium oxide. CNT has very sharp cutting edges. So when the Extrusion pressure is applied it easily cuts the peak of the roughness and causes more MR.

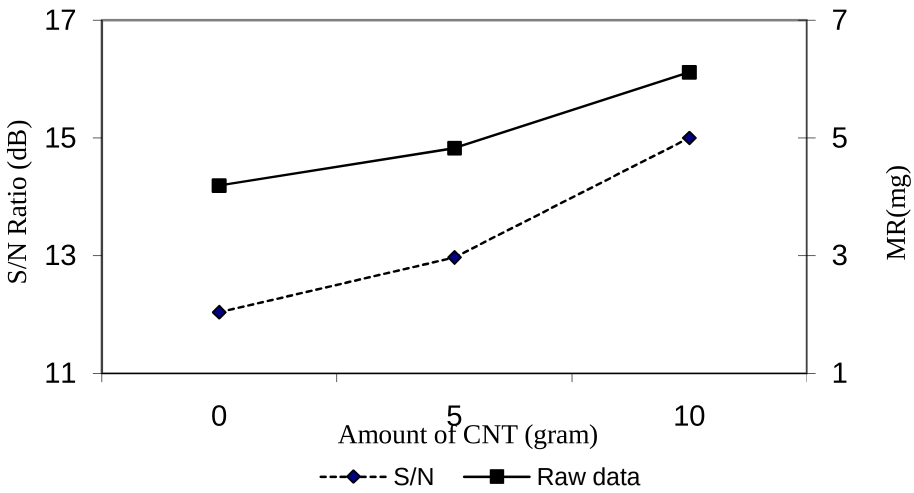


Figure 19. Effect of CNT particles on the S/N Ratio and MR

6.3 Selection of optimum levels

In order to study the significance of the process parameters towards the MR, analysis of variance (ANOVA) was performed. The pooled versions of ANOVA of the raw data and the S/N data for MR are given in Tables 7 & 8. From these tables, it is clear that the parameters pressure, amount of CNT and no. of cycle significantly affect both the mean and the variation in MR values.

Table 7. Pooled ANOVA (Raw Data) (MR)

Source	SS	DOF	V	F-Ratio	SS’	**P%**
No. of Cycle	20.13	2	10.07	13.54*	18.64	20.84
Pressure	37.12	2	18.56	24.98*	35.64	39.84
Amount of CNT	17.33	2	8.67	11.66*	15.85	17.71
e	14.86	20	0.74	------	19.32	21.61
Total (T)	89.44	26	*	-------	89.45	100

*Significant at 95% confidence level, F critical =3.4928
SS-Sum of Squares, DOF-Degree of Freedom, V-Variance, SS’-Pure sum of Squares

Table 8.Pooled ANOVA (S/N Data) (MR)

Source	SS	DOF	V	F-Ratio	SS'	P%
No. of Cycle	11.44	2	5.72	34.71*	11.11	13.67
Pressure	55.68	2	27.84	168.95*	55.35	68.12
Amount of CNT	13.81	2	6.91	41.89*	13.48	16.58
e	0.33	2	0.16	------	1.32	1.63
Total (T)	81.26	8	--------	-------	81.26	100
*Significant at 95% confidence level, F critical =19 SS-Sum of Squares, DOF-Degree of Freedom, V-Variance, SS'-Pure sum of Squares						

6.4 Effect on percentage improvement in surface roughness

The average values of percentage improvement in surface roughness and S/N ratio for each parameter at Level L1, L2 and L3 are calculated and given in Table 9.

Table 9. Average values and Main Effects: % improvement in Ra

Process Parameter	Level	No. of Cycle (N)		Pressure(P)		Amount of CNT(C)	
Type of Data		Raw Data	S/N Ratio	Raw Data	S/N Ratio	Raw Data	S/N Ratio
Average Values(%Ra)	L1	13.35	21.41	16.95	23.43	14.26	22.83
	L2	14.23	22.91	12.46	21.43	14.31	21.99
	L3	23.19	27.02	21.36	26.48	22.21	26.52
Main Effects(%Ra)	L2-L1	0.88	1.5	-4.49	-2	0.05	-0.84
	L3-L2	8.96	4.11	8.9	5.05	7.9	4.53
Difference (L3-L2)–(L2-L1)		8.08	2.61	13.39	7.05	7.85	5.37
L1,L2,L3 represent levels 1,2 and 3 respectively of parameters. (L2-L1) is the average main effect when the corresponding parameter changes from Level 1 to Level 2. (L3-L2)is the main effect hen the corresponding parameter changes from Level 2 to Level 3.							

From Figure 20 it can be clearly concluded that as the number of cycle is increased the % surface finish is increased.

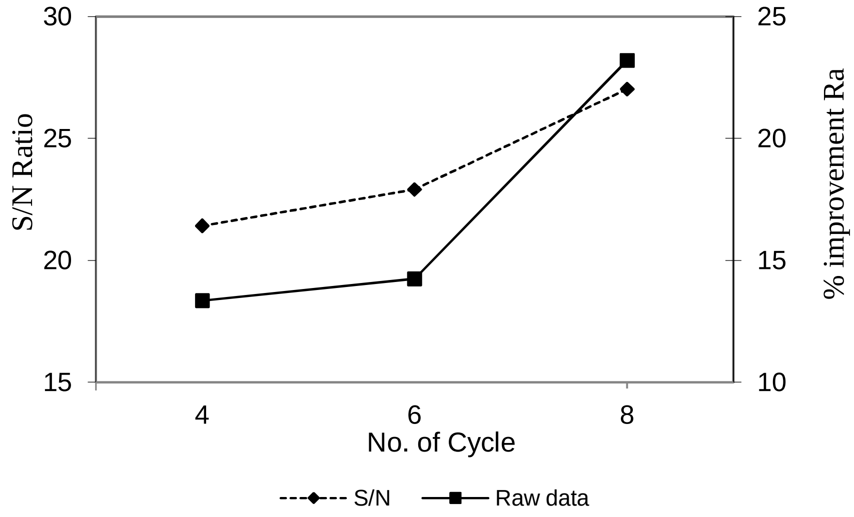


Figure 20.Effect of No. of Cycle on S/N Ratio and % improvement in Ra

It can be clearly concluded from the figure 21 that as the extrusion pressure increases, initially the surface finishing of the work piece decreases but after level 2 of pressure the value of surface finishing increases.

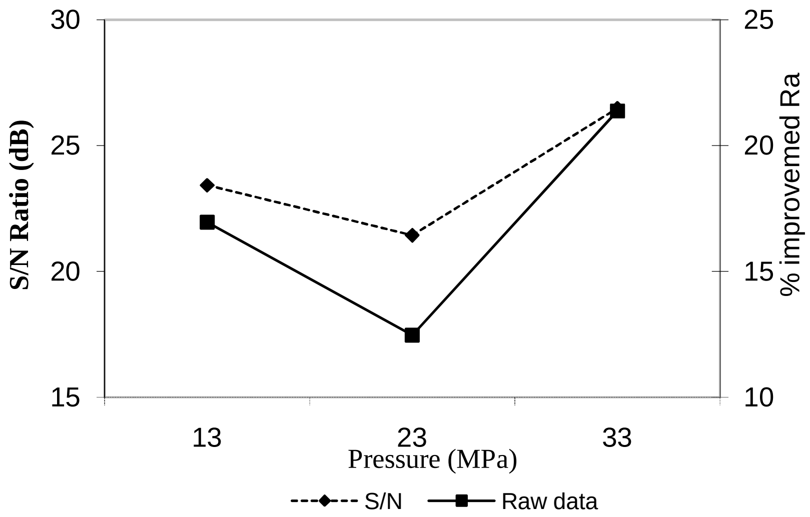


Figure 21. Effect of extrusion pressure on S/N ratio and % improvement in Ra

It can be seen from the figure 22 that as the amount of CNT increases the % increase in Ra slightly increases but after level 2, % improvement in Ra sharply increased. This is due to more number of abrasive particles taking part in machining process and also continues to remove fresh materials from the work surface which lead to increase in MR and surface finish.

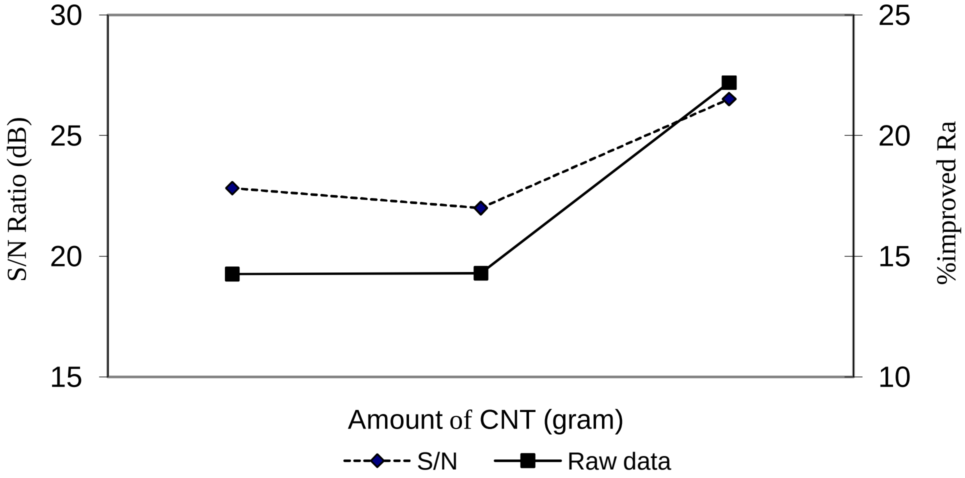


Figure 22. Effect of Amount of CNT on S/N Ratio and % improvement in Ra

6.5 Selection of optimum levels

In order to study the significance of the process parameters towards the percentage improvement in Ra, analysis of variance (ANOVA) was performed. The pooled versions of ANOVA of the raw data and the S/N data for change in Ra are given in table 10 and 11.From these tables it is clear parameters Pressure, Amount of CNT and No. of Cycle significantly affect both the mean and the variation in the percentage improvement in Ra values.

Table 10. Pooled ANOVA (Raw Data) (ΔRa)

Source	SS	DOF	V	F-Ratio	SS'	P%
No. of Cycle	534.16	2	267.08	164.32*	530.91	40.82
Pressure	357.53	2	178.77	109.98*	354.28	27.24
Amount of CNT	376.54	2	188.27	115.84*	373.29	28.70
e	32.51	20	1.63	------	42.26	3.24
Total (T)	1300.74	26	*	-------	1300.74	100

*Significant at 95% confidence level, F critical =3.4928
SS-Sum of Squares, DOF-Degree of Freedom, V-Variance, SS'-Pure sum of Squares

Table 11. Pooled ANOVA (S/N Data) (ΔRa)

Source	SS	DOF	V	F-Ratio	SS'	P%
No. of Cycle	50.55	2	25.27	13.39*	50.10	40.22
Pressure	38.81	2	19.40	87.06*	38.37	30.79
Amount of CNT	34.78	2	17.39	78.02*	34.34	27.56
er	0.45	2	0.22	------	1.78	1.43
Total (T)	124.59	8	--------	-------	124.59	100
*Significant at 95% confidence level, $F_{critical}$ =19 SS-Sum of Squares, DOF-Degree of Freedom, V-Variance, SS'-Pure sum of Squares						

6.6 Estimation of optimum response characteristics

In this section, the optimum values of the response characteristics along with their respective confidence intervals have been predicted. The results of confirmation experiments have also been presented to validate optimal result .The optimal level of the process parameters have been identified from the selected response characteristics. The optimal value of each response characteristic is predicted considering the effect of the significant parameters only. The average value of the response characteristic obtained through the confirmation experiments must lie within the 95% confidence level, CI_{CE}. However the average value of quality characteristic obtained from the confirmation experiments may or may not lie within 95% confidence interval, CI_{POP}.

As observed the optimum values for the maximum MR are $N_2P_2C_3$ [Table-5] for both raw data and S/N data. For the confirmation experiments on the basis of raw data the optimal settings have been taken as $N_2P_2C_3$.

As observed the optimum values for the maximum % improvement in ΔRa are $N_3P_1C_3$ [Table-5] for both raw data and S/N data. For the confirmation experiments on the basis of raw data the optimal settings have been taken as $N_3P_1C_3$.

Based on the optimal selection of the process the optimum response parameters of the material removal and Percentage improvement in surface roughness have been estimated with the confidence intervals as further.

6.7 Material removal (MR)

The mean at the optimal MR (optimum values of the response characteristics) is estimated as

$$\mu = \overline{N}_2 + \overline{P}_2 + \overline{C}_3 - 2\overline{T}$$

$\bar{T}$= overall mean of the response =5.04 mg [Table-5]

$\bar{N}2$ =Average value of MR at the second level of no. of cycle = 6.19mg [Table-6]

$\bar{P}2$ =Average value of MR at the second level of Pressure = 6.16mg [Table-6]

$\bar{C}3$ =Average value of MR at the third level of CNT = 6.11 mg[Table-6]

Substituting these values, Mean MR = 8.38 mg

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

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

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

Where $F_\alpha\,(1, f_e)$ = The F- ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e = 3.49(Tabulated Value)

f_e = error DOF = 20

N = Total no of result =27 (treatment =9, repetition =3)

R = Sample size for confirmation experiments = 3

V_e = Error variance =0.74

$$n_{eff} = \frac{N}{1+[\text{DOF associated in the estimate of mean responce}]} = 3.86$$

So, $CI_{CE} = \pm\ 1.24$

And $CI_{POP} = \pm\ 0.67$

The 95% confirmation interval of predicted optimal range (for confirmation run of three experiments) is:

$$\text{Mean MR} - CI_{CE} < MR < MR + CI_{CE}$$

$$7.26 < MR < 9.50$$

The 95% confirmation interval of the predicted mean is :

$$\text{Mean MR} - CI_{POP} < MR > MR + CI_{POP}$$

$$7.71 < MR < 9.05$$

6.8 Percentage improvement in Ra

The mean of the percentage improvement in R_a optimum values of the response characteristics is estimated as:

$$\mu = \bar{N}_3 + \bar{P}_1 + \bar{C}_3 + -2\bar{T}$$

$\bar{T}$ = overall mean of the response = 16.92 % [Table-5]

$\bar{N}3$ = Avg. value of % improvement in R_a at the third level of No. of Cycle=23.19% [Table-6]

$\bar{P}1$ =Avg. value of % improvement in R_a at the first level of extrusion Pr. = 16.95% [Table-6]

$\bar{C}3$ = Avg. value of % improvement in R_a at the third level of CNT= 22.21 % [Table-6]

Substituting these values, % improvement in R_a = 28.51 %

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

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

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

Where $F_\alpha\,(1, f_e)$ = The F- ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom fe = 3.49 (Tabulated Value)

fe =error DOF = 20

N= Total no of result =27 (treatment =9, repetition =3)

R = Sample size for confirmation experiments = 3

Ve = Error variance =1.63

$$n_{eff} = \frac{N}{1+[\text{DOF associated in the estimate of mean responce}]} = 3.86$$

So, $CI_{CE} = \pm\ 1.84$ and $CI_{POP} = \pm\ 1.21$

The 95% confirmation interval of predicted optimal range (for confirmation run of three experiments) is:

$$26.67 < \%\ \text{improvement in}\ \Delta R_a < 30.35$$

The 95% confirmation interval of predicted mean is

$$27.3 < \%\ \text{improvement in}\ \Delta R_a < 29.72$$

6.9 Confirmation Experiments

In order to validate the results obtained, three confirmation experiments have been conducted for response characteristics of MR and % improvement in surface roughness .For the maximum MR, the optimal levels of the process parameter are $N_2P_2C_3$, whereas for the maximum % improvement surface roughness the optimal parameters settings are $N_3P_1C_3$.

P_1 = Extrusion Pressure at first level =13 MPa

P_2 = Extrusion Pressure at second level =23 MPa

C_3 = Amount of CNT at Third level =10 gram

N_2 =No. of Cycle at first level =6

N_3 = No. of Cycle at first level =8

The results are given in table below. The values of MR and % improvement in Ra obtained through the confirmation experiments are within 95% of Cl_{CE} of respective response characteristic. It is to be pointed out that these optimal values are within the specified range of process parameters. Any exploration should be confirmed through additional experiments.

Table 12. Predicted Optimal Values, Confidence Intervals and Results of Confirmation Experiments

Response Characteristic	Optimal Process Parameters	Predicted Optimal Value	Confidence Intervals 95%	Actual Value(Avg of Confirmation Exp)
MR	$N_2P_2C_3$	8.38mg	CI_{CE} 7.26.<MR<9.50 CI_{POP}:7.71<MR<9.05	8.7 mg
%Improvement ΔRa	$N_3P_1C_3$	28.51 %	CI_{CE}:26.67<%ΔR_a<30.35 CI_{POP}:27.3<%ΔR_a<29.72	29.40%
CI_{CE} – Confidence interval for the mean of the confirmation experiments CI_{POP} – Confidence interval for the mean of the population				

6.10 Characterization of developed Media

The newly developed media which having aluminium Oxide, polymer and hydrocarbon gel is mixed properly in predetermined proportion to get the viscous elastic media which can machine effectively, Firstly the samples are machined without CNTs particles after level first samples were machined with media having Fe-filled CNTs particles. An attempt is made to characterise the media through scanning electron microscope (SEM).

Figure 23 is the SEM micrograph of the media (Al_2O_3 and Carrier only) before addition of CNTs where, (a) is the SEM micrograph at scale bar of 100 µm in which abrasives edges are not clearly visible, (b) is the SEM micrograph at a scale bar of 5µm in which abrasive edges are visible.

Figure 24 is the SEM micrograph of the media (Al_2O_3 +carrier+ Fe-filled CNTs) after addition of CNTs where the sharp edges of Alumina particle are clearly visible which is responsible for machining the work surface.

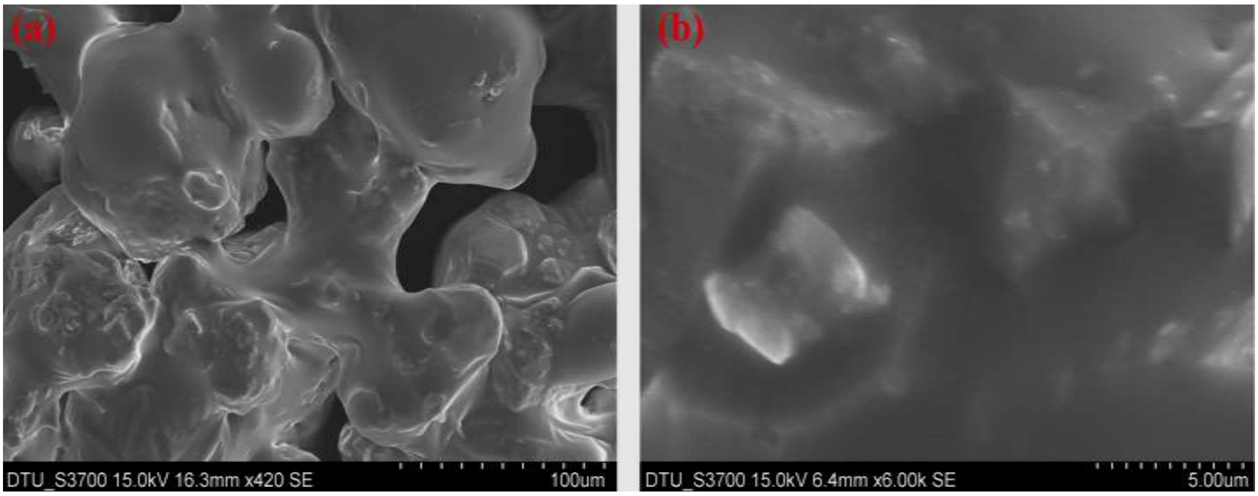


Figure 23.SEM image of media(Al_2O_3 and Carrier only)

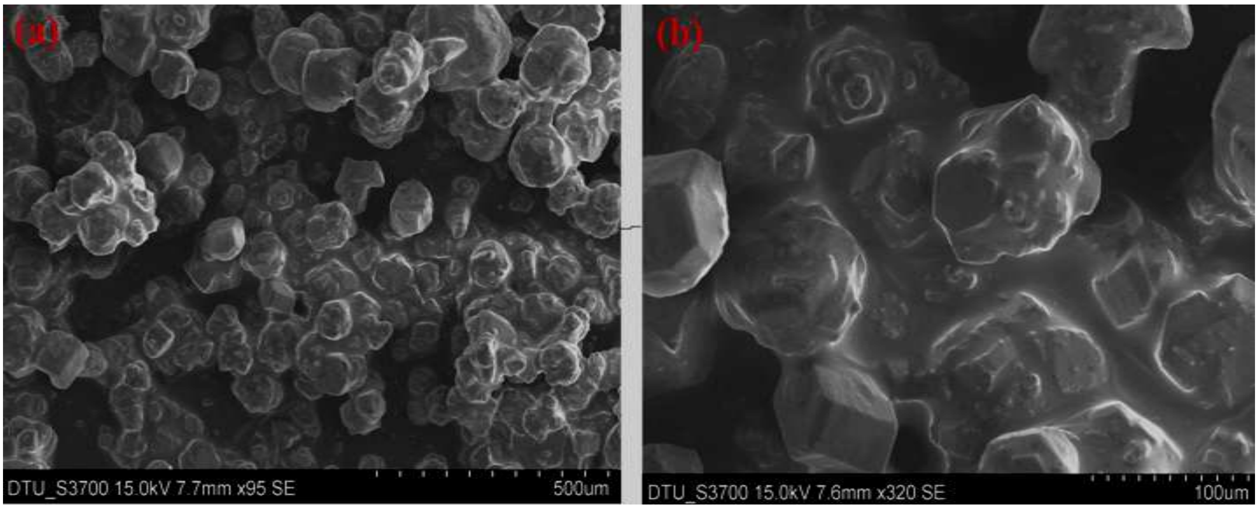


Figure 24.SEM image of media(Al_2O_3 +carrier+ Fe-filled CNTs)

CHAPTER 7

CONCLUSION AND SCOPE FOR FUTURE WORK

7.1 Conclusions

Experiments were carried out for evaluating performance of newly developed media(carrier+Al_2O_3+CNTs) using the double acting, vertical type AFM setup to study its performance in terms of the improvement in material removal and surface finish of "**cast iron**" work pieces. It has been found that the use of CNTs with media led to an improvement in the response parameter of percentage improvement in surface finish and material removal.

- For the design of experiment, the Taguchi method approach has been employed. L_9 OA has been used for the plan of experiments.
- The three process parameters viz. number of cycles, extrusion pressure and amount of CNTs all have significant effect for the response parameter of MR .
- The process parameter extrusion pressure and number of cycle is significant for response.
- At selected parameters a maximum improvement of **8.38mg** has been observed in the material removal on the inner cylindrical surface of the **cast iron** work piece.
- At selected parameters a maximum improvement of **28.51%** has been observed in the Surface finish on the inner cylindrical surface of the **cast iron** work piece.

7.2 Scope of future work

- CNTs filled with Fe, Co and Ni which is ferromagnetic in nature can be explored in MAFM for better result.
- Results can be analyzed for different industrial material.
- The set up can be optimized for many other process parameters like different shapes of work materials, different abrasives, flow rate of media etc.

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