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Experimental Investigation of Electrochemical-Magnetic Assisted Helical Abrasive Flow Machining for Surface Roughness Improvement and Material Removal

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Abstract - The increasing use of advanced engineering materials and components with intricate internal geometries has created a growing demand for precision finishing processes capable of achieving superior surface quality in difficult-to-access regions. Abrasive Flow Machining (AFM) is an effective non-traditional finishing technique in which a viscoelastic abrasive medium is extruded through or across the workpiece to improve surface characteristics. However, its relatively low material removal rate and prolonged finishing time limit its use in precision applications. To address these limitations, this study proposes and experimentally investigates an Electrochemical-assisted Magnetic Helical Abrasive Flow Machining (ECMHAFM) process for finishing the internal surface of a brass workpiece. The proposed hybrid process integrates electrochemical dissolution, magnetic assistance, and helical abrasive motion to intensify the interaction between the abrasive medium and the workpiece surface. A guar-gum based semi-solid abrasive medium containing aluminium oxide (Al2O3) and magnetic abrasive particles is employed, with sodium chloride (NaCl) serving as electrolyte. The abrasive medium is extruded through the machining zone under controlled pressure using a helical-profile rod, thereby promoting enhanced abrasive contact and material removal along the internal surface. The machining performance of the proposed process is evaluated in terms of material removal and percentage improvement in surface roughness. The study provides an experimental assessment of the synergistic contribution of electrochemical action, magnetic particle manipulation, and helical abrasive flow to surface finishing performance. The proposed ECMHAFM approach offers a potential route for improving the efficiency and surface-finishing capability of conventional abrasive flow machining, particularly for precision finishing of complex internal surfaces.

Keywords: Abrasive Flow Machining; Electrochemical Machining; Magnetic Assistance; Helical Abrasive Flow; Surface Roughness; Material Removal

1. INTRODUCTION

Surface finishing is a critical stage in the manufacture of precision components because the final surface condition directly influences dimensional accuracy, friction, wear, fatigue behaviour, corrosion resistance, sealing performance, and, consequently, the functional life of a component. The requirement becomes particularly demanding when the component contains internal passages, narrow channels, blind cavities, intersecting holes, or intricate profiles that are difficult to reach with conventional finishing tools. Although conventional processes such as grinding, honing, lapping, and polishing can produce high-quality surfaces, their effectiveness is strongly dependent on tool accessibility and geometric simplicity. These limitations have encouraged the development of non-traditional finishing processes capable of delivering

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controlled material removal from geometrically complex and difficult-to-access regions.

Among the advanced finishing processes, **Abrasive Flow Machining (AFM)** has attracted considerable attention because it employs a deformable abrasive-laden medium as a flexible finishing tool. In AFM, a viscoelastic or viscoplastic medium containing abrasive particles is forced through or across the surface to be finished. The medium adapts to the geometry of the restricted passage, while the abrasive particles interact with surface asperities and remove a small amount of material during repeated extrusion cycles. This characteristic enables AFM to finish internal passages and complex profiles that are difficult to process using rigid conventional tools [1]. Experimental investigations have demonstrated that abrasive concentration, abrasive size, number of cycles, and media flow conditions have a significant influence on material removal and surface-finish characteristics [1].

The effectiveness of AFM originates from the localized interaction between the abrasive-laden medium and the workpiece surface. As the medium passes through a restricted machining zone, the abrasive particles experience forces that promote their interaction with surface asperities. Material removal can occur through mechanisms such as micro-cutting, micro-ploughing, and rubbing, depending on the abrasive characteristics, workpiece material, and process conditions [2]. The flexible nature of the medium is particularly advantageous for internal and complex geometries because the finishing action is not restricted by the accessibility limitations associated with conventional rigid tools. Consequently, AFM has been investigated for a wide range of engineering applications involving aerospace, automotive, tooling, biomedical, and other precision components [1,3].

Despite these advantages, **low material removal and the associated requirement for multiple finishing cycles remain important limitations of conventional AFM**. Increasing the extrusion pressure or abrasive concentration can enhance the finishing action, but such changes alone do not necessarily provide an adequate solution because the process response is also governed by the rheological behaviour of the medium, abrasive characteristics, workpiece geometry, and flow conditions [1,3]. Thus, simply increasing the severity of conventional AFM may lead to an undesirable compromise between productivity, dimensional control, and surface quality. This limitation has motivated researchers to develop hybrid and assisted variants of AFM in which an additional energy field or machining mechanism is introduced into the conventional abrasive-flow environment.

One important development in this direction is **magnetic assistance**. The application of a magnetic field can influence the behaviour and distribution of magnetic abrasive particles within the machining zone and can increase their interaction with the workpiece surface. Singh and Shan demonstrated the development of magneto abrasive flow machining by incorporating magnetic assistance into AFM and reported improvements in material removal and surface-finishing performance for brass components compared with conventional AFM [4]. Such findings established magnetic assistance as a promising approach for overcoming the productivity limitations associated with conventional abrasive flow machining.

A second approach is the incorporation of **electrochemical action** into AFM. Electrochemical machining removes material through controlled anodic dissolution and therefore does not depend solely on mechanical contact between abrasive

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particles and the workpiece. The combination of electrochemical dissolution with abrasive action has the potential to modify the surface layer and facilitate subsequent mechanical removal. Dabrowski et al. investigated abrasive flow machining with an electrochemical process aid and demonstrated the feasibility of electrochemically assisted AFM using polymeric electrolytes [5]. More recently, electrochemical-aided AFM has been investigated as a hybrid process specifically to address the low material-removal characteristic of conventional AFM [6].

The individual introduction of magnetic and electrochemical assistance provides useful improvements; however, the simultaneous integration of these mechanisms with a **controlled helical abrasive-flow path** presents an opportunity to further intensify the finishing action. A helical-profile tool can modify the local flow path of the abrasive medium and promote repeated interaction between the abrasive particles and the internal surface. When magnetic abrasive particles are subjected to magnetic assistance, their movement and concentration near the machining zone can additionally be influenced, while the electrolyte provides an environment for electrochemical dissolution. The combined action therefore has the potential to create a more active finishing zone than that obtained through abrasive flow alone.

Based on this concept, the present investigation develops an **Electrochemical-assisted Magnetic Helical Abrasive Flow Machining (ECMHAFM)** process for finishing the internal surface of a brass workpiece. The process employs a guar gum-based abrasive medium containing aluminium oxide (Al_2O_3) and magnetic abrasive particles, with sodium chloride (NaCl) used as the electrolyte. The medium is extruded through the machining region under controlled pressure in the presence of a helical-profile rod. The proposed configuration is intended to combine the mechanical action of abrasive particles, electrochemical dissolution of the workpiece surface, magnetic manipulation of the abrasive particles, and the altered flow characteristics produced by the helical profile.

Accordingly, the present study focuses on experimentally evaluating the effect of the proposed hybrid process on two principal finishing responses: **material removal and percentage improvement in surface roughness**. Particular attention is given to the role of the combined electrochemical, magnetic, and helical-flow effects rather than treating each mechanism as an isolated finishing technique. The study therefore seeks to establish the feasibility of ECMHAFM as an intensified abrasive-flow finishing route for internal brass surfaces and to provide an experimental basis for understanding its potential to overcome the productivity limitations of conventional AFM.

2. LITERATURE REVIEW

The limitations of conventional abrasive flow machining (AFM), particularly its relatively low material removal rate and long processing time, have encouraged researchers to modify the process through changes in tooling, abrasive media, flow conditions, and the incorporation of additional energy fields. Rather than relying solely on the mechanical action generated by the reciprocating abrasive medium, hybrid AFM processes seek to introduce an additional mechanism that increases the activity of abrasive particles at the machining surface. The development of these processes has progressively moved from **tool-assisted and force-assisted AFM toward**

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electrochemical, magnetic, and multifunctional hybrid approaches.

2.1 Productivity enhancement in abrasive flow machining

Early investigations into AFM established that the machining response is strongly dependent on the characteristics of the abrasive medium and process conditions. Jain and Adsul reported that abrasive concentration, abrasive mesh size, number of extrusion cycles, and media flow speed substantially affect material removal and surface-finish improvement when machining brass and aluminium [1]. Although AFM provides an important capability for finishing inaccessible surfaces, the relatively slow rate of surface generation remains a major limitation for industrial implementation. Walia et al. subsequently demonstrated that modification of the tooling arrangement could substantially improve AFM productivity. In their centrifugal-force-assisted configuration, a rotating rod was incorporated inside a cylindrical workpiece to generate an additional force on the abrasive particles. The authors reported that, for a specified improvement in surface roughness, processing time could be reduced considerably compared with conventional AFM [7].

These developments established an important principle for AFM enhancement: **increasing the effectiveness of abrasive–workpiece interaction can improve productivity without necessarily increasing the severity of the extrusion process**. Subsequent researchers therefore explored rotational motion, centrifugal effects, guided abrasive motion, and specially designed tooling as alternative routes for increasing the number and activity of abrasive grains in the finishing zone.

2.2 Tool- and motion-assisted abrasive flow machining

Sankar et al. developed a drill-bit-guided abrasive flow finishing (DBG-AFF) process in which a rotating drill bit was used to influence the motion of the abrasive medium inside the workpiece [8]. The modified flow pattern promoted greater interaction between the abrasive particles and the workpiece surface and was investigated as a means of improving finishing performance. In another investigation, Sankar et al. introduced rotational abrasive flow finishing (R-AFF), in which rotational motion was imparted to the workpiece during extrusion of the abrasive medium [9]. The additional motion altered the shearing conditions at the surface and demonstrated the potential of rotational assistance for reducing the limitations of conventional AFM.

A related approach was reported by Brar et al. through the development of **helical abrasive flow machining (HLX-AFM)** for internal cylindrical surfaces [10]. In this configuration, a helical tool was positioned within the workpiece to modify the flow path of the abrasive medium. The resulting helical movement increased the interaction between the abrasive medium and the internal surface and was shown to enhance material removal. A subsequent study by the same research group further examined the robustness of the HLX-AFM process and used Taguchi-based experimentation to establish suitable process conditions for enhanced material removal [11]. These studies are particularly relevant to the present work because they demonstrate that **controlled modification of the abrasive-flow trajectory can be used as an active means of increasing finishing intensity** rather than treating the tooling merely as a passive flow-confining element.

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2.3 Electrochemical-assisted abrasive flow machining

Another significant direction in AFM development has been the introduction of electrochemical dissolution into the finishing process. Dabrowski et al. investigated electrochemical-aided abrasive flow machining (ECAFM) using polymeric electrolytes [5]. Their work demonstrated the feasibility of combining anodic dissolution with mechanical abrasion, although the electrochemical contribution was strongly affected by electrolyte conductivity, abrasive loading, interelectrode gap, and the rheological characteristics of the semi-liquid electrolyte. The study primarily addressed the finishing of flat surfaces and therefore left scope for further development of electrochemical-assisted AFM for complex internal geometries.

Brar et al. subsequently developed the **electrochemical-aided abrasive flow machining (ECA²FM)** process by combining AFM and electrochemical machining for the finishing of internal holes and prismatic recesses [6]. The hybrid process was intended to exploit the complementary mechanisms of the two processes: electrochemical dissolution facilitates material removal at the surface, while abrasive particles mechanically remove the surface layer and products generated during electrochemical action. The authors reported enhanced material removal and demonstrated the potential of the hybrid process for reducing the time required for fine finishing.

Further experimental work on ECA²FM established that process variables such as applied voltage, electrolyte concentration, number of machining cycles, abrasive-to-medium ratio, abrasive characteristics, and tooling conditions influence the resulting material removal and surface-finish improvement [12]. These findings indicate that electrochemical assistance can address the low material-removal characteristic of AFM; however, the process must be carefully controlled because excessive electrochemical action may adversely affect surface uniformity. This issue is important for hybrid processes in which electrochemical dissolution and mechanical abrasion operate simultaneously.

The role of abrasives in electrochemical machining has also been examined independently. Sankar et al. investigated abrasive-assisted electrochemical machining of an aluminium–boron carbide–graphite composite and reported that the incorporation of abrasive particles produced a more uniform machined surface than electrochemical machining without abrasive assistance [13]. Their observations support the concept that mechanical abrasion can assist in removing reaction products and surface irregularities generated during electrochemical dissolution. Thus, the combined action of electrochemical and abrasive mechanisms can provide advantages over either mechanism operating independently.

2.4 Magnetic assistance in abrasive flow machining

Magnetic assistance represents another important route for intensifying abrasive action. Singh and Shan introduced **magneto abrasive flow machining (MAFM)** by applying an external magnetic field around the workpiece [4]. The magnetic field generates an additional force on magnetic abrasive particles, thereby modifying their interaction with the workpiece surface. Their investigation demonstrated that magnetic assistance could increase material removal and improve surface roughness compared with conventional AFM. The response was also dependent on the magnetic-field strength, indicating that the magnetic field must be selected appropriately because excessive magnetic force can alter the

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movement and engagement of abrasive particles in an undesirable manner.

Singh and Walia later investigated a hybrid magnetic-force-assisted AFM configuration in which a magnetic field was generated around a cylindrical workpiece using a solenoid [14]. Their results further confirmed that magnetic force can be used to increase the effectiveness of abrasive particles and enhance material removal. These studies established magnetic assistance as a viable means of improving the productivity of AFM without fundamentally changing its flexible finishing principle.

The subsequent development of magnetically assisted AFM has been reviewed by Singh et al., who identified magnetic flux density, extrusion pressure, abrasive type and size, abrasive concentration, number of cycles, medium properties, and workpiece configuration as important variables governing the process response [15]. The review also highlights the increasing use of magnetic abrasive media and externally applied magnetic fields for finishing complex and difficult-to-reach surfaces. Verma et al. experimentally investigated internal magnetic abrasive finishing of pipes using a specially designed magnetic tool and reported that magnetic flux density was a dominant parameter in their investigated range [16]. Their results demonstrated the capability of magnetic assistance to produce highly refined internal surfaces.

Numerical and experimental investigations have also been undertaken to understand the role of the magnetic field in controlling the finishing action. Barman and Das analysed magnetic-field distribution and the behaviour of magnetorheological finishing media under magnetic and non-magnetic conditions [17]. Their work showed that the applied magnetic field modifies the flow behaviour and abrasive indentation characteristics of the finishing medium, providing a physical basis for controlling the finishing force through magnetic assistance.

2.5 Electrochemical–magnetic abrasive finishing

The combination of electrochemical and magnetic mechanisms provides a further level of process integration. Kumar et al. investigated electrochemical magnetic abrasive finishing (ECMAF) of SS304 and developed a process configuration intended to prevent the abrasive particles from being washed away from the machining zone by the electrolyte [18]. Their work demonstrated the feasibility of combining electrochemical dissolution with magnetic abrasive action for surface finishing. In such a process, electrochemical dissolution can weaken or remove material at the surface while the magnetic abrasive mechanism provides controlled mechanical action.

The literature therefore shows that three different approaches have been independently explored to overcome the limitations of conventional AFM: electrochemical assistance to increase material removal through anodic dissolution, magnetic assistance to intensify abrasive-particle interaction, and helical/tool assistance to modify the flow trajectory and increase abrasive–surface contact**.** However, these approaches have largely been investigated as separate process modifications. The available literature [19-21] does not establish a comprehensive experimental framework in which these three mechanisms are simultaneously integrated within an abrasive-flow environment for internal finishing of brass.

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2.6 Comparative assessment of previous studies

Table 1 Development of assisted and hybrid abrasive flow finishing processes reported in the literature

Ref.	Process / approach	Principal modification	Workpiece / application	Major contribution	Remaining limitation/research opportunity
[1]	Conventional AFM	Abrasive-laden viscoelastic medium	Brass, aluminium	Established influence of abrasive concentration, grit size, cycles and flow speed	Relatively low material removal and long processing time
[7]	CFAAFM	Rotating centrifugal-force-generating rod	Cylindrical workpiece	Increased abrasive activity and reduced processing time	Additional force mechanism without electrochemical assistance
[8]	DBG-AFF	Drill-bit-guided abrasive flow	Internal surfaces	Modified abrasive-medium motion and improved finishing action	Primarily mechanical assistance
[9]	R-AFF	Rotating workpiece	Aluminium-based materials/MMCs	Additional rotational shearing improved finishing performance	No electrochemical or magnetic contribution
[10, 11]	HLX-AFM	Helical-profile/drill-bit tooling	Internal cylindrical surfaces	Modified flow trajectory and enhanced material removal	Helical assistance investigated independently
[5]	ECAFM	Electrochemical process aid	Flat surfaces	Combined anodic dissolution and mechanical abrasion	Limited geometric scope and electrolyte/rheology constraints
[6,12]	ECA²FM	ECM + AFM	Internal holes/recesses	Increased material removal and improved finishing capability	Magnetic and helical assistance not simultaneously incorporated
[13]	Abrasive-assisted ECM	ECM + abrasive particles	Al–B_4C–graphite composite	Abrasive action improved surface uniformity	Not an abrasive-flow process
[4,14]	MAFM / magnetic-force-	External magnetic field	Cylindrical/internal surfaces	Increased abrasive action and material removal	Electrochemical dissolution absent

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	assisted AFM				
[15]	Magnetically assisted AFM	Review of magnetic assistance	Complex/internal surfaces	Identified important magnetic, abrasive and process variables	Calls for further process integration
[16]	Internal MAF	Magnetic tool	SS304 pipes	Demonstrated strong effect of magnetic flux density on internal finishing	Conventional magnetic abrasive mechanism
[17]	MFAF/MR finishing	Magnetic-field-controlled finishing medium	Flat surfaces	Explained magnetic-field influence on flow and abrasive indentation	Different from abrasive-flow/electrochemical configuration
[18]	ECMAF	Electrochemical + magnetic abrasive finishing	SS304	Demonstrated combined electrochemical and magnetic finishing	Does not incorporate helical AFM flow assistance

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2.7 Research gap and motivation for the present study

The reviewed literature clearly demonstrates that hybridization can improve the performance of abrasive-flow-based finishing processes. Nevertheless, the mechanisms introduced in previous studies have generally been investigated **individually or in two-process combinations**. Mechanical/rotational assistance increases abrasive interaction, electrochemical assistance introduces anodic material dissolution, and magnetic assistance enhances the action of magnetic abrasive particles. A logical next step is to integrate these effects within a single controlled abrasive-flow environment.

The present study therefore proposes **Electrochemical-assisted Magnetic Helical Abrasive Flow Machining (ECMHAFM)**, in which electrochemical dissolution, magnetic assistance, and helical flow modification are simultaneously employed for internal finishing of a brass workpiece. Unlike conventional AFM, the proposed configuration uses a guar gum-based abrasive medium containing aluminium oxide (Al_2O_3) and magnetic abrasive particles, with NaCl serving as the electrolyte. A helical-profile rod is introduced into the machining zone to alter the flow path and promote repeated abrasive interaction with the internal surface.

The research gap addressed by the present investigation can therefore be summarized as follows:

1. **Conventional AFM** provides excellent accessibility but suffers from relatively low material removal and prolonged processing time.
2. **Tool and rotation-assisted AFM** improves abrasive interaction but remains predominantly mechanical.
3. **Electrochemical-assisted AFM** increases material removal through the addition of anodic dissolution but does not exploit magnetic control of abrasive particles.
4. **Magnetic-assisted AFM** increases abrasive activity through magnetic forces but does not incorporate electrochemical dissolution.
5. **Electrochemical–magnetic finishing** demonstrates the potential of combining the two mechanisms, but the abrasive-flow trajectory and helical assistance have not been simultaneously integrated into the process considered here.
6. Consequently, there is a need to investigate a **three-way hybridization of electrochemical action, magnetic assistance, and helical abrasive flow** and to determine its influence on material removal and surface-finish improvement.

Accordingly, the present work experimentally investigates ECMHAFM with particular emphasis on **material removal and percentage improvement in surface roughness**. The study is intended to determine whether the combined action of electrochemical dissolution, magnetic abrasive activation, and helical modification of abrasive-media flow can provide a more effective finishing mechanism than conventional abrasive flow machining.

3. EXPERIMENTATION

In the present work a modified setup for ECMHAFM process, employs an axially held standard helical profile rods HSS act as cathode and workpiece as anode and electromagnet which are placed around the workpiece to provide uniform magnetic field by using DC supply. In the electrochemical machining the workpiece material is removed due to the combined effect of electrochemical reactions and the cutting

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action of abrasive particles. This media is made with the mixture of laden media, electrolytic salt, ferromagnetic and abrasive particles. This media is continuously extruded back and forth through the narrow gap between the **drill bit helical profile rod** and the inner surface of the hollow anodic workpiece [22].

In electrochemical machining (ECM), an electric current is passed between the workpiece and the electrode, leading to electrochemical reactions at the surface. These reactions result in the formation of an oxide layer on the workpiece. This oxide film is continuously removed by the action of magnetic abrasive particles during the machining process. Additionally, the orientation and movement of these abrasive particles are influenced by helical drill bit which enhance their cutting effectiveness [22].

In this investigation, to enable simultaneous electrolytic machining and magnetic abrasive cutting, a specially designed nylon fixture was developed. The fixture consists of three parts and is designed to securely hold a cylindrical copper rod (cathode) concentrically inside a hollow cylindrical workpiece (anode) using appropriate retainers and fasteners. The axial copper rod is supported at both ends by copper retainers, ensuring proper alignment without obstructing the flow of abrasive media or affecting sealing.

Two electrodes are incorporated into the fixture, the cathode is connected to the axial copper rod through a retainer and linked to the negative terminal of a DC power supply, while the anode is connected to the workpiece and linked to the positive terminal. A Scientech DC power supply with an operating range of 0–30 V is used to provide the required electrical input.

Experimental setup: The main innovative and functional characteristics of the equipment for processing by electrochemical magnetic helical abrasive flow machining are:

• I.D. of Hydraulic actuators (Di): 100 mm
• Stroke length of piston (l): 300 mm
• The media cylinders outer diameter: 73 mm
• The media cylinders inner diameter:63 mm
• Pillar to pillar distance longitudinal: 320 mm
• Pillar to pillar distance laterally: 50 mm

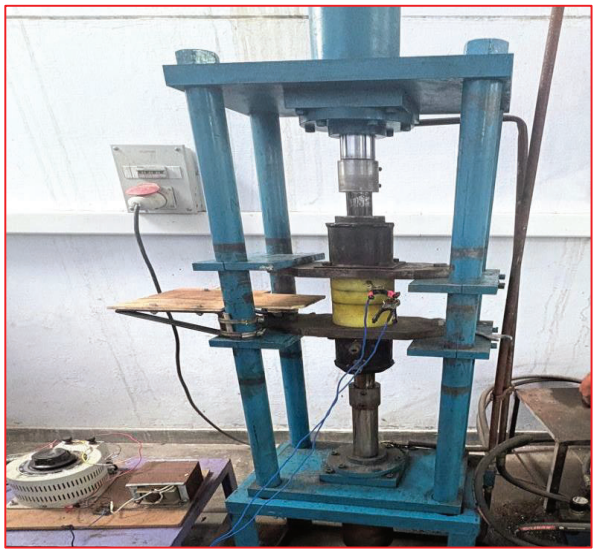


Figure 1: Experimental Setup

Electromagnets: In the experimental setup, electromagnet poles are positioned on both sides of the workpiece to ensure a strong and uniform magnetic field in the machining zone. The design and placement of these electromagnets are optimized to maximize magnetic field intensity around the workpiece. A key advantage of electromagnets over permanent magnets is their ability to provide adjustable magnetic field strength. The intensity of the magnetic field can be varied by changing the current supplied, and the polarity of the field can be reversed simply by reversing the direction of current flow. The strength of the magnetic field produced by an electromagnet is

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directly proportional to the product of the number of turns in the coil (N) and the current (I), expressed as NI.

In the present study, the magnetic field intensity is controlled within a range of 0.2 to 2 Tesla, allowing flexibility in analysing its effect on the machining performance.

Workpiece material: A hollow cylindrical brass workpiece (yellow brass consisting of 65% Cu and 35% Zn) with a Brinell hardness of 156 BHN was used in the study. The initial surface roughness ranging from 0.66 to 1.68 µm.



Fig. 2(a). Hollow cylindrical workpiece

The workpiece dimensions include an inner diameter of 8 mm, an outer diameter of 12.6 mm, and a length of 16 mm. During machining, abrasive-laden media is extruded through the internal passage of the workpiece to facilitate material removal.

The workpiece is securely mounted in the setup using specially designed nylon fixtures. The in-house developed experimental setup is capable of generating a maximum extrusion pressure of 25 N/mm². The abrasive media is driven by two actuators connected to separate media cylinders. During operation, the media flows from one cylinder to the other through the workpiece. Upon completion of one stroke, the flow direction is reversed, and the return stroke begins. Together, the forward and backward movements constitute one complete machining cycle.

The material removal was determined by measuring the weight of the workpieces before and after each experiment using a precision electronic balance (CX220) with a resolution of 0.1 mg. Surface roughness was evaluated using a precision profilometer (Mitutoyo SJ-201), and the reported values represent the average of three measurements to ensure accuracy and consistency in assessing the machined surface quality.

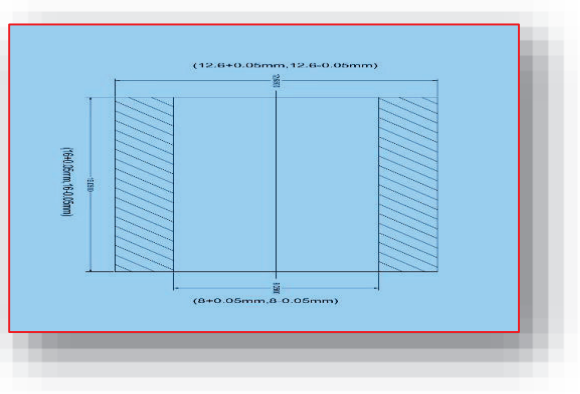


Fig. 2 (b). Dimension of hollow cylindrical workpiece

Media: In the present study, a low-cost and eco-friendly abrasive-laden organic medium guar gum has been used the base material. Sodium chloride (NaCl) is incorporated as the electrolyte to promote electrochemical dissolution, while magnetic abrasive particles are added with aluminium oxide abrasive to enable magnetic field-assisted finishing. Abrasive to media ratio is taken as 1:1 and aluminium oxide abrasive and magnetic abrasive particle size of 150 micron have been used. The guar gum acts as a biodegradable binder, ensuring proper suspension and controlled flow of the abrasive particles. Guar gum as an organic -laden medium which is low-cost, eco-friendly and easily available which is already used as media [23-25,27, 28].

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Additionally, the use of a helical tool or flow path induces a spiral motion in the abrasive media, enhancing the interaction between abrasive particles and the workpiece surface. This helical movement improves abrasive mixing and increases contact length, leading to more effective material removal and improved surface finish. The combined action of electrochemical reaction, magnetic forces, and helical flow results in a highly efficient and sustainable machining process [26, 27].

4. EXPERIMENTAL DESIGN:

The effects of machining parameters associated with AFM on machining characteristics were extensively investigated in this research. The various process parameters different profile rods, number of cycles and also to operate it at different voltages and current flow rates were varied to find their effect on the machining characteristics of material removal and percentage improvement in surface roughness. The experiments were designed to study the effect of these on response characteristics of AFM process. **Table 1** shows the various process parameter levels and value of other fixed parameters

Table 1: Process parameter and their values at different levels

Characteristics	Process Parameters	Unit	Level 1	Level 2	Level 3
P	Profile rods	-	3-start drill bit	2-start drill bit	Spline
V	Voltage	Volt	3	6	9
N	Numbers of cycles	-	2	4	6
Polymer to gel ratio-1:1, workpiece material- Brass, media flow rate-310 cm^3 abrasive type- Al_2O_3, magnetic field-0.6T, Temperture-32±2, Initial Roughness of workpiece-0.66-1.68.					

Response parameters

The effect of the selected parameters was studied on the following response characteristics of ECMHAFM process. The quality characteristic under consideration is material removal (MR, in mg) and Percentage Improvement in Surface Roughness (%ΔRa). The material removal signifies the amount of material that has been removed from a work piece in a specified number of cycles [13].

Material Removal is calculated by using:

Material Removal (MR) = (Initial Weight- Final Weight) * 1000 (mg)

Percentage Improvement in Surface Roughness is calculated by using:

Surface Roughness Improvement (%ΔRa) =

$$\frac{Initial\ Roughness - Final\ Roughness}{Initail\ Roughness} * 100$$

The surface roughness testing machine (Mitutoyo SJ-201) was used to measure the initial and final roughness is shown in **Figure 3.**



Figure 3: Surface roughness testing machine

Experimental design based on Taguchi Method

The orthogonal array L9 has been selected. It had nine rows and four columns. The first three columns had

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three parameters allocated to them, and the rows represented nine tests with different combinations of the chosen machining parameters. Only three criteria, each at three levels, were taken into account in this study. For every experiment, three observed MR values and the percentage improvement in surface finish (ΔRa) were analyzed. Based on the Taguchi approach, the L9 orthogonal array was used to determine the levels of each machining parameter. Additionally, ANOVA based on S/N ratio was used to identify the relevant machining factors linked to MR and % Improvement in (ΔRa).

Experimentation: The L9 OA's test conditions were followed for conducting the **experiments (Table 2).** In every trial condition, every experiment was performed three times. As a result, twenty-seven workpieces with starting surfaces between 0.66 and 1.68 microns were chosen. The percentage improvement in surface roughness and material removal was calculated for each trial condition and replication.

Analysis and Discussion

Analysis by Taguchi Method

The parametric technique of Taguchi's Method was used to plan the experiments. Table 2 provides the response characteristic data. Taguchi's suggested standard approach to data analysis based on S/N ratio is developed. Experimental data is used to calculate the average values of the S/N Ratio of the quality/response characteristics for each parameter at various levels. The S/N ratio for these kinds of responses is shown below since both the response parameters—material removal and percentage improvement in surface finish—are of the "higher the better" kind of machining quality characteristics.

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

where

$$MSD_{HB} = \frac{1}{R}\sum_{j=1}^{R}\left(1/y_j^2\right)$$

,R = Number of repetitions,y_j = Response value

The main effects of process parameters for S/N Ratio for each response are plotted by calculating the average values of response characteristics for each parameter at level one, level two and level three (M1,M2, M3). The analysis of variance (ANOVA) of S/N Ratio data is performed to identify the significant parameters and to quantify their effect on the response characteristics. Helical profiles 3-Start, 2-Start helical rod and Spline, Voltage 3,6,9 and Number of cycles 2,4,6.

Effect on Material Removal (MR)

Helical profile Rod: it is clearly shown in graph that 3-Start helical profile rod gave maximum material removal. In this setup helical rod are used which force the media to undergo multiple motions, including axial flow, helical flow along the flute, and scooping action. The interplay of these flow mechanisms increases the effective contact length between abrasive particles and work surface, thus enhancing material removal.

Voltage: For the selected value of voltage potential, the material removal (MR) is increase with the increase of applied voltage. It is due to more machining action take place due to more electrolytic dissolution and magnetic action at the workpiece which enhance the cutting action. Due to the electrochemical and magnetic machining attack, the surface becomes soft as any oxide layer/hard surface is eroded [27].

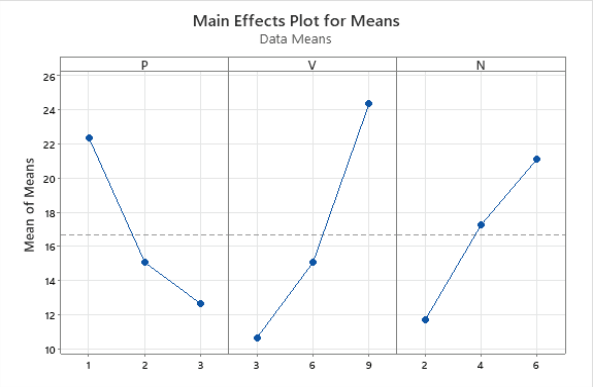
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Number of cycles: As the number of cycles increase from 2 to 6, the material removal (MR) is also increase. More number of cycles means more abrasion action and higher material removal.

Table 2: Response table for material removal

Exp No	1	2	3	Response of material removal			
	P	V	N	R1	R2	R3	S/N Ratio
1	1	1	1	7.60	10.3	9.2	18.91
2	1	2	2	20.40	19.6	18.9	25.85
3	1	3	3	38.15	34	47	31.40
4	2	1	3	12.50	14.7	13.5	22.59
5	2	2	1	15.00	16.5	15.2	23.82
6	2	3	2	17.15	16.6	14.4	24.03
7	3	1	2	10.50	8.6	9.0	19.34
8	3	2	3	6.80	5.5	17.6	17.14
9	3	3	1	15.00	21.2	19.5	25.09



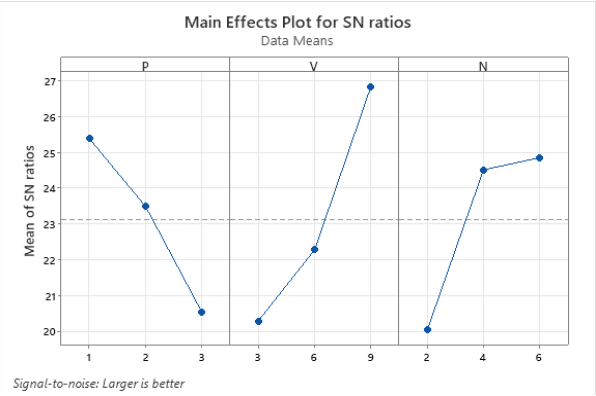


Table 3: Response table for Means of Material Removal

Level	P	V	N
1	22.35	10.66	11.68
2	15.06	15.06	17.26
3	12.63	24.33	21.11
Delta	9.72	13.68	9.42
Rank	2	1	3

Table 4: Anova S/N ratio for Material removal

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Profile	36.01	2	18.00	24.14	19.52	YES (SIGNIFICANT)
Voltage	67.84	2	33.92	45.48	36.77	YES (SIGNIFICANT)
Number of Cycle	43.44	2	21.72	29.12	23.54	YES (SIGNIFICANT)
Error	1.844	2	0.92	1.23		
T	149.14	8				
*** Significant at 95 % confidence level, Fcritical = 19 SS – Sum of Squares, DOF – Degree of Freedom, V – Variance, SS' – Pure Sum of Squares**						

The percentage contribution of Voltage is 45.48%, number of cycle 29.12% and profile 24.14%. So, the voltage is the most significant parameter.

Table 5: Anova for Raw data

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Profile	460.30	2	230.15	21.01	10.27	YES (SIGNIFICANT)
Voltage	877.55	2	438.77	40.07	19.58	YES (SIGNIFICANT)
Number of Cycle	403.95	2	201.97	18.44	9.01	YES (SIGNIFICANT)
Error	448.16	20	22.40	20.46		
T	2189.97	26				
*** * Significant at 95 % confidence level, Fcritical = 3.5 SS – Sum of Squares, DOF – Degree of Freedom, V – Variance, SS' – Pure Sum of Squares**						

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Effect on Surface Roughness (ΔRa)

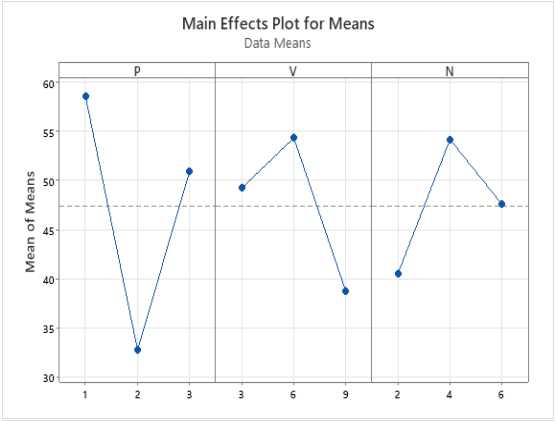
Helical profile Rod: 3- Start helical profile rod gave maximum surface roughness because of media undergo multiple motions, including axial flow, helical flow along the flute, and scooping action. The interplay of these flow mechanisms increases the effective contact length between magnetic abrasive particles and work surface, thus enhance surface roughness.

Voltage: The main effect for surface roughness with respect to voltage indicates that surface roughness decreases as the applied voltage increases. At lower voltage levels, the helical electrochemical action removes micro peaks while magnetic abrasive smooths the surface so the improvement in surface roughness is higher, whereas at higher voltages, the improvement in surface roughness becomes lower because of over-etching or pitting action occur that produce uneven surface [27].

Number of cycles: In the beginning, ΔRa rises as the number of cycles increases because there are more peaks and valleys to be finished. However, in the later stages, most of the peaks and valleys disappear, therefore ΔRa decreases as the number of cycles increases.

Table 6: Response table for % improvement of Surface Roughness

Exp No	1	2	3	Response of Surface Roughness			
	P	V	N	R1	R2	R3	S/N Ratio
1	1	1	1	59.00	54.00	48.00	34.50
2	1	2	2	75.00	85.00	65.00	37.34
3	1	3	3	55.00	46.00	40.00	33.22
4	2	1	3	35.00	40.00	40.00	31.61
5	2	2	1	45.00	30.00	45.00	31.55
6	2	3	2	18.60	25.00	16.00	25.53
7	3	1	2	59.00	52.00	56.00	34.87
8	3	2	3	51.00	55.00	38.00	33.28
9	3	3	1	44.00	48.60	55.00	33.73



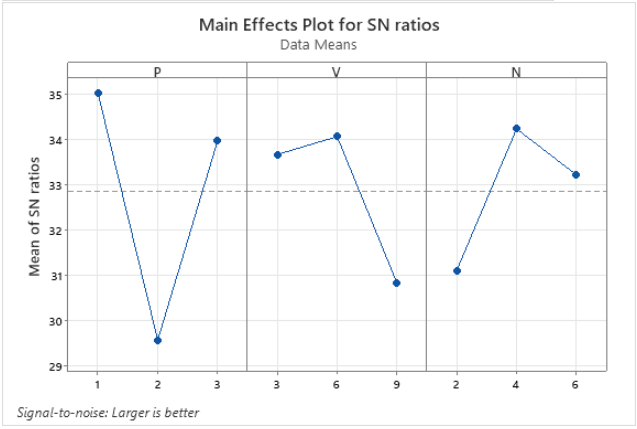


Table 7: Response table for Means of % improvement in Surface Roughness

Level	P	V	N
1	58.56	49.22	40.51
2	32.73	54.33	54.18
3	50.96	38.69	47.56
Delta	25.82	15.64	13.67
Rank	1	2	3

Table 8: Anova S/N ratio for Surface Roughness

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Profile	50.23	2	25.11	59.14	64.49	YES (SIGNIFICANT)
Voltage	18.65	2	9.32	21.96	23.95	YES (SIGNIFICANT)
Number of Cycle	15.26	2	7.63	17.96	19.59	YES (SIGNIFICANT)
Error	0.77	2	0.38	0.91		
T	149.14	8				
*** Significant at 95 % confidence level, Fcritical = 19 SS – Sum of Squares, DOF – Degree of Freedom, V – Variance, SS' – Pure Sum of Squares**						

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The percentage contribution of Voltage is 21.96%, number of cycle 17.96% and profile 59.14%. So, the 3- start helical profile rod is the most significant parameter.

Table 9: Anova for Raw data

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Profile	3169.78	2	1584.89	51.68	32.46	YES (SIGNIFICANT)
Voltage	1145.46	2	572.73	18.67	11.73	YES (SIGNIFICANT)
Number of Cycle	840.76	2	420.38	13.71	8.61	YES (SIGNIFICANT)
Error	976.44	20	48.822	15.92		
T	6132.47	26				
*** * Significant at 95 % confidence level, Fcritical = 3.5 SS – Sum of Squares, DOF – Degree of Freedom, V – Variance, SS' – Pure Sum of Squares**						

5. CONCLUSIONS

Based on the experimental investigation of **Electrochemical-assisted Magnetic Helical Abrasive Flow Machining (ECMHAFM)** for finishing the internal surface of brass, the following conclusions can be drawn:

1. **The proposed ECMHAFM process effectively integrates electrochemical dissolution, magnetic abrasive action, and helical abrasive flow to enhance the finishing performance of conventional abrasive flow machining.** The combined action facilitates material removal and surface asperity reduction, demonstrating the potential of ECMHAFM as an effective hybrid process for precision finishing of internal surfaces.
2. **Applied voltage has a significant influence on both material removal and surface-finish improvement.** An appropriate voltage promotes electrochemical dissolution and complements the mechanical action of the abrasive particles. However, excessive voltage may produce undesirable electrochemical effects and adversely affect surface quality. Therefore, the applied voltage must be optimized to achieve a suitable balance between material removal and surface finishing.
3. **Material removal is predominantly influenced by the applied voltage.** The analysis of variance indicates that voltage contributes **45.48%** to the variation in material removal, followed by the number of machining cycles (**29.12%**) and helical profile (**24.14%**). The signal-to-noise ratio analysis identifies **9 V, 6 machining cycles, and a 3-start helical-profile rod (P1V3N3)** as the optimum combination for maximizing material removal within the investigated experimental range.
4. **The helical-profile configuration is the most influential parameter for improving surface roughness.** For percentage improvement in surface roughness (%ΔRa), the contributions of helical profile, voltage, and number of cycles are **59.14%, 21.96%, and 17.96%**, respectively. The substantially higher contribution of the helical profile indicates that modification of the abrasive-medium flow path plays a dominant role in surface-finish enhancement.
5. The signal-to-noise ratio analysis shows that the combination of a **3-start helical-profile rod, 6 V applied voltage, and 6 machining cycles (P1V2N2)** provides the optimum condition for maximizing the percentage improvement in surface roughness. This condition differs from the optimum condition for material removal, indicating that **maximum material removal and maximum surface-finish improvement do not necessarily occur at the same process setting**.
6. The results demonstrate that **process optimization must therefore be response-specific**. A higher voltage and appropriate number of cycles favour

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material removal, whereas the helical-profile geometry has a comparatively stronger influence on surface-finish improvement. This distinction is important for selecting ECMHAFM parameters according to the desired machining objective.

7. Overall, the experimental findings establish that **electrochemical, magnetic, and helical assistance can be effectively integrated within an abrasive-flow machining environment** to improve the finishing performance of brass internal surfaces. The ECMHAFM process provides a promising route for reducing the limitations of conventional AFM and can be further investigated for complex internal geometries and other difficult-to-finish engineering components.

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