Design and development of fixture and modification of existing AFM setup to magnetic abrasive flow machining (MAFM) process setup

Gagandeep Chawla\textsuperscript{1}, Vinod Kumar Mittal\textsuperscript{2} and Sushil Mittal\textsuperscript{3}

\textsuperscript{1}PhD Scholar, Department of Mechanical Engineering, NIT, Kurukshetra, India
\textsuperscript{2}Associate Professor, Department of Mechanical Engineering, NIT, Kurukshetra, India
\textsuperscript{3}Associate Professor, Department of Mechanical Engineering, Chandigarh University, India

E-mail: gagan1984mech@gmail.com

Abstract. To finish multifaceted geometries, miniaturized parts, especially of internal inaccessible cavities or recesses by the use of abrasives media with other constituents is known as abrasive flow machining (AFM). With the help of hydraulic pressure system, the media is extruded to-and-fro over the surface in this process. Recently, numerous amendments have been made for improving the performance of the AFM process. This paper presents a new modified AFM process known as magnetic abrasive flow machining process (MAFM) that is used to finish internal cylindrical surfaces. In MAFM process the electromagnet is made-up to locate around the cylindrical work-piece. For providing maximum magnetic field nearby the whole internal surface of the work-piece, there are two poles that are bounded by copper coils. In MAFM, aluminium fixture is considered to enhance the magnetic effect around the workpiece surface that helps in increasing the MRR and change in surface roughness (ΔRa).

1. Introduction

The concept of AFM is developed in USA by the “Extrude Hone Corporation” in 1960s, which possesses excellent capabilities for polishing unsymmetrical surfaces and interior structure of parts. Abrasive flow machining also called the abrasive flow deburr or extrude polishing, is a surface finishing process that is characterized through passing an abrasive laden fluid from the interior surface of the workpiece. Abrasive medium, machine and tooling are the essential elements of abrasive flow machining process. Although AFM process has many advantages such as excellent control of process, finishing and intricate shaped components, radius generation, faster change of work piece, faster changeover of the media etc. while it has some drawbacks also \textit{i.e.} the finishing rate is low, it is not capable of correcting the form geometry, closed environment and start-up hole is required for this process. Numerous researches have been made for improving finishing rate, integrity in surface and compressive residual stresses formed on the workpiece surface which introduced many setups for improved AFM process such as magneto abrasive flow machining (MAFM), magnetorheological abrasive flow finishing (MRAFF) etc. Ahmad et al. [1] used a tool named magnetic abrasive particles for finishing throughout the magnetic abrasive finishing (MAF) process. Sintering method was used to produce the magnetic abrasive particles. Once the sintering process was completed, authors found the
magnetic abrasives which were of better quality and those abrasive particles stick on the base metal matrix. They used alumina powder as an abrasive particle and iron powder was taken as the magnetic particle. They performed experiments on stainless steel 202 by using Taguchi’s orthogonal array (L9).

Mittal et al. [2] created the samples with aluminium (base metal) and investigated the SiC MMCs by using AFM process. Authors chose various input variables like extrusion pressure, mesh number, work piece material and concentration of abrasives etc. for finding out the output variables like Δ Ra and MRR. Mittal et al. [3] used aluminium (base material) with different values of SiC in different percentages (i.e. 20%, 40% and 60%) for investigation of Al/SiC MMCs. They analysed the parameters effect by using Taguchi design method (L27 orthogonal array). Sadiq et al. [4] established magneto-rheological abrasive honing process and analysed the magnetic field’s effect on workpiece that was fixed in a holder and subjected to MRAH. Wani et al. [5] developed a finite element model for finding out magnetic potential distribution present within the magnetic abrasive brush that was designed through finishing action. Then authors used that to calculate surface finish and material removal. From experimental outcomes Singh et al. [6] recommended that there was a strong effect of magnetic field on the material removal in AFM by using magnetically assisted AFM. Singh et al. [7] observed that when brass was used as workpiece material, the magnetic field had a major effect on MR and change in surface. Nagdeve et al. [8] observed it very difficult and challenging task to attain the surface finish that was uniform nanoscale into the contact zone, particularly on those sculptured surfaces that had dissimilar curvatures at different locations. Khaire et al. [9] used magneto rheological abrasive flow finishing process for improving the AISI stainless steel 316L surface quality to the nano-level surface finish. Authors built up a response surface model for determining the effect of various input parameters on the output parameters like final surface roughness (SR) and MRR. Experiments were conducted by Guo et al. [10] for magnetic field-assisted finishing using a dual magnetic roller tool combined with a 6-axis robot arm. Judal et al. [11] fabricated vibration assisted cylindrically magnetic abrasive finishing process and reported the experimentally investigated effect of many process variables on VAC–MAF setup through finishing of aluminium workpieces. Mulik et al. [12] measured normal force and finishing torque using kistler’s dynamometer at various processing conditions during ultrasonic assisted magnetic abrasive finishing methodology. Authors found that torque and finishing forces were mainly affected by the finishing gap and the voltage that was supplied to the electromagnet. The magnetorheological abrasive honing (MRAH) setup was designed and developed by Sadiq et al. [13]. Authors used a direct current (DC) electromagnet having the pole faces that were cylindrical in nature for measuring the magnetic flux density. They conducted the experiments with aluminum alloy (AL6063) and austenitic stainless steel (SS316L) workpiece for understanding the magnetic field’s effect. Jain [14] offered a generalized tool of MR for numerous flowing abrasive based micro-/nano-machining (MNM) processes. The MNM processes like AFF, MAF, elastic emission machining, magnetorheological finishing, MAFF, and magnetic float polishing had been discussed. Das et al. [15] discovered a novel accurate finishing method known as magnetorheological abrasive flow finishing (MRAFF), that was developed by blending AFM with magnetorheological finishing, and especially designed for nano-finishing of various parts and difficult geometry for a broad variety of industrial applications. Jayswal et al. [16] designed a finite element model for finding out the magnetic force distribution over the workpiece surface. They declared that by the use of magnetic abrasive finishing (MAF) process, very little quantity of material was removed by indentation and revolution of magnetic abrasive particles into the circular tracks. Singh et al. [17] examined the magnetic abrasive finishing setup and used Taguchi experimental design method L9 (3^4) orthogonal array for attaining the significant parameters that had an influence on the surface quality produced in the MAF. The negative imitation of the knee joint implant like a fixture was designed by Nagdeve et al. [18] and they used rotational-magnetorheological abrasive flow finishing method for finishing that.

In this paper the concept of magnetization has been added to enhance the efficiency of AFM process. Also the aluminium fixture has replaced the nylon fixture due to its low magnetic permeability for magnetic line of forces which can hinder the process of finishing of internal cavity in the workpiece.
2. MAFM experimental set-up

In the present research work, an existing AFM setup has been modified by replacing nylon fixture with an aluminium fixture and by applying electromagnetic effect around the workpiece. Figure 1(a) shows the structural representation of MAFM and figure 1(b) shows the pictorial view of MAFM setup. The designed setup has a maximum extrusion pressure of 10MPa. All through the forward stroke, the media is extruded by two hydraulic actuators and passed from one media cylinder to the other, through the workpiece.

After completing this stroke, the reverse process is repeated and both of these forward and backward strokes establish one complete cycle. The stroke length is kept at a constant value of 250 mm and value of media volume is taken as 300cc. During the abrasion process, when the extrusion of abrasive laden media through the workpiece occurs, it causes the finishing of the inner cylindrical surface of the workpiece. When the magnetic field is applied, the abrasion only takes place around the workpiece surface where it is applied, while the remaining areas are unaffected. The location of the electromagnet is around the cylindrical workpiece. For providing maximum effect of magnetic field nearby the whole inner surface of the work-piece, there are two poles that are bounded by copper coils. When smoothening of the workpiece is done in the presence of magnetic field and with the help of magnetic and abrasive particles, this process is known as magnetic abrasive finishing (MAF). Different possible combinations of abrasive mediums such as {abrasive particle (silicon carbide) + silly putty (molding clay) + silicon oil};{silicon (Si) based polymer + hydrocarbon gel + abrasive particles: 40% ferromagnetic constituents + 45% Al₂O₃ +15% Si₃N₄} etc. can be used. The machining of each specimen is done for a prearranged number of cycles. For counting number of cycles, a digital counter is used.
3. Design and fabrication of novel MAFM from existing AFM set-up
An experimental setup has been designed that is powered hydraulically and fabricated for MAFM process in the laboratory. The basic useful requirements of various parts and vital mechanisms of the process are kept in mind while developing the MAFM setup.

3.1. Requirements for designing the MAFM set-up
- Media cylinders and pistons.
- Hydraulic unit.
- Design and development of novel workpiece fixture.
- Design and development of novel magnetization system.

3.1.1. Media cylinders and pistons. The MAFM setup contains the media cylinders which are used for holding the sufficient media. With help of piston movement the magnetic abrasive particles (media) flows under pressure from the lower media cylinder to the upper media cylinder through the work piece. The maximum pressure for hydraulic cylinders is up to 10 Mpa. The volume required for cylinders is fixed as 300 cc approximately. Because of the good tensile strength, EN8 (a medium strength carbon steel) is used for manufacturing the hydraulic cylinders. To meet the requirements of desired pressure, the piston material is cast off grey cast iron. To provide the appropriate displacement to media for passing through the workpiece, the stroke length is taken as 250 mm. From figure 2 the internal diameter of cylinder can be calculated as:

\[ A = \frac{\pi D^2}{4} \]  

Where, \( A \) = Cross sectional area of the piston, \( D \) = Diameter of the piston.

Hence,

\[ D = \sqrt{\frac{4A}{\pi}} \]  

Also, we know that 

\[ A = \frac{F}{P} \]  

Where, \( F \) = Force applied, \( P \) = Fluid pressure (10 Mpa), as per our requirement.

From equation (3) the value of \( A \) can be obtained and by putting it in equation (2) the piston diameter \( (D) \) is found as, 90 mm.

![Figure 2. Cylinder and piston drawing.](image)

3.1.2. Hydraulic unit. A hydraulic unit having the preferred pressure of up to 10 MPa has been designed for MAFM Process. There is a hydraulic gear pump whose function is to pump the hydraulic oil from tank and pass it to the whole circuit. The hydraulic oil number 68 has been used. A 2
horsepower and 1440 rpm flange type motor has been used. On the hydraulic unit, two direction control valves (DCV1 & DCV2- stainless steel, three positions four ways) have been fixed. For actuation of up movement of hydraulic cylinder, DCV1 is used while for actuation of down movement of hydraulic cylinder, DCV2 is used. For maintaining the required pressure, two pressure relief valves (PRV1 & PRV2, stainless steel) have been attached and to read the pressure, two pressure gauges both of 3000 psi have been mounted in the circuit. The flow chart of MAFM setup is displayed in figure 3.

Here are the design aspects of hydraulic pump:
Pressure requirement used for experimentation = 10 MPa ≈ 1450 psi
The formula to drive Power is given as:

\[ P = \frac{Q \times p}{1714} \]  \hspace{1cm} (4)

Hence,

\[ p = \frac{P \times 1714}{Q} \]  \hspace{1cm} (5)

Where, \( P \) = Power in \{Horsepower (HP)\}
\( Q \) = Discharge \{(Gallons/Min. (gpm)}\)
\( p \) = Pressure \{pounds per square inch (psi)}
\( Q \) can be calculated using, \( Q = n \times V_{stroke} \times \eta_{vol} \)  \hspace{1cm} (6)
\( V_{stroke} \) = Volume swept = Cylinder volume
\( \eta_{vol} \) = Volumetric efficiency (For gear pump it can taken as 95%)
\( V_{stroke} \) = Volume swept = Cylinder volume = \( \Pi r^2 h \)
\( V_{stroke} = 3.14 \times (45)^2 \times 250 \)
\[ V_{\text{stroke}} = 1589625 \ \text{mm}^3 \]

\[ V_{\text{stroke}} = 0.0015 \ \text{m}^3 \]

Hence, \( Q = \frac{1}{10} \times 0.0015 \times 0.95 \)

\[ Q = 0.00014 \ \text{m}^3/s = 2.22 \ \text{gal/min} \]

\{ \text{we know, } 1 \ \text{m}^3/s = 15850.32314 \ \text{gal/min} \} \]

By putting the value of \( Q \) in equation (5) we get, pressure:

\[ p = \frac{2 \times 1714}{2.22} \]

\[ p = 1544 \ \text{psi} \]

The hydraulic oil is drawn from the tank through the filter by the electric motor driven gear hydraulic pump and passes it to both the manually actuated direction control valves DCV1 and DCV2 through pressure relief valves PRV1 & PRV2. To control the pressure to a desired value, pressure relief valves are used in the system. The pressure in the upper hydraulic cylinder is kept high by using PRV1 and low in upper cylinder using PRV2 during downward stroke pressure. By actuating DCV1 and by keeping knob of DCV2 in central position, downward stroke is completed. After completing the downward stroke, using PRV2 the pressure in lower cylinder is maintained at a high level and in upper cylinder, it is maintained at low level using PRV1. Positions of DCV1 and DCV2 have been reversed. After completing the upward stroke, one cycle is completed. For counting the number of cycles, a digital counter is used in MAFM setup.

3.1.3. **Design and development of novel workpiece fixture.** Work piece fixture guides the media that is to be machined to pass through the work surface, so it plays a significant role. The material used for the fixtures in earlier work as per literature survey is nylon. The following drawback has been observed for using nylon as fixture material in MAFM. Nylon has low magnetic permeability for magnetic line of forces; therefore it can hinder the process of finishing of internal cavity in the workpiece. Therefore, a novel aluminium fixture has been developed and fabricated in which the workpiece comes exactly between magnetic field generated by electromagnet coils of MAFM setup. Drawing & pictorial view of work piece fixture is shown in figure 4 & 5.

Aluminium is taken as the material for the work piece fixture. There is a hole cut in the fixture that holds the work piece which is same as the outer shape and size of work piece. During machining to avoid the vibration, the fixture diameter is decreased gradually. The fixture is designed so that it can accommodate the electromagnet poles and can generate maximum magnetic pull near the inner surface of the workpiece.
3.1.4. **Design and development of novel magnetization system.** A novel electromagnetic system has been developed for experimental MAFM setup. As per rigorous literature survey it has been found that the researchers have used permanent magnets for their work. Such kinds of magnets have the capability to produce fixed value of magnetic flux density, which cannot be varied if needed for finishing of different materials, therefore limiting their use for certain materials only. For newly developed experimental setup coil type magnets are developed in which magnetic flux density can be varied from 0–2 Tesla. Such type of modification has made the developed MAFM setup more versatile. Below is detailed description of novel magnetization system.

3.1.4.1. **The electromagnet.** The electromagnet is fabricated and designed in such a way so that it can locate around the cylindrical work-piece. There are two poles surrounded by the copper coils which are arranged to deliver the magnetic field to be maximum near the whole inner surface of the work-piece. The specifications of electromagnet are shown in table 1.

### Table 1. Electromagnet specifications.

| Specification          | Description                                      |
|------------------------|--------------------------------------------------|
| Core material          | Mild steel (M.S.)                                |
| Core size              | Length = 175mm, Core rod diameter = 35mm, Core radius = 25mm |
| Coil                   | Copper wire, 23 Gauge, Ø 0.5733mm, 2500 turns, 3.820 kg / coil weight |
| Power supply to coil   | 0-240 V (DC)                                     |
| Magnetic flux density  | 0-2 Tesla                                        |

3.1.4.2. **The core.** Due to the high magnetic permeability, mild steel material (M.S) is used to fabricate the core. The drawing of core part A & part B is shown in figure 6 and 7 respectively. For avoiding larger magnetic field gradient at the corners, the diameter of the core is taken more than workpiece length. The Pictorial View of c-shaped core (part B) is shown in figure 8.

![Figure 6. Core drawing (Part A).](image)

![Figure 7. Core drawing (c-shaped) (part B).](image)

![Figure 8. Pictorial view of core (part B).](image)

Figure 9 & 10 shows the drawing and pictorial view of core assembly of part A & part B respectively.
3.1.4.3. Functioning of magnetization system. It has been observed from the literature that with an increase in the applied magnetic flux density the material removal rate (MRR) is also increased. Each coil is prepared by copper wire winding of 2500 turns per coil. The working gap between the electromagnet poles and the workpiece is taken as 1-2 mm and the maximum flux density of 0-2 tesla is used between them. Magnetic flux density can be changed by applying different values of input current to the poles and digital gauss meter (model DGM-202) is used for measuring it with the probe of DGM-202. Figure 11 and 12 shows the coil vobin drawing and the pictorial view of coil vobin (i) before coiling (ii) after coiling. Figure 13 shows the magnetization effect.
4. Results and discussion
The experimental MAFM setup was tested to analyse whether it is performing as per requirements i.e. the range of magnetic flux density, effectiveness of newly developed aluminium fixture. To check magnetic flux density range, digital gauss meter (Model DGM-202) has been used. The necessary variation was checked by varying the voltage from 0–240 volts. The magnetic flux density of 0–2 Tesla has been obtained. The observation of magnetic flux density in tesla with varying the voltage and current are shown in table 2.

| Sr. No. | Voltage (V) | Current (Amp.) | Magnetic Flux Density (Tesla) |
|---------|-------------|----------------|-----------------------------|
| 1)      | 0           | 0              | 0                           |
| 2)      | 9           | 0.7            | 0.07                        |
| 3)      | 18          | 1.3            | 0.15                        |
| 4)      | 27          | 1.52           | 0.25                        |
| 5)      | 36          | 2.0            | 0.3                         |
| 6)      | 45          | 2.5            | 0.45                        |

5. Conclusion
After making modification in existing AFM setup, the novel MAFM setup has been developed successfully. In this setup the permanent magnets have been replaced by coil type magnets in which magnetic flux density can be varied from 0-2 Tesla. Such type of modification has made the developed MAFM setup more versatile. For creating a restrictive passage or directing the media to desired locations in the workpiece, a fixture is usually required. An aluminium fixture has been used and proved to be very effective in comparison to nylon fixture, as this fixture does not exist between workpiece and electromagnet coils due to which the role of magnetic permeability of fixture material gets vanished.

6. References
[1] Ahmad S, Gangwar S, Yadav P C and Singh D K 2017 Materials and Manuf. Processes 1-7
[2] Mittal S, Kumar V and Kumar H 2016 Journal of Materials: Design and Applications 1-14
[3] Mittal S, Kumar V and Kumar H 2015 Materials and Manufacturing Processes 30 902-911
[4] Sadiq A and Shunmugam M S 2010 Tribology International 43 1122-1126
[5] Wani A M, Yadava V and Khatri A 2007 Journal of Materials Processing Tech. 190 282-290
[6] Singh S, Shan H S and Kumar P 2002 Journal of Material Processing Technology 128 155-161
[7] Singh S and Shan H S 2002 International Journal of Machine Tools & Manufacture 42 953-959
[8] Nagdeve L, Jain V K and Ramkumar J 2018 Machining Science and Technology 1-25
[9] Kathiresan S and Mohan B 2017 Materials and Manufacturing Processes 1-11
[10] Guo J, Tan Z E, Au K H and Liu K 2017 Int. J. Adv. Manuf. Technology 90 1881-1888
[11] Judal K B, Yadava V and Pathak D 2013 Materials and Manufacturing Processes 28 1196-1202
[12] Mulik R S and Pandey P M 2012 Journal of Manuf. Sci. and Engg. 134 051008-1 to 051008-12
[13] Sadiq A and Shunmugam M S 2009 Int. J. of Machine Tools and Manufacture 49 554-560
[14] Jain V K 2009 Journal of Materials Processing Technology 209 6022-6038
[15] Das M, Jain V K and Ghoshdastidar P S 2008 Int. J. of Machine Tools & Manufacture 48 415-426
[16] Jayswal S C, Jain V K and Dixit P M 2005 International J. Adv. Manuf. Tech. 26 477-490
[17] Singh D K, Jain V K and Raghuram V 2004 Journal of Materials Processing Tech. 149 22-29
[18] Nagdeve L, Jain V K and Ramkumar J 2016 Procedia CIRP 42 793-798