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Review article

A State-of-the-Art Review on the Recent Advancements in the Electrochemical Abrasive Flow Machining Process

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A B S T R A C T

Abrasive flow machining (AFM) is a non-conventional machining method used for the fine finishing of complex external/internal surfaces of metallic parts. Generally, this process has a low material removal rate (MRR) and is a more time-consuming process. So, to overcome this problem, various researchers employed hybridization of the abrasive flow machining process (AFM) with a distinct nontraditional machining process. Hence, this paper aims to provide a detailed review of the electro-chemical assisted AFM (ECA2FM) process, which is a combination of electrochemical machining and abrasive flow process. Then, the effect of processing parameters such as grit size and type, the total number of cycles, current, voltage, abrasive type and size, extrusion pressure, design of workpiece holding device and proper tooling on the material abrasion and surface finishing is summarized. Thereafter the Progressive outlook on the integration of electrochemical AFM with magnetic energy is given. Finally, the emerging applications of the electrochemical AFM process are discussed.

1. INTRODUCTION

In the manufacturing industries, achieving high efficiency and surface finish is not only a significant necessity for researchers but also an indispensable need in the manufacturing sector. However, conventional methods are very time-consuming and do not produce a precisely finished surface because it involves a single process and that only process cannot fulfil the nowadays demand of achieving a better finish surface and attaining high efficiency [1].

AFM also known as extrude-honing, is a way used to smooth and polish internal surfaces and create managed radii. The main purpose of non-traditional machining process like AFM is to attain good surface finish at low cost. The schematic illustration of AFM process is depicted in Fig. 1 [1].

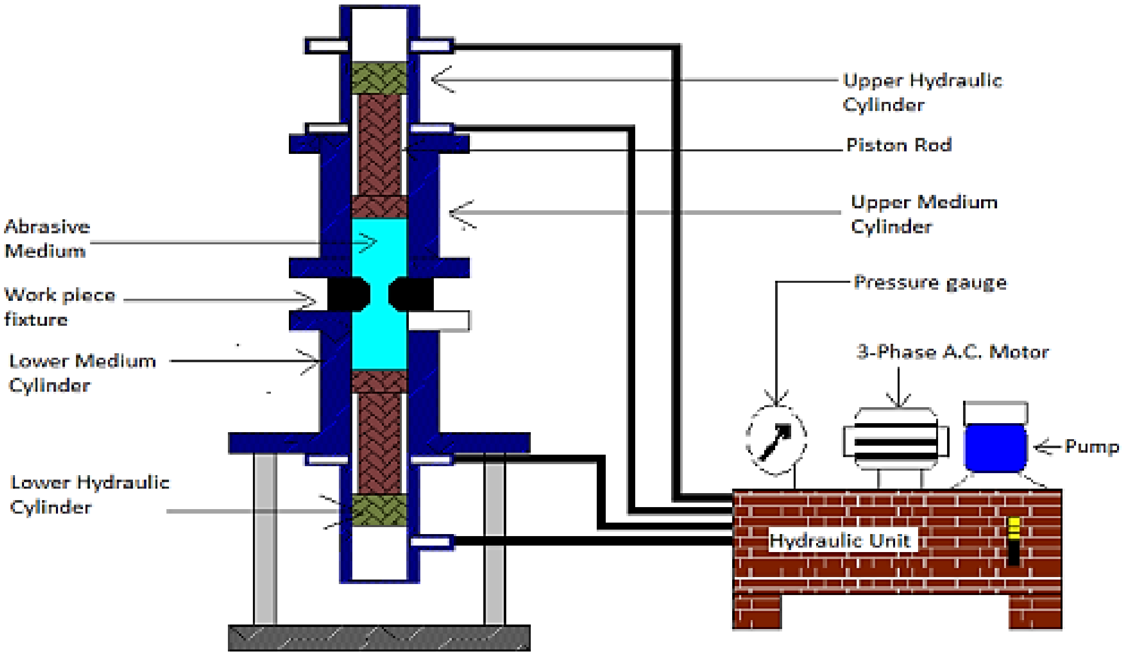


Fig. 1. Schematic illustration of AFM process.

However, the performance of AFM process is depends upon various process variables including number of cycles, abrasive concentration, extrusion pressure grain size, and kinematic viscosity on the surface finish and MRR etc. [2]. The classification of AFM based on abrasive flow media, process parameters and performance measure of AFM is depicted in Fig. 2.

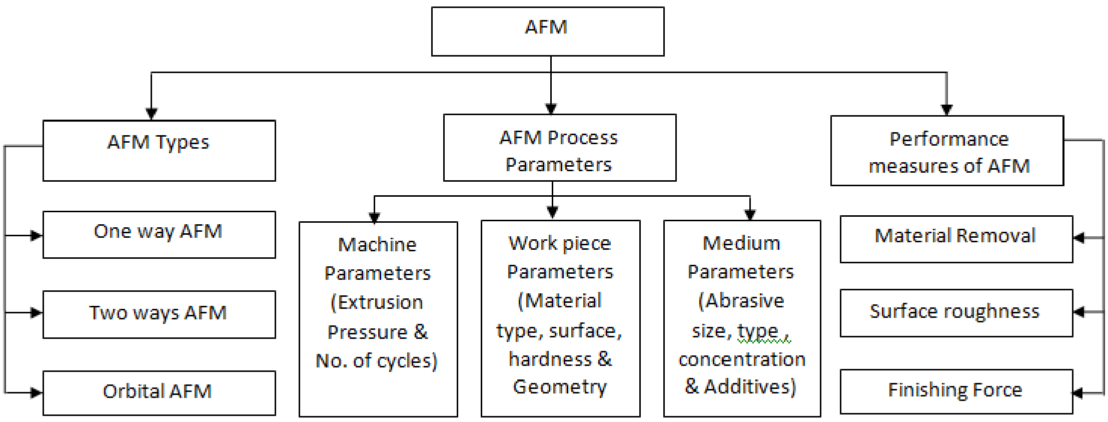


Fig. 2. Classification of AFM.

2. TYPES OF AFM

Based on abrasive flow media, AFM process is divided into three types: (a) One way AFM (b) Two way AFM (c) Orbital AFM.

2.1 One way AFM

In the One-way system, media pass by the workpiece, and then it exits from the segment [3]. Two vertically opposite cylinders have been used in two-way, in which abrasive media flows in the backward and forward direction (Fig. 3).

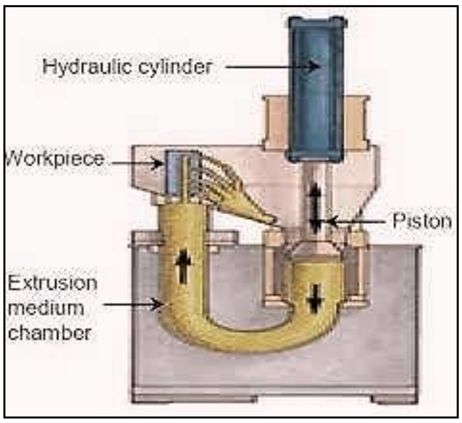


Fig. 3. One way AFM process.

In the 1970s, Extrude Hone Corporation first patented this process. The most time-consuming and labour-intensive production segment in today's industry is accurate and finishing complex parts. This absorbs up to 5–15 percent of the total manufacturing-process expenditure. The design of precise parts stresses final workmanship, which may account for 15% of overall production costs. AFM can provide finishing parts with high-precision and economical means. Economic and efficient finishing of inaccessible areas and complicated internal passages can be achieved with this process [4]. This method is especially useful for cavities, edges, internal pathways and curves that are difficult to enter. But the MRR is very less in the AFM process and is not suitable for form corrections or major machining operations. AFM provides high precision and economical means of finishing parts. With this method, it is possible to achieve economical and productive completion of inaccessible areas and complicated internal passages. This method is especially useful for bends, curves, bends, cavities and internal corridors which are difficult to access. However, the removal rate of the substance is considerably reduced in the AFM process and cannot be adapted for shape corrections or major workflows [5].

2.2 Two-way AFM technology

In the two-way AFM, an abrasive media extrudes through a pathway built by the tool and workpiece with the aid of a system of hydraulic pressure using hydraulic actuators. In a Two-way AFM machine, a media cylinder (02) and a hydraulic cylinder (02) are used. The hydraulic pressure system extrudes the abrasive media backwards and forward through a passage formed by the tooling and workpiece. The most restrictive passage, from which the medium approaches and passes, accompanied by abrasion, happens [6]. The piston forces the medium in a forward direction into one cylinder and as it is extruded through to another cylinder all over the workpiece. Consequently, in a work holder and fitting the medium abrades the workpiece. Then the process is inverted, and a process loop is made up by mixing forward and backward strokes. When the media goes inside and moves through the most restrictive passage then abrasion takes place. The media works with good fluidity and viscidity like an abrasive self-modulating medium, rendering the cutting tools flexible [6]. Therefore, in the working holder and mounting the media wears the work object. The schematic illustration of two-way AFM process is depicted in Fig. 4 [7].

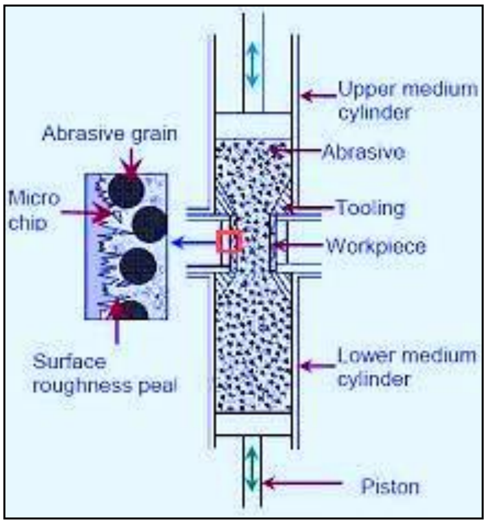


Fig. 4. Schematic of two-way AFM.

2.3 Orbital AFM

In this process the finishing of the component is obtained by providing small oscillation to the substrate. Then, the oscillation is applied in either 2D or 3D within the flowing 'pad' of AFM medium as depicted in Fig. 5 [8]. This technique is also employed to finish the edge of parts by small orbital vibrations [8].

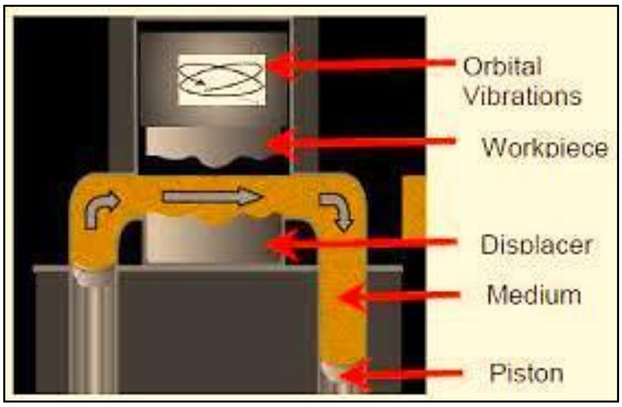


Fig. 5. Schematic of orbital AFM process.

3. ADVANCEMENTS IN THE AFM TOOLING

Tooling is the main component of the AFM system, which is utilized to restrain and direct the flow of media to restricted passage. AFM tooling has two objectives, first to hold the workpiece in the correct position and second to control and direct the media flow. A replaceable attachment made of nylon, Teflon and similar other materials is generally used to hold the workpiece in the AFM machine. If a breakdown of these attachments takes place, then these can be easily replaced [8].

3.1 Progressive overview of the abrasives laden media

The main component of the AFM process is abrasive media. The media is made up of non-Newtonian liquid polymer that consists of abrasive particles. For this, Non-Newtonian liquid polymer serves as a carrier medium and the wearing particles serve as a cutting tool that abrades the material from the substrate. The most used wearing particles are Al_2O_3, SiC, B_4C or diamond. The additives are taken to adjust the base polymer to achieve optimal flow capacity and rheological character of the medium. The concentration of abrasive particles, media of flow and dynamic viscosity can also be varied. The different Process Parameter for AFM Research Area is shown below in Fig. 6.

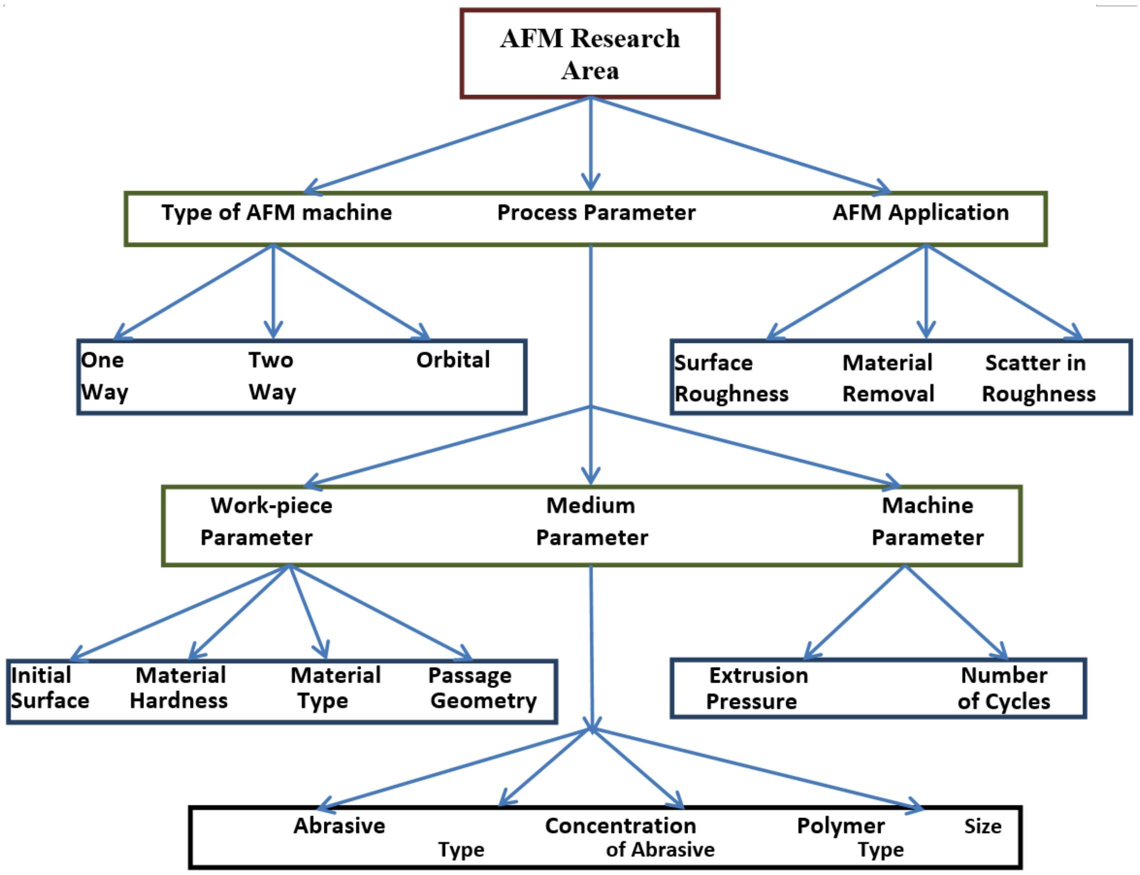


Fig. 6. Process flow chart of AFM.

3.2 State-of-art on the applications of AFM

AFM is suitable for work-pieces with complicated intersections (AFM polishes complex inlet manifolds and ports that lead to smoothness and more precise fuel and air distribution which results in more horsepower and fuel efficiency of the automobile), AFM is also used in extrusion dies as well as space and aeronautics Industry to remove very thin layers of coatings from the turbine blades for re-coating. AFM is also used in medical technology, and the automobile Industry (with the AFM of diesel injector holes made by EDM, holes are of correct radius and ragged edges are removed, thus it minimizes erosion and emission remains consistent for a very long duration [9]). Hydraulics and pneumatics, chemical and pharmaceutical Industry also uses AFM for deburring, rounding off edges or polishing in difficult-to-reach areas of the process components of the brewery, beverages, dairy and food industries requiring high hygiene and sterile manufacturing conditions. AFM is also used in the textile industry, electronics industries for the piercing of many fine holes. AFM is suitable for single pieces and batch production, in improving the surface finish of internal surfaces of Mass Flow Controllers, removing the burr in spring collets [10] and AFM of advanced technical ceramics [11].

3.3 Hydraulic circuit for two-way AFM setup

In the 2-way AFM setup, there is a vertical location of 02 media cylinders and 02 hydraulic cylinders as shown in Fig. 7. It is designed to extrude the media from top to bottom of these cylinders passing through a work-piece held in a nylon fixture. The setup is designed for maximum media pressure of 25N/mm^2. The media is to be extruded at different flow rates and different pressures. The media flow rate and the pressure of the media are adjustable. The media-flow rate changes by changing the pressure difference across the two hydraulic cylinders and it also controls the media pressure by changing resistance to the media flow. The media flow is adjusted by changing the back pressure of the opposing cylinder (the upper cylinder while moving up). Once the stroke is complete, then the direction gets reversed and it maintains the same pressure combinations thus the lower cylinder maintains the same back pressure. The combination of strokes up and down completes the AFM in a single step. The requisite numbers of extrusion cycles are completed. After the extrusion is complete, the AFM machine should have a provision for the withdrawal of the finished (or final) workpiece held in the nylon fixtures from the machine without excessive force due to piston arrangement [12].

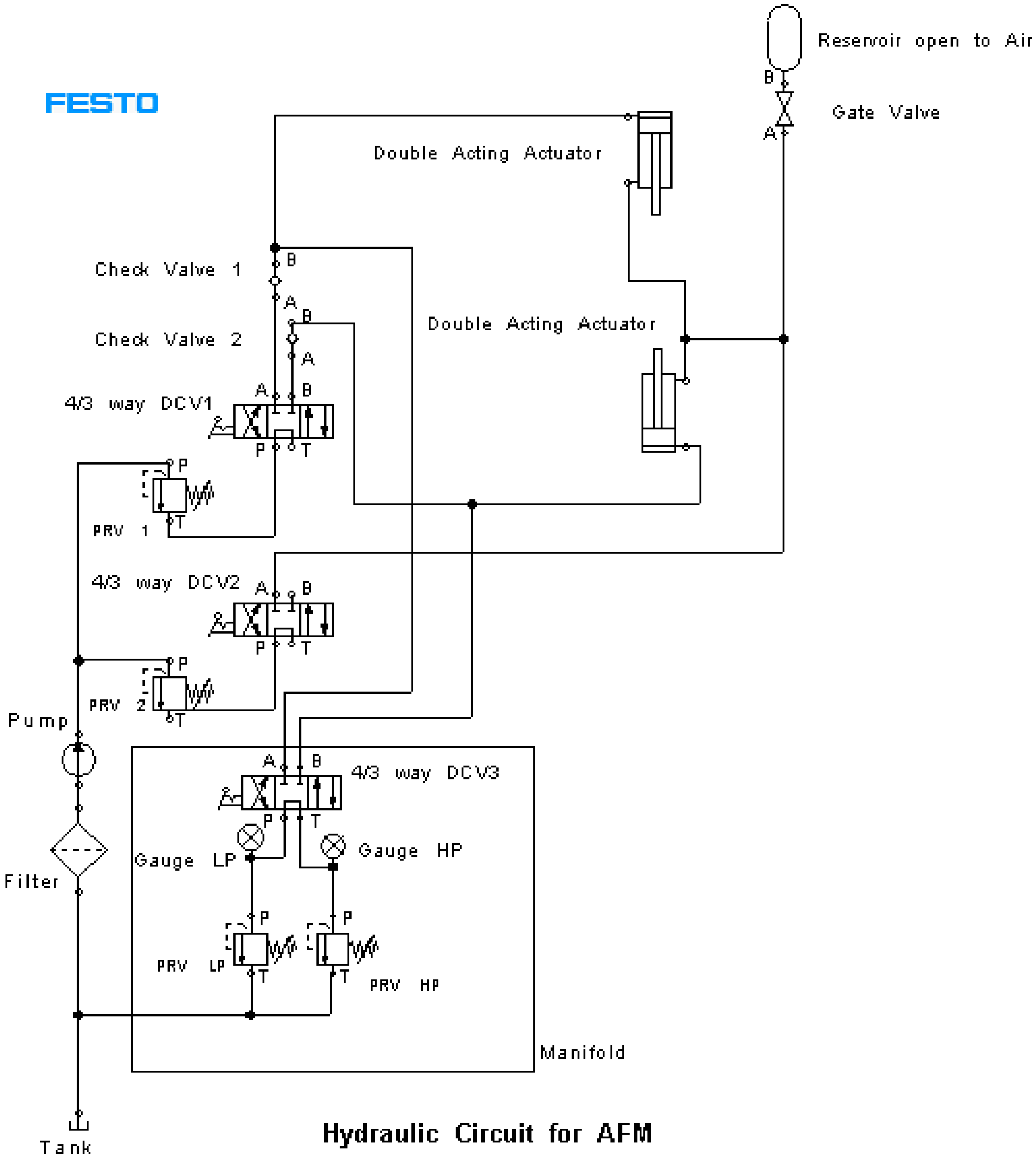


Fig. 7 Hydraulic circuit of two-way AFM [12].

3.4 Recent progress in simple AFM process

As the MRR of AFM is not efficient, so the researchers have tried to use additional energy resources while, the extrusion of abrasive-laden media is taking place through the substrate. Energy resources ranging from magnetic to ultrasonic have been employed to enhance the forces on the cutting abrasive grains, which results in the faster finishing of the surfaces. Many of the researchers have succeeded in enhancing the machining efficiency of the AFM process by integrating it with other non-traditional machining techniques and thus numerous Hybrid AFM techniques have been developed [1-3].

3.4.1 Magnetic Field-Assisted Abrasive Flow Finishing (MAAFF)

Singh and Shan developed the magneto abrasive flow machining (MAFM) technique in which a magnetic field is applied around the substrate to increase the MRR and decrease surface roughness. The most significant parameters such as volume flow rate, flux density, and abrasive grit size, no. of cycles, abrasive concentration, and reduction ratios are identified by the ANOVA technique. Results showed that Magnetic field considerably affects both MR and ΔRa. It was observed that under the effect of the magnetic field, more abrading was for brass than the aluminium workpiece. The development of additional forces with the magnetic field increases material removal and enhances the surface finishing. It also observed that less number of cycles are required as compared to simple AFM to remove an equal quantity of material from the component [13]. Patil and Ashtekar developed a flexible magnetic brush with the help to use of magnetic force, which provides an additional cutting force on the metal surface and also produced a better-polished surface as compared to simple AFM [14]. Barman and Das simulate the magnetic field distribution during the finishing of the MFAF process which was done in a static condition. The flow behaviours of MR fluid Newtonian (without magnetic field) and non-Newtonian (with magnetic field) were studied. The final surface roughness profiles indicate good agreement between them for both simulated and experimental results [15]. Verma et al. successfully investigated two like magnetic poles (north-north) and diamagnetic properties of copper, which produced a high magnetic flux density at the periphery of the ferromagnetic disc. The developed model showed that in the given range of variables, the most effective parameter is magnetic flux density. Working parameters such as 0.8 T magnetic flux density, 500 rpm, 20 percent abrasive weight, and 1200 abrasive mesh number led to a better 89.6 percent improvement in surface roughness and 56 nm surface finish [16].

3.4.2 Magneto Rheological Abrasive Flow Finishing (MRAFF)

Jha and Jain researched the method of MRAFF process for finishing the internal complex geometries. The magneto rheological polishing fluid is made up of carbonyl iron powder and silicon abrasive particles which are mixed with visco- elastic base grease and mineral oil for finishing the work-piece of stainless steel. In this technique, without a magnetic field zero improvements is observed but significant improvement was observed at higher magnetic field strength [17]. Jha and Jain developed an MRAFF model for the measurement of abrasive grit forces and correlated them with surface roughness value enhancement [18]. Das et al. suggested for enhancing the finishing quality of the MRAFF process Rotational MRAFF process was used. In this process, the rotating magnetic field provides rotation & reciprocating motion to the abrasive medium. This method produces smooth and mirror-like surfaces in both substrate (brass and stainless steel) [19]. Aggarwal and Patnayak developed magneto rheological finishing (MRF) by rotating a workpiece (non-magnetic) which was submerged in the MR fluid. Magneto-rheological fluid contains Carbonyl-iron particles which were magnetize-able, mineral oil used as a Non-Magnetic career form, silicon carbide as abrasive particles and grease as an additive. The magnetic field regulates the grinding force. The iron particles in the carrier fluid aggregated in the columnar chain were oriented in the field direction by using the external magnetic field [20]. Sidpara and Jain observed that the maximum percentage contribution in MRR and surface finishing is coming from the flux density of magnet and CIPs which gave 47.58% and 44.85% respectively [21-23].

3.4.3 Ultrasonic Assisted Abrasive Flow Finishing (UAAFF)

Jones and Hull integrate an ultrasonic machine with an abrasive flow machining process to form Ultrasonic Flow Polishing (UFP). AFM does not give a better surface finish in closed die; however, do give an excellent finish in open die. But USM is suitable for precise material removal methods for closed dies. Ultrasonic Flow Polishing can be the desired method for the polishing of closed dies [24].

Malik and Pandey proposed the integration of two non-conventional machining processes MAF and UFM to make a highly accurate UAMAF process to enhance the morphology of the surface within a short time. The vibration and combination of flow resulted in more effecting abrading of the workpiece and the surface finish also improved. By the parametric study of the UAMAF 2/3rd upgrade was recorded in MRR in terms of quality [25].

Sharma et al. developed UAAFF by supplying the work-piece with ultrasonic vibrations in the transverse direction, i.e. perpendicular to the flow direction of the finishing medium consisting of natural rubber mixture, abrasive SiC and naphthenic based processing oil. The extrusion pressure is applied in the flow direction over the AFF medium and ultrasonic vibrations acting in the transverse direction force it towards the substrate at the same time. The maximum enhancement in surface finish and material removals were 81.02 % and 0.05% respectively. The Ultrasonic vibrating, abrasive particles strike the workpiece with greater energy resulting in an improvement in surface quality and material removal. For better surface characteristics reasonably less frequency is required [26-28].

3.4.4 Centrifugal Force Assisted AFM

Walia and colleagues created this idea in 2006. For work-piece finishing, researchers have rotated different types of rods at the media flow path's centre. The abrasive-laden media was rotated by the centrifugal force action with the help of the centrifugal force-generating (CFG) rod, which increased the intensity of abrasive particle action over the substrate. They came to the conclusion that the MRR and scatter of surface roughness (SSR) values in AFM are enhanced by the centrifugal force. The CFG rod's rotational speed, extrusion pressure, and abrasive grit size all have a significant impact on the amount of material removed [29]. In order to improve the capabilities of the conventional AFM process, in which centrifugal force is applied to the abrasive particles, Reddy et al. investigated the centrifugal force-assisted abrasive flow machining (CFAAFM) procedure. The combination of severe pressure and a higher CFG rod speed was found to be more advantageous for achieving a higher degree of finished surface, whereas the combination of a larger grain size and a higher CFG rod speed results in a higher rate of material removal [30].

3.4.5 Rotational AFM

The rotational AFM, in which the workpiece rotates, was studied by Sankar et al. Five key elements are examined in this process: machine structure, rotating set-up, tooling, hydraulic power pack, and medium. In comparison to the straightforward AFF procedure, rotational AFM can enhance smoothness by 44 percent and remove 81.8% more material [31]. The main distinction between Sankar et al. rotational abrasive flow machine and the CFAAFM is the use of an appropriate configuration to rotate the workpiece rather than a rod to generate centrifugal force [32].

3.4.6 Helical AFF (HLX-AFF)

Brar et al. developed the Helical AFM by placing a coaxial stationary drill bit inside the hollow cylindrical workpiece to boost the machining productivity and efficiency of the AFM process. The experimental setup was simple and rugged because no extra power is required to produce a centrifugal effect. The abrasive-laden media passed through the circular space between the workpiece and the drill bit. The presence of a drill bit increased the MRR by a factor of 2.66 in comparison to the basic AFM technique setup [33]. Brar et al. studied helical AFM (HLX-AFF) by placing an axial drill in a hollow cylindrical workpiece to enhance the finishing of the workpiece. They concluded that HLX-AFF improves material removal rate 2.5 times more than simple AFM and also MRR increases with several finishing cycles [34]. Chen and Chang examined the HLX-AFF CFD simulation process to analyze the effect of the no. of finishing cycles and the cross-section of the SKD-11 die steel work-piece. In this process, the mixture of SiC abrasive and silicon polymer is used as a finishing medium. Authors reported that the application of helical passageways increased the surface finish by 60-70 percent [35]. Kumar et al. studied the HLX-AFM process by using a three-star drill bit for the machining of three different ductile materials (brass, mild steel and gun metal). Inside the hollow annular workpiece, the three-star drill bit is positioned coaxially to create an angle in the direction of abrasive-laden media, contributing to the creation of centrifugal forces in addition to the combination of distinct media flows. For the high MRR, the percentage contribution of different process variables like extrusion pressure, number of cycles and process variable was 20.43%, 26.9%, and 29.57% respectively [36]. Wang et al. used three starts helical twisted strips to examine the material removal rate of brass, gun metal and mild steel in the AFF process. They stated that MRR is more in brass than to mild steel and gun metal. In addition it increases with raised extrusion pressure and several finishing cycles [37]. Brar et al. further experimented with the Helical AFM process and developed two additional profile rods to study their effects. The three different helical profile rods viz. drill, three-start helical profile rod spline was used as three helical profile parameters and a 15% major improvement in the surface finish was observed than the helical AFM process with standard drill-bit [38].

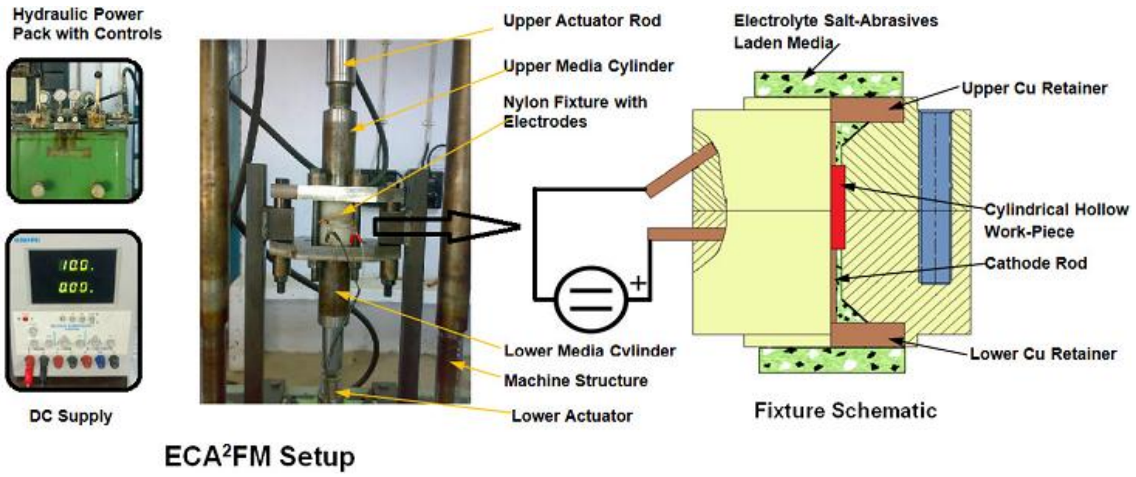
Many other different types of hybridization have been done with the abrasive flow machining (AFM) process to attain a greater MRR and enhanced surface finish. So, to improve the MRR, the AFM process is successfully integrated with an electrochemical machine. Some of the researchers provided additional mechanical energy or generated centrifugal forces while the media was extruding to get a higher MRR. So, the hybrid AFM has generally the advantages of all the contributing machining processes [39].

3.5 Hybridization of Electrochemical with AFM process

The incorporation of electrochemical with the AFM process has a new process for internal finishing of substrate having complex geometry. In the simple AFM process, only abrasive was used to remove the material from the workpiece which is too slow and less MRR produced. But in the electrochemical AFM process, the conventional abrasive gel or paste changes with polymeric electrolyte which plays the role of transport media for abrasive grain also ECM generates the oxidation film because of anodic dissolution and it reduces the hardness of the base material and at the same time, abrasive particles cut the oxidation film so the cutting difficulty is shortened effectively [40]. In this process, a copper electrode rod was held co-axially inside the workpiece and made a cathode while the workpiece is acting as an anode. A nylon fixture was employed to hold the substrate in the proper position and direct the flow of abrasive-laden media through the workpiece. ECA^2FM is a reverse electroplating process in which electrons move from positive to negative and resulted from soft material from the workpiece that is abraded by the abrasive grains. The DC power range of 0-30 V is used to supply the electrodes. The combination of ECM and AFM gives an excellent surface finish and increased material removal [40-44].

The stationary cathode rod is placed inside the hollow substrate for the completion of the electrochemical machining circuit. In this process, nylon fixtures and electrolytic abrasive-laden media are used. This laden media consists of silicon-based polymer, aluminium oxide or silicon carbide, CBN-like abrasive particles, and hydrocarbon gel with a different types of salt like NaCl, KI and NaI. This laden media goes by the space between the stationary-cathode rod and anode hollow substrate with the help of a hydraulic system in which a backward and forward extrusion process is used that is already available in basic two-way AFM machine as shown in Fig. 4. The up and down strokes complete a series of processes.

When this laden media has passed the gap between the stationary rod and workpiece, the MRR and machining efficiency has been improved due to the mechanical machining action of the electrolytic abrasive particles [40, 42, 44-45]. The schematic illustration of the Electrochemical AFM Process is depicted in Fig. 8.



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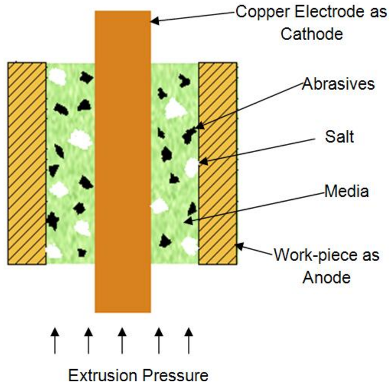


(b)

Fig. 8. (a) and (b) show the schematic of the electrochemical AFM process [42, 43].

4. POTENTIAL OUTLOOK ON THE DEVELOPMENTS IN THE ELECTROCHEMICAL AFM PROCESS

Several researchers successfully hybridized electrochemical machining with the AFM process to enhance the MRR and mechanical efficiency. In the ECA²FM process, different types of parameters were used by the researcher such as abrasives particles concentration, no. of cycles, abrasive grain size, voltage, speed of media and temperature of the media for gaining better surface finish and improving machining capability [40, 41]. Brar et al. developed Electrochemical Aided AFM (ECA²FM) Process by the integration of AFM and Electrochemical and finished internal surfaces of hollow cylindrical work-pieces. The combination of ECM and AFM gives an excellent surface finish and increased MRR.In this process, a copper electrode rod was held co-axially inside the workpiece and made a cathode while the workpiece is acting as an anode. The Media which has been used consists of SiC, hydrocarbon gel and Al_2O_3Abrasive particles along with NaI salt. At higher operating voltage, more electrolytic dissolution results in deeper abrasive scratches but the material removal increases [42]. Brar et al. studied the regression model for hollow cylindrical brass substrate for internal surface finishing. They concluded that by the combination of AFM with ECM machining gave higher material abrasion as compared to simple AFM. The effect of increasing the no. of cycles is quadratic and more material is removed in the initial cycles, but with increasing the no. of cycles, the rate of MR goes on decreasing as represented in Fig. 9 [43].

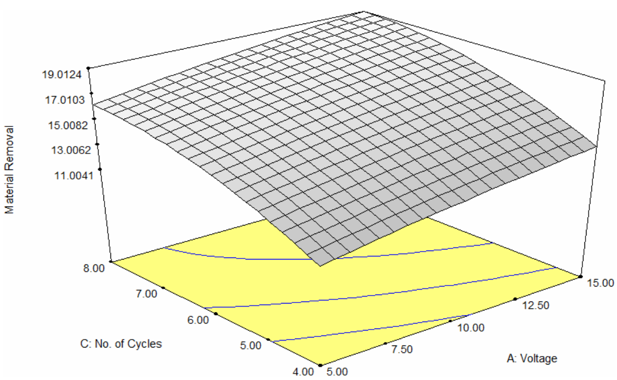
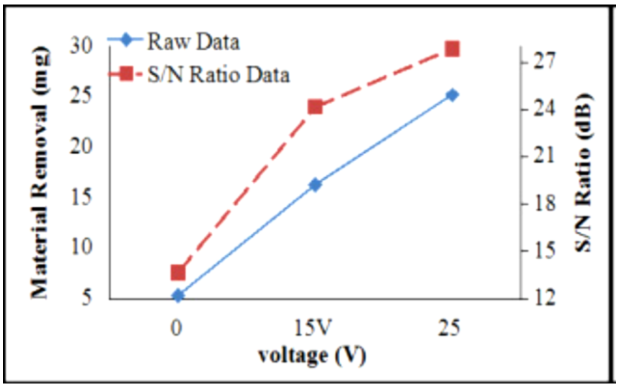


Fig. 9. Shows the response surface for the effect of the Number of cycles vs Voltage [43].

Shankar M et al. experimented on an Abrasive assisted electrochemical machine (AECM). In this operation, graphite was used as a solid lubricant for improving the tribological characteristics of Al-B_4C and also used as SiC abrasive (size=50 µm) along with NaCl electrolyte. This combined method enhances the MRR and gives a better finish surface by anodic dissolution & mechanical abrasion. ECM-assisted Abrasive for MRR was raised when a SiC abrasive size of 50µm with NaCl electrolyte was used. The AECM process gave better MRR and improves the SR as compared to simple ECM [39]. Pankaj et al. observed the different parameters used in the electrochemical-assisted AFM process. They concluded that with the integration of electrochemical with the AFM process, the MRR increases. But at high voltage, the surface becomes irregular resulting in deep cuts on the substrate surface [44]. Gupta et al. investigated the importance of various process parameters during Electrochemical Assist Abrasive Flow Machining for material removal. They concluded that the method of ECA^2FM enhances the capability of machining, SR and MRR. The percentage contribution to the MRR improvement is in the order of voltage > molal concentration > no cycle > rod diameter [45]. Vaishya et al. developed a setup with the integration with centrifugal force-assisted AFM and electrochemical, termed EC^2A^2FM. With the combination of C.F.G. and E.C.M., 70 to 80% machining time reduces and a surface finish of 0.5-0.6 Ra was achieved. M.R.R. increases when the C.F.G. rod rotates at 25 rpm and then decreased. The abrasive size particles affect the M.R.R., if increase the size of the abrasive then M.R.R. decreased as exhibited in Fig. 10 (a-e) [46].



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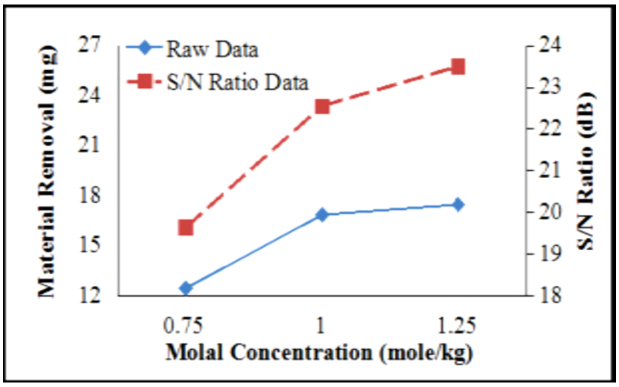

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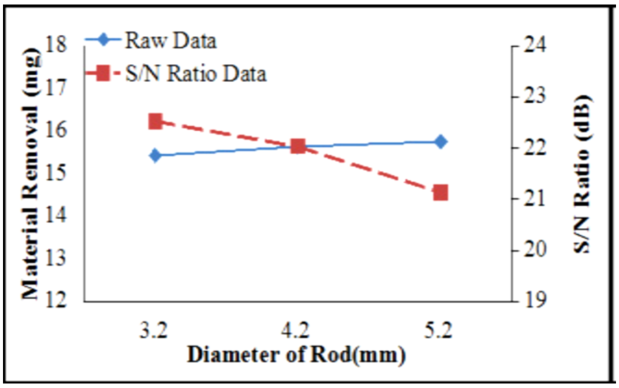

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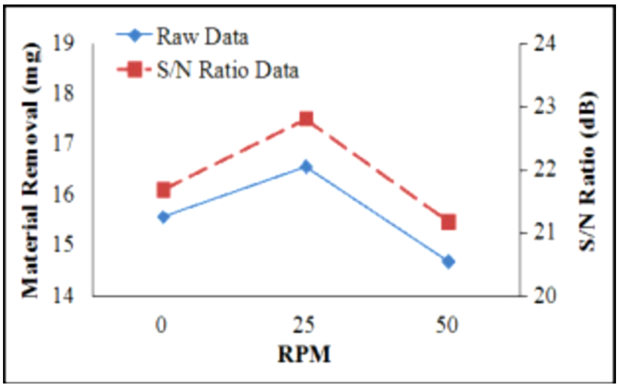

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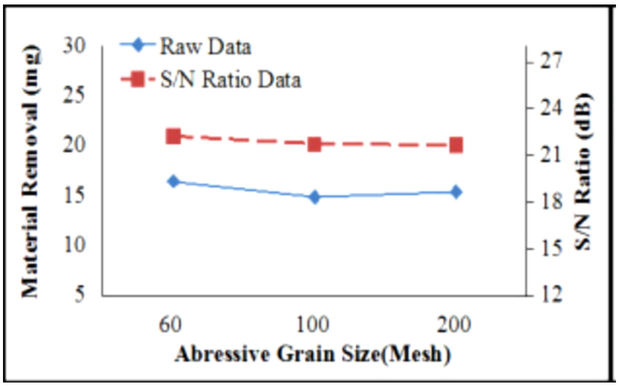


(e)

Fig. 10. Marginal, S-N-ratio plots for "MRR" in 'mg'; (a) influence of Volt. on "MRR"; (b) influence of molarity concentration on "MRR".; (c) influence of C.F.G. rod-dia. on "MRR"; (d) influence of R.P.M. on "MRR".; (e) influence of abrasive particulate size on "MRR" [46].

Brar et al. examined the influence of various machining variables on the machining characteristic for MRR in the ECA²FM process. They concluded that the ECA²FM process with fewer extrusion cycles gives a better-finished surface and also enhanced the MRR of the internal surface of the cylindrical substrate. The other various parameters voltage, electrode size, abrasive size and extrusion pressure as shown in Figure 11 (a-b) significantly affect the MRR and SR [47].

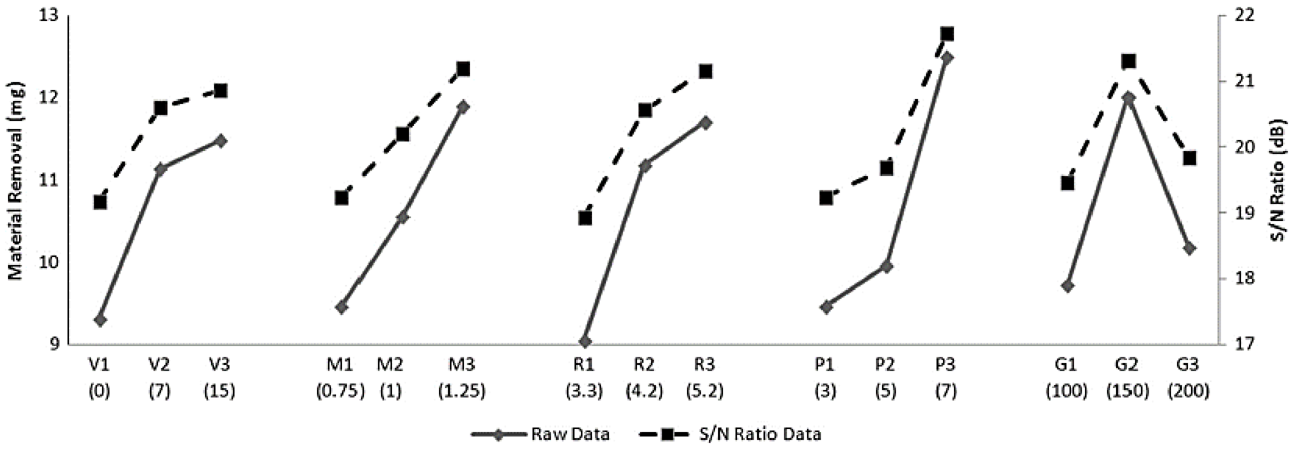


Fig. 11. (a) Shows the main effects of material removal in mg (S/N ratio in dB) [47].

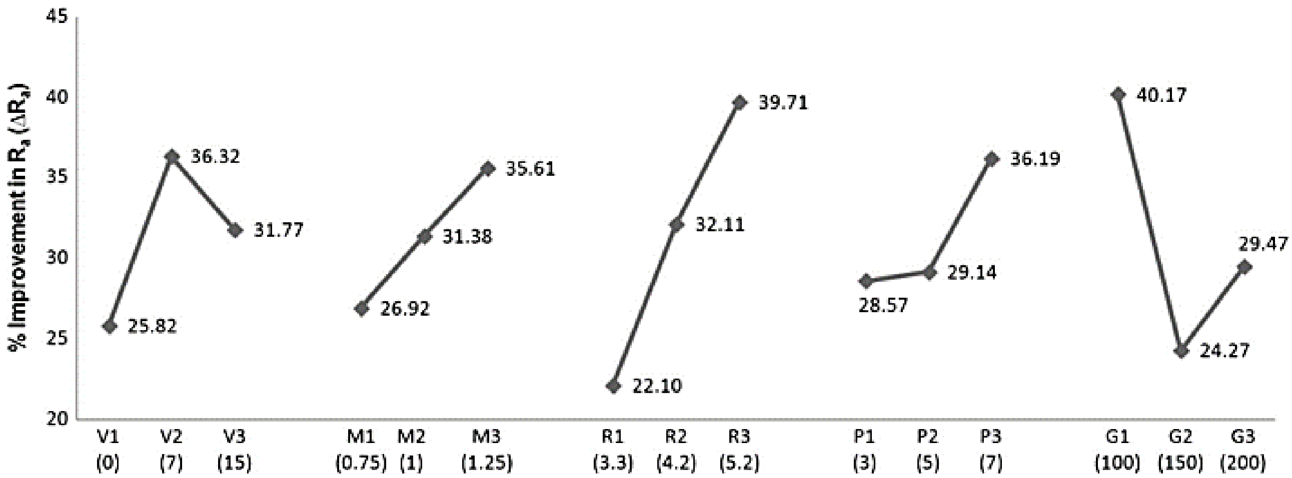
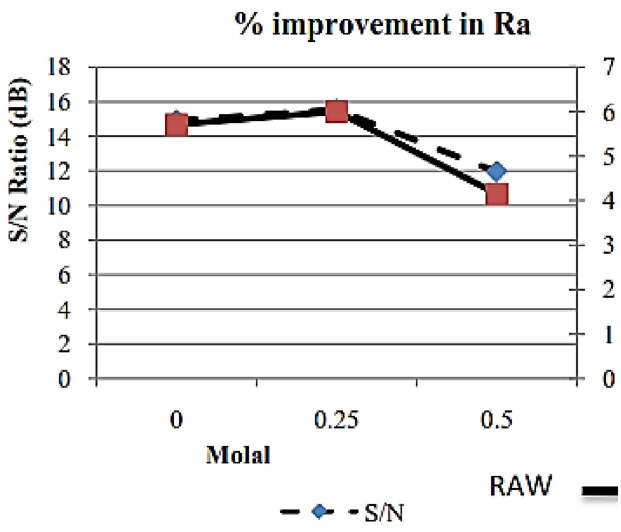
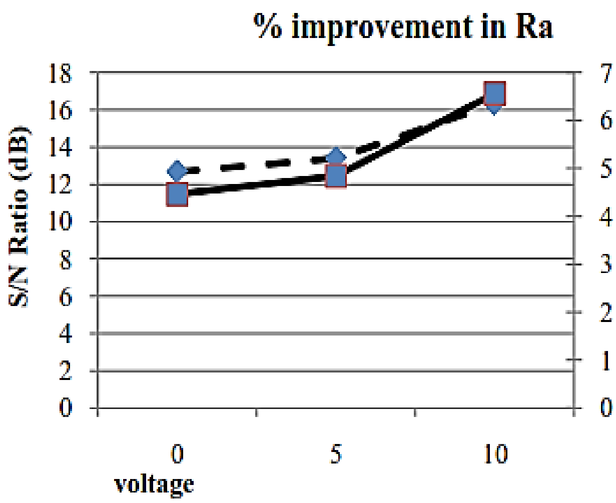


Fig. 11. (b) shows main influence for percentage enhancement in surface roughness (%ΔRa) [47].

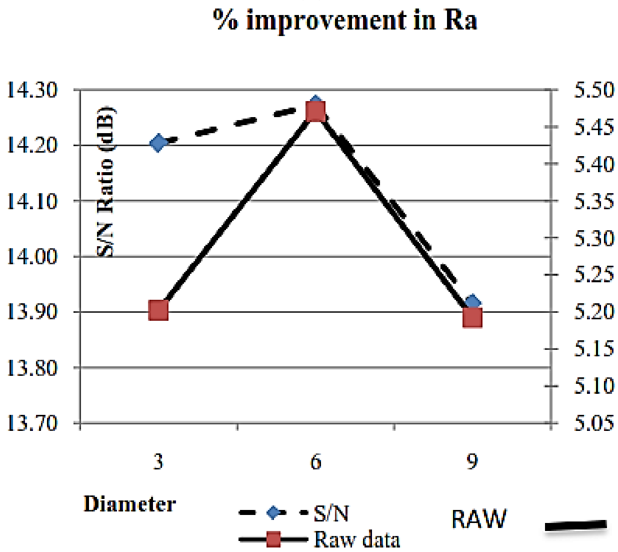
Chahal and Gupta experimented with electrochemical AFM to enhance the internal quality of the surface of gun metal by using different process parameters at various levels. They concluded that when the electrochemical process integrates with simple AFM it produces a greater impact on the value of surface roughness. More improved results can be achieved by clubbing together further processes such as electrochemical and magnetic with simple AFM. The optimal parameter for successful material removal was achieved with zero voltage, zero molal concentration, 5.5 mm diameter of the rod and with nine no. of cycles as depicted in Fig. 12 (a-d) [48].



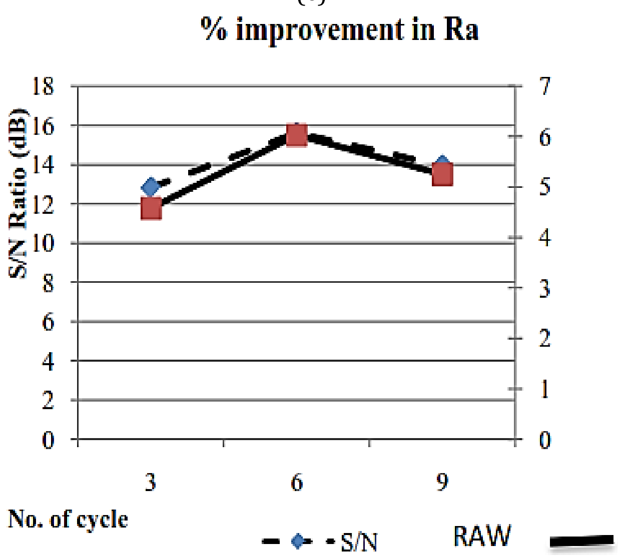
(a)



(b)



(c)



(d)

Fig. 12 (a) show the influence of molal concentration on S/N data & RAW; (b) the influence of voltage on S/N data&RAW data; (c) the influence of diameter of the rod on S/N data & RAW data and (d) influence of no. of cycles on S/N data & RAW data [48].

Sankar et al. investigated an electrochemical AFM process with the Al 6061-boron carbide (5-15 wt. %) composites, NaCl electrolyte with varying percentages and SiC abrasive particles. It concluded that a 20% of electrolytic concentration gave a better result as compared to a higher concentration and produced a better-finished surface. Fig. 13 indicates that the MRR increase with raise in NaCl concentration [49].

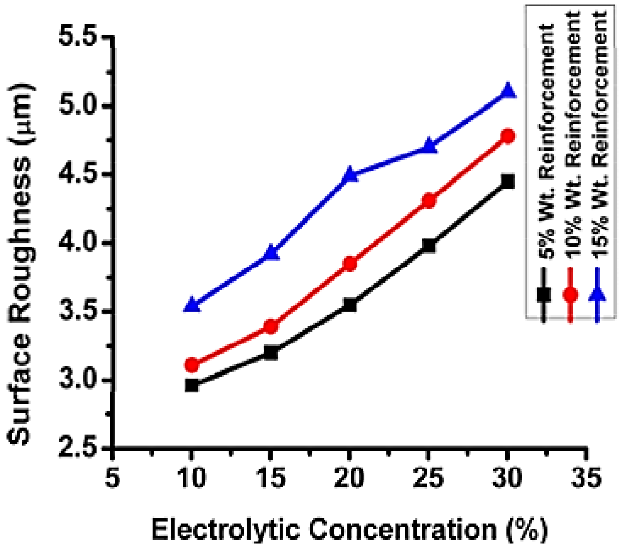


Fig. 13. Shows the surface roughness of substrate with electrolyte concentration [49].

Sankar et al. experimented to check the machinability behaviour of Al6061-10%Gr-10%B4C MMC under a silicon carbide abrasive-assisted ECM process with the copper cathode. They concluded that the optimum value of current (240A), voltage (14V) and electrolytic concentration (25%) obtained better surface finishing and higher MRR as shown in figure 14 [50].

Singh and Kumar investigated different parameters for achieving the best optimal value for surface finish and MRR in the electrochemical abrasive flow machining process. They concluded that the best-optimised parameter like a voltage of 25V, a molar concentration of 1.25 microns, an abrasive concentration of 1.2, several processing cycles of 12 and a Diameter of the rod was 5.2mm used to achieve a good surface quality of the substrate [51]. The results of various researchers on the Electrochemical AFM process are represented in Table 1.

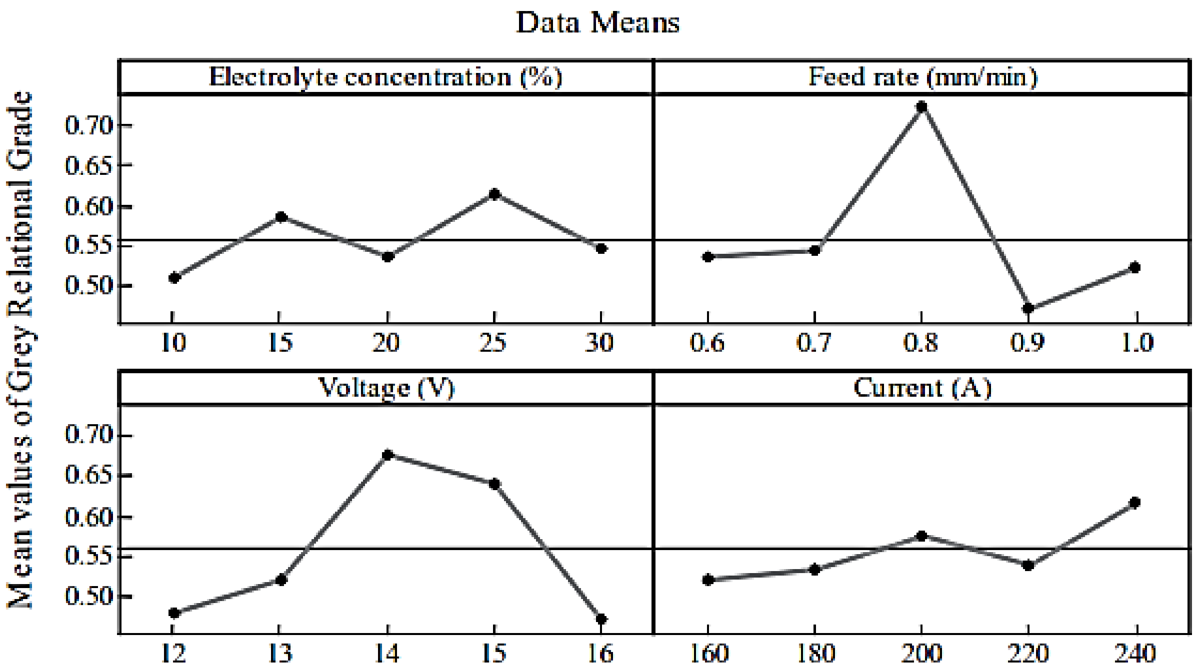


Fig. 14. indicate the response plot of Grey's relational grade [50].

Table 1. Past research in the electrochemical AFM process.

References	Developed process	Extrusion pressure	Workpiece material	Abrasive media	Process parameter used	Major observations and remarks
Dabrowski et al., 2006 [40]	ECAFM	0.7 MPa - 6 MPa	Stainless steel	Polypropylene glycol (PPG) and polyethene glycol (PEG) with SiC, Al_2O_3 as abrasive	No. of finishing cycle:20,40,60,80,100 Abrasive size: 46 µm Voltage:5-15(V) Electric current: 2-8 A	SR is mainly influenced by the composition of finishing media Required less no of finishing cycle as compared to AFM for obtaining the same surface finish
Dabrowski et al., 2006 [41]	ECAFM	0.7 MPa - 1.7MPa	Stainless steel 1H18N9T	PPG with NaI and PEG with KSCN salt with SiC, Al_2O_3 abrasive and SiO_2 as an additive	No. of finishing cycle: 50 Voltage:5;15;21; 50 (V) Working temperature: 30°C	PEG with KSCN enhance the MRR and SR as compared to AFM
Brar et al., 2012 [42]	ECA^2FM	5MPa	Brass	NaI salt, Silicon-based polymer, Al_2O_3 abrasive	No. of finishing cycle: 10 Voltage:30 (V) Working temperature: 32±2°C Grit size: 600 (13-16 microns)	MMR goes on increasing with increasing the applied voltage, surface finish improved
Brar et al., 2014 [43]	ECA^2FM	2-10 MPa	Brass	NaI salt, Silicon-based polymer, Al_2O_3 abrasive	No. of finishing cycle: 2-10 Voltage:0-20 (V) Working temperature: 32±2°C Abrasive grain size:150mesh (100 microns) abrasive to media concentration: 0.5-1.5 (% by weight)	SR and MRR improved

Sankar M. et al.,2014 [39]	AECM		Al-B4C graphite composite	NaCl as electrolyte and SiC as abrasive	Abrasive size:50 μm Voltage:8, 11, 14 V Current: 60,180,240 A Feed rate: 0.4, 0.5, 0.6	SiC abrasive help to improve machining performance. AECM gave higher MRR than simple ECM.
Pankaj et al., [44]	ECA²FM	5MPa	Gun Metal	NaI salt with Al_2O_3 abrasive	No of finishing cycle: 8 Voltage: 0-30 (V) Working temperature: 32±2°C Grit size: 600 (13-16 microns)	The abrasion of the workpiece increase with this process, and the surface becomes rough at the higher voltage
Gupta et al. [45]	ECA²FM	6 MPa	Gun Metal	Al_2O_3 abrasive, hydrogen-gel, Silicon-based-polymer with NaCl salt	Abrasive size: 150 microns No of finishing cycle: 3,6,9 Voltage :0-10(V) Working temperature: 32±2°C polymer-gel ratio: 1:1(by wt.)	Voltage and the number of finishing cycles significantly affect the MRR.
Vaishya et al., [46]	EC²A²FM	6 MPa	brass	KI salt, Silicon-based polymer (poly boro-siloxane) and hydrocarbon gel, Al_2O_3 abrasive	No. of finishing cycle: 10 Voltage: 0-30 (V) Working temperature: 32±2°C Abrasive grain size: 60,100,200 microns Polymer gel-ratio: 1:1 (% by wt.) shape of CFG rod: square	less finishing time (70-80%) for obtaining SR of 0.5-0.6 μm, MRR increase with the voltage, concentration of salt, RPM and abrasive grain size
Brar et al., [47]	ECA²FM	5MPa	Brass	NaI salt, Silicon-based polymer (polyborosiloxane), Al_2O_3abrasive, hydro-carbon gel	Voltage :0-20 (V) Working temperature: 32±2°C Abrasive grain size: 100-200 Abrasive to media concentration: 0.5-1.5 (% by weight) No of finishing cycle: 10	MRR improved, lesser extrusion cycles used, electrode size, voltage, extrusion pressure, and molal concentration have significantly affected the response parameter for MRR and better finishing
Chahal and Gupta [48]	ECA²FM	6MPa	Gun metal	NaI salt, Silicon-based polymer (poly-borosiloxane), Al2O3 abrasive, hydro-carbon gel	Voltage:0-20 (V) Working temperature: 24±2°C Abrasive grain size: 150 No of finishing cycle: 3,6,9	The diameter of rod size, voltage, extrusion pressure, and molal concentration has significantly affected the response parameter for MRR and better finishing
Sankar M. et al., [49]	AECM		Al6061-boron carbide composite	NaCl as electrolyte and SiC as abrasive	Abrasive size:50 μm Voltage: 14V Current: 150A Tool feed rate: 1mm/min Electrolyte flow rate: 15 litres/min	The hard material is easily machined. 20% electrolytic concentration gave better results as compared to others.

Sankar M. et al., [50]	AECM		Al6061-5%Gr-10%B4C metal matrix composite	NaCl as electrolyte and SiC as abrasive	Abrasive size:50 µm Voltage:10-20 V Current: 160-240 A Feed rate: 0.4-1.0 Electrolyte flow rate: 30 ltrs/min	The hard material is easily machined. feed and voltage are significant parameters for lower SR and improve MRR
Singh S and Kumar S [51]	ECA^{2}FM	5MPa	Gun metal	NaI salt, Silicon-based polymer (poly-borosiloxane), Al_2O_3 abrasive, hydro-carbon gel	Voltage :0-25 (V) Working temperature: 30±2° Abrasive-media concentration: 0.8-1.2 (% by weight) No of finishing cycle: 8,10,12	Molal concentration, voltage, no. of cycles has significantly affected the response parameter for MRR and better finishing

5. PROGRESSIVE OUTLOOK ON THE INTEGRATION OF ELECTROCHEMICAL AFM WITH MAGNETIC ENERGY

Researchers have integrated an electrochemical machine with a magnetic AFM process for achieving a higher finished surface for a complicated geometry. In the electrochemical magnetic AFM process, the ECM generate the oxidation film because of anodic dissolution and it makes the hardness much lower than that of the base material at the same time, magnetic particles help to remove that oxidation film so the cutting difficulty is shortened effectively. This process is worked by placing slurry that consists of magnetic abrasive (cobalt, nickel, steel and iron), white alumina and polishing agent with the presence of magnetic poles [52-55].

Kim et al. researched the effect of a magnetic field on the MRR and surface roughness during the magnetic electrolyte abrasive polishing (MEAP) process. The NaCl electrolyte was accounted to prevent the built passive film (oxide film) on the surface of the anode because if the passive film is built up then it eventually insulates the electrical contact between the anode and cathode, resulting in poor electrolytic reaction, which helps to improve surface-quality of finishing and efficiency. The plot between MRR and SR with magnetic flux density with (20%) NaCl electrolyte is illustrated in Fig. 15 (a-b). They conclude that the magnetic field improves the machining efficiency, SR and MRR [52].

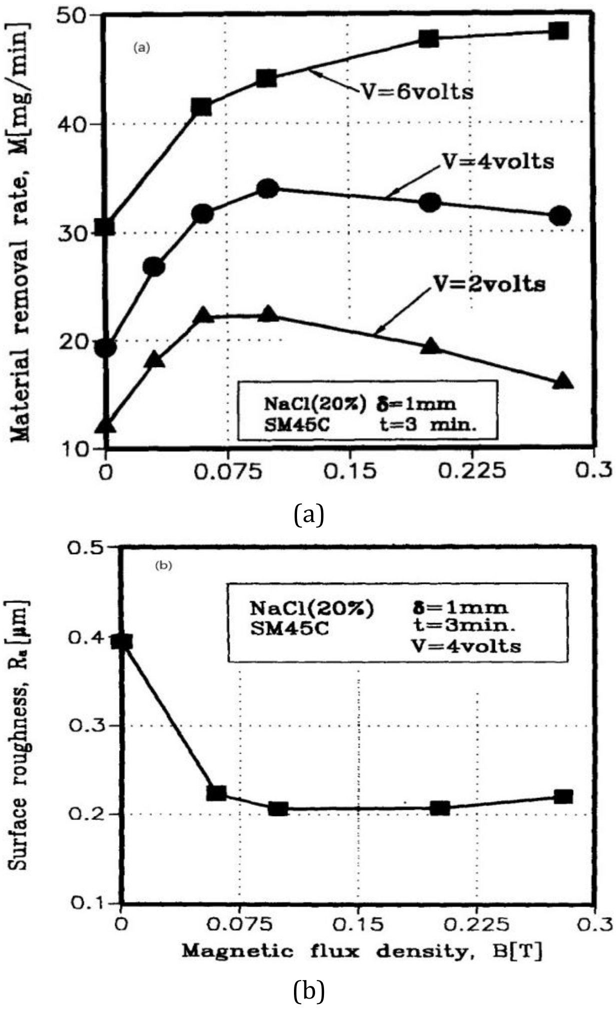


Fig. 15. (a) The relationship between MRR with magnetic flux density with (20%) NaCl electrolyte, (b) The relationship between MRR and SR with magnetic flux density with (20%) NaCl electrolyte [52].

Fang et al. examined the role of the magnetic field on the surface of the substrate. They conclude that the magnetic field effect on the rough surface is more than the fine surface and also improves finishing efficiency as illustrated in Fig.16 [53].

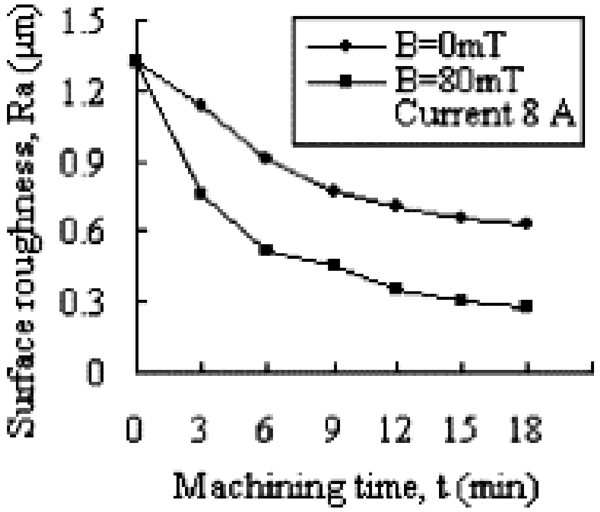


Fig. 16. Influence on the finishing-efficiency [53].

Yan et al. developed EMAF and compared it with MAF using different process parameters i.e.electrode gap, substrate revolution rate and electrolytic current while examining MRR and SR. Findings indicated that EMAF provides better finishing than MAF at more electrolytic current as revealed in fig.17 (a-b). They concluded that the finishing efficiency and SR improve with increasing the electrolytic current and rate of substrate revolution [54].

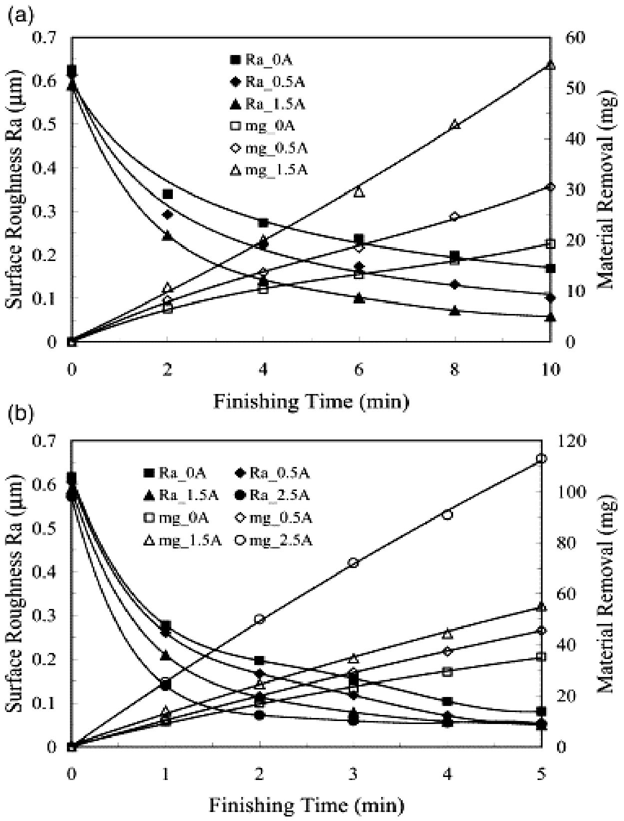


Fig. 17. Influences of electrolyte-current on S.R. and M.R. with EMAF finish-period. (a) 200 rpm-2 Hertz; (b) 500 rpm-5 Hertz [54].

El-Taweel created mathematical models for an in-depth study on the effects of hybrid ECTMAF i.e., electrochemical turning (ECT) process and magnetic abrasive finishing (MAF) process on the MRR and surface roughness. They concluded that the integrated magnetic abrasive machining and electrochemical turning process which improve the MMR and reduce the SR. This process improves the surface quality 33% more than simple electrochemical turning was recorded [55,56]. Judal et al. experiment with a C-EMAM process setup in which different processing parameters like an electromagnet, rotating speed of work-piece, vibration frequency and electrolytic current were studied to enhance the MRR and surface roughness of stainless steel (AISI304). They concluded that MRRraise and surface roughness reduces with increasing both vibration frequency and speed of rotation of the workpiece as indicated in figure 18 (a-b) [57].

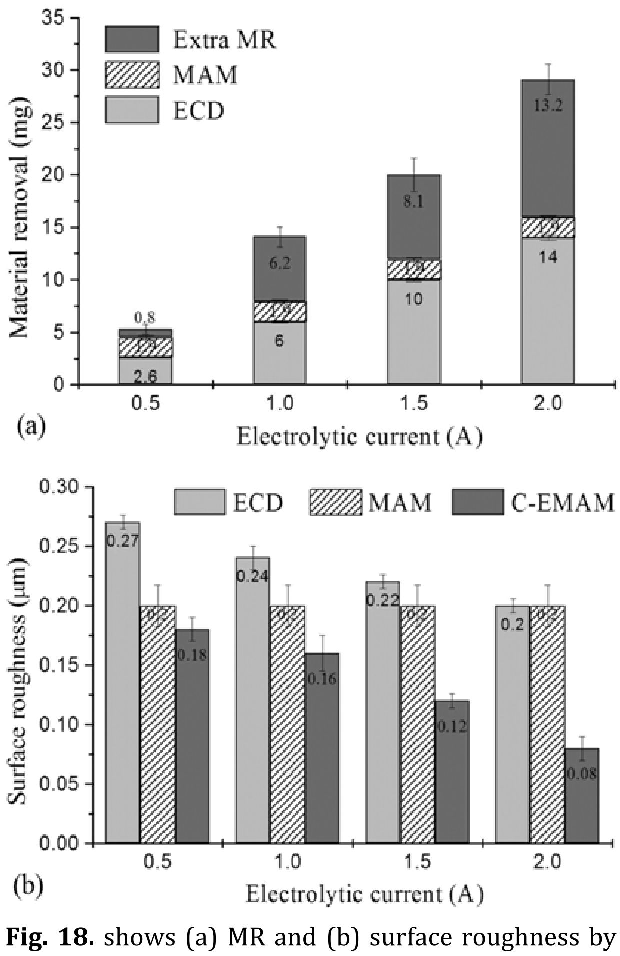


Fig. 18. shows (a) MR and (b) surface roughness by constituent processes and the C-EMAM process.Condition: 710 RPM rotational speed current to electromagnet 1A, vibration frequency 4 Hz [57].

Liu et al. investigate the effect of EMAF i.e., combined electrochemical machine (ECM) and MAF process on MRR and SR and compare their results with traditional MAF. They conclude that the EMAF process gives a better surface finish and enhances MRR compared with simple MAF as demonstrated in Fig. 19 [58].

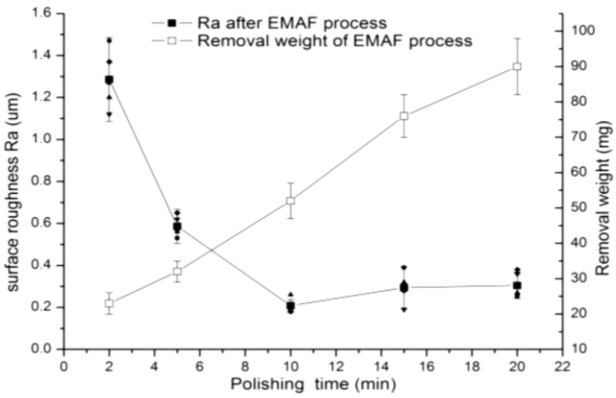


Fig. 19. shows the variation of S.R. (R_a) and M.R. against Polish time [58].

Ridha examined with EMAF process to check the influence on the surface roughness of aluminium tubes. The effect of finishing time on surface roughness is indicated in fig. 20. They concluded that the ECM create the oxidation film and MAF removed that oxidation film at the same time and finish the surface. This method takes 60-70% less time when compared with MAF for the same surface finish. [59].

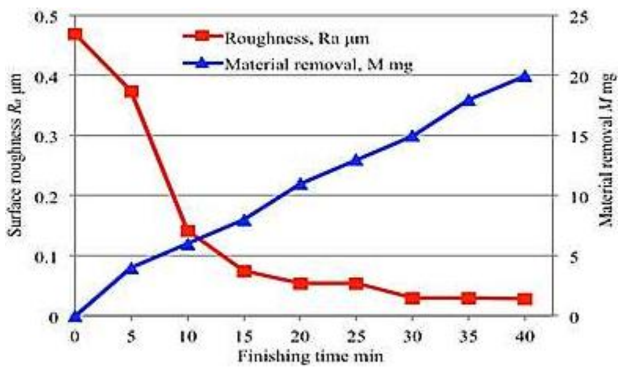


Fig. 20. show the surface roughness and MR weight change against finishing time [59].

Du et al. experimented with the EMAF process for enhancing the surface quality of nickel-based superalloy. The variation of surface roughness with magnetic and electrochemical assistant magnetic abrasive finishing is indicated in fig. 21. Author concluded that the EMAF process softens the work-piece surface by electrolytic polishing so it is easier for removing the material. This process also makes the surface morphology denser and uniform which helps to improve the surface quality [60].

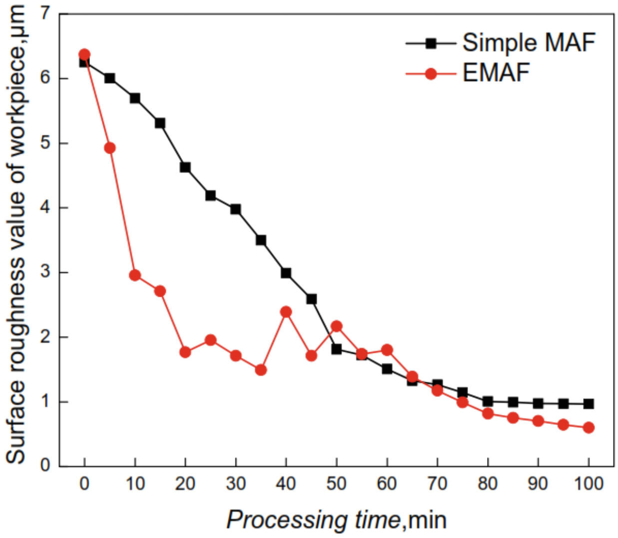


Fig. 21. indicate the variation of the surface roughness curve with time [60].

Muhamad et al. researched the effect of magnetic abrasive finishing (MAF) combined with electrolysis on finishing characteristics of the tube's internal finishing. Fig. 22 represented the effect of finishing time on the MRR and surface roughness. They concluded that the MRR enhance with EMAF as compared to the traditional process. The value of SR reduces to less than half in the first few minutes [61].

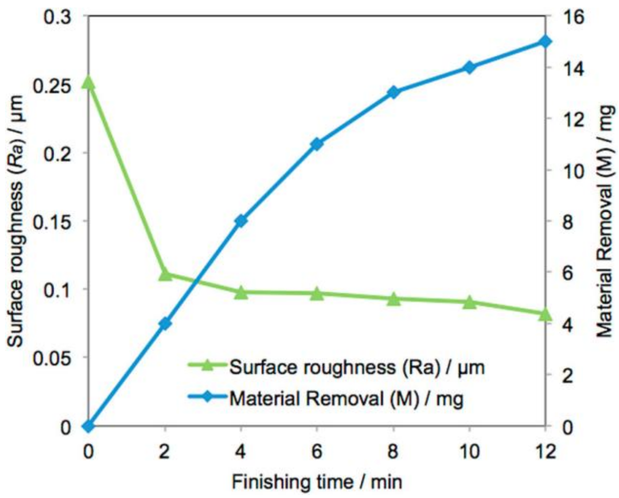


Fig. 22. shows variations in surface roughness and MRR during the finishing process [61].

Sun X. studied the EMAF process which was made up of the integration of the electrolytic process and MAF to enhance the machining efficiency of the stainless steel workpiece. Figure 19 shows the comparison of the EMAF process and MAF process for MRR and Surface roughness value. They concluded that the EMAF process improve the quality of the surface and also improved machining efficiency by about 50% when compared with the MAF method. The surface roughness instantly reduces within a short period from 393.08 to 30.94 nm Ra with the EMAF process [62] (Fig. 23).

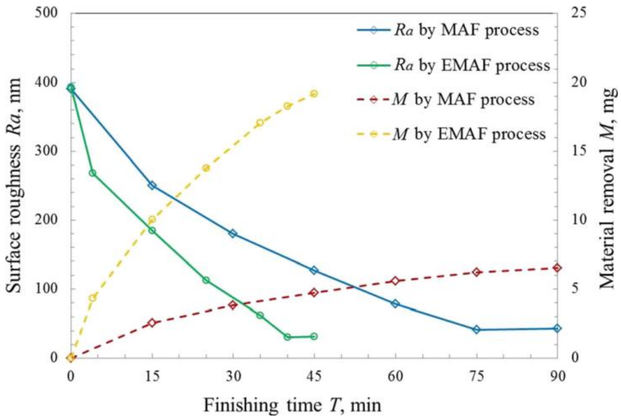


Fig. 23. Shows the comparison of the MAF and EMAF processes for MRR and Surface roughness [62].

Muhamad et al. experimented to analyze the effects of a combined electrochemical machining process and MAF during the internal finishing of an AA6063-T1 tube on surface roughness and MRR. The effect of finishing time on surface roughness and material removal is depicted in figure 24. They concluded that the EMAF take 60% less finishing time as compared to the simple MAF process and SR was decreased instantly in the initial finishing [63].

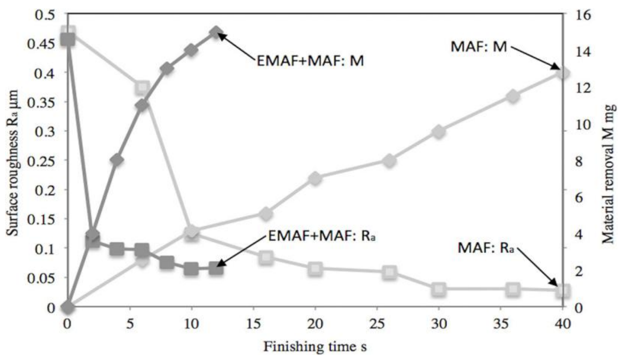


Fig. 24. shows the changes that occur in surface roughness and MRR with finishing time [63].

Pandey et al. develop a mathematical model to analyze the influence of electrode gap on surface roughness value and material removal rate during the EMAF process. They concluded that a higher rate of work-piece revolution gave more MRR. The use of higher electrolytic current and lower inter-electrode distance result in a better-finished surface and more MRR [64].

Sun and Zou investigate the effect of electrolytic magnetic abrasive finishing (EMAF) on mechanical finishing characteristics to enhance the finishing efficiency of traditional magnetic abrasive finishing (MAF). Fig. 25 shows the combination of the EMAF and MAF process on the effect of surface roughness and MRR. They conclude that through the creation of passive film from the electrolytic process, the machinability of Stainless Steel (SUS304) can be superior. It also noted that for the compound machining tool, a smaller SR and more MRR can be accomplished by comparatively higher rotational speed (450 rpm) and a smaller gap in working distance (1 mm) [65].

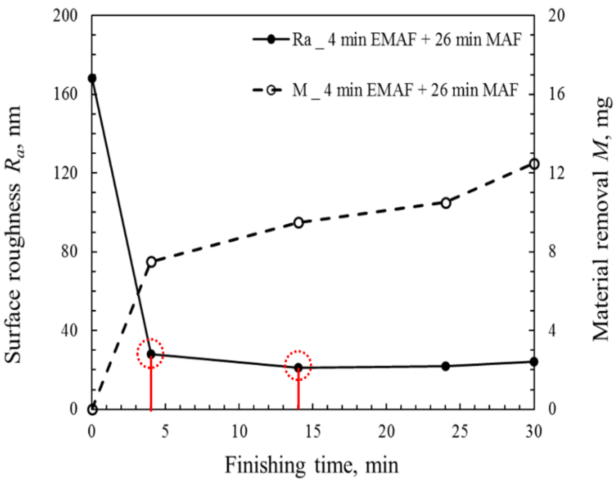


Fig. 25. shows the change in the surface roughness and material removal rate during the combination of 4 min EMAF with 26 min MAF process [65].

Farwaha et al. perform an experiment to obtain optimal process parameters (Rotational Speed, abrasives percentage and Ultrasonic Frequency time) of UEMAF on SS 316 workpiece. They concluded that 4.34 % abrasives wt. with ultrasonic frequency-time (13.39%) and maximum rotational speed (82.2%), for achieving high MRR and better surface finish. With the UEMAF process, a surface finish improvement of 82 percent was observed at optimum levels [66].

Dhull et al. generate a mathematical model of the Electrochem-magnetic abrasive flow machining process for calculating the magnetic force and material removal for the workpiece and then compared it with experimental results. In this process normal salt was used as an electrolyte with a molal concentration of 1:1 and different media was used to achieve the maximum MRR for brass work-piece material. It has been concluded that this hybrid process gave material removal 0.17gm at 4 and 5 mm rod size and 0.125 gm at 6 mm rod size. It also found that silicone rubber-based media gave maximum MRR and polyborosiloxane gave less material removal as compared to other media [67].

Farwaha et al. drive a mathematical model for the experimentation of the UEMAM hybrid machining process for 316L stainless steel material that is used for biomedical applications. In the UEMAM process, ultrasonic vibration is used for the machining zone of the ECM process and the MAF process is used for finishing and achieving high-quality surfaces within a very short time. In this process, a mathematical derivation has been derived to calculate the pressure on all factors like a magnetic force, ultrasonic vibration force and electrolytic action. The suggested mathematical model was validated by a comparison of experimental and theoretical data. When comparing experimental findings to the mathematical model's calculation results, the maximum amount of error is not greater than 7.351, indicating that the mathematical model is appropriate [68, 69].

Further, the summary of past research in some other integration with the electrochemical AFM process is given in Table 2.

Table 2. Summary of past research in some other integration with the electrochemical AFM process.

References	Developed process	Workpiece material	Abrasive media	Process parameters	Major observations and remarks
Kim D. J et al., [52]	MEAP	Steel SM45C	NaCl as electrolyte	no of finishing cycle: 8voltage: 0.5-10 (V) working time :3 min	SR and MRR improve
Fang J.C. et al., [53]		Carbon steel	acidic (static)	working temperature: 70°C finishing time: 6 min voltage: 6-12 (V) electric current: 6-12A	SR improves, by applying a magnetic field the effect on a rough surface is more robust than that on a fine surface and also improves finishing efficiency
Yan et al., [54]	EMAF	SKD11, HRC61	electrolyte solution NaNO3 and white alumina (WA 1.2 μm), SiC abrasives, the concentration of electrolyte: 20%	working rev: 200,500 rpm working gap: 1mm steel grit 180 μm electrode gap: 5,3or 2mm flow rate of electrolyte: 90mi/min weight ratio: 1:100	EMAF gave a better-finished surface than MAF, increasing electrolytic current and rate of workpiece rev. increase the finishing efficiency and improve SR.
El-Taweel T.A., [55]	ECT-MAF	Al 6061/Al2O3	A mixture of steel grit and Al_2O_3 abrasive, $NaNO_3$ electrolyte	tool material: Brass voltage:8-24 V rotation speed: 150-750 rev/min	this process Improved the machining efficiency and surface quality
Judal et al., [56]	C-EMAM	Stainless steel AISI-304	magnetic abrasive steel grit and SiC abrasive, $NaNO_3$ as electrolyte	steel grit size: 180 μm SiC size:10 μm voltage:0-50 V Current: 0-2.5 A working- electrode gap (mm):1:3 frequency of vibration: 2,3,4,5,6 Hz	SR and MRR improve, frequency of vibration also affects the value of SR.
Judal et al., [57]	C-EMAM	Stainless steel AISI-304	unbonded magnetic abrasive steel grit, SiC abrasive and $NaNO_3$ as electrolyte	steel grit size: 180 μm SiC size:10 μm voltage:0-50 V Current: 0-2 A working-electrode gap (mm) 1:2 frequency of vibration: 2,4,6 Hz work-piece rotation speed:250,420,710 RPM	The electrochemical process removes the major amount of material and MAM only assist to dissolve peaks of the surface profile. The frequency of vibration and rotational speed also affect the MRR and SR.

Liu et al., [58]	EMAF	Al 6061	electrolyte solution Na_3PO_4 and Na_2CO_3, SiC abrasive with ferriferous oxide powder	flow rate: static pulse frequency:5KHz abrasive size: 25 µm voltage: 12 (V) electric current: 20 A	SR improves within a few minutes with the EMAF process, obtain an EMAF gave good surface quality as compared with MAF Process
Ridha et al., [59]	EMAF	Al 6063	the magnetic particle-like iron powder as abrasive, white alumina and polishing agent, $NaNO_3$ as electrolyte	abrasive size:149 µm Current: 0.5 A pool-tube gap: 8 mm electrolyte amount: 30ml/min	Finishing time reduces as compared to MAF, the finishing time ratio for MAF and ECM was 2:9 to achieve a mirror-like surface.
Du et al., [60]	EMAF	Nickel based super alloy GH4169	magnetic abrasive particles composite of iron and aluminium oxide	abrasive size:250 µm voltage:6V work-piece feed speed:60 mm/min	This process Improved the SR from Ra 6.2526 µm to Ra 1.7689 µm; this process can make the surface morphology denser and more uniform and thus improve surface quality.
Muhamad et al., [61]	EMAF	Al (A6063)	magnetic abrasive particles: iron particle 3 g and white alumina 0.5 g and polishing agent-2 ml with $NaNO_3$ electrolyte	iron particle size: 149 µm voltage:5 V Current: 0.5,0.8,1.1 A pole-pipe gap (mm):4,5,6,7,8,9 frequency of vibration: 2,4,6 Hz work-piece rotation speed: 200 RPM pole rotation speed: 50 RPM	iron particles with white alumina abrasive contribute to a fast-resurfacing process, MRR improved
Sun et al., [62]	EMAF	Stainless Steel SUS 304	electrolytic iron powder, WA particles, oily grinding fluid and $NaNO_3$	iron particle size: 149,75,30 µm voltage:8 V Current: 0.5,0.8,1.1 A working gap: 1 mm flow rate: 300ml/min tool rotation speed: 450 RPM electrolytic test time: 10 min	Obtained higher finish and machining efficiency, improved by up to 50%.
Muhamad M. R et al. [63]	EMAF	Aluminium alloy (AA6063-T1)	magnetic abrasive particles: iron particle 3.5 g and white alumina 0.5 g and $NaNO_3$ electrolyte	iron particle size: 149 µm voltage:5 V Current: 0.5,0.8,1.1 A pole-pipe gap (mm):6 work-piece rotation speed: 200 RPM pole rotation speed: 50 RPM finishing time: 8 min	Reduce finishing time up to 60% SR declined instantly and MRR improved.
Pandey N et al. [64]	EMAF (mathematical model)	Triangular profile	Wedge shape magnetic abrasive particles	Current: 0.5 A work-piece rotation speed: 200,500 RPM finishing time: 5 min	MRR and SR improve drastically, high electrolytic current and high rotation of the work-piece gave better MRR
Sun and Zou. [65]	EMAF	Stainless Steel SUS 304	Electrolytic-iron powder, WA particles, oily grinding fluid and $NaNO_3$	iron particle size: 149 µm voltage:12V Current: 0.5,0.8,1.1 A working gap: 1 mm tool rotation speed:450 RPM finishing time:30 min	High MRR obtained at a smaller working gap and high RPM; less time consumed as compared to MAF

Farwaha H.S et al. [66]	UEMAF	Stainless Steel SS 316L	copper electrode, electrolyte $NaNO_3$, magnetic abrasive particles	workpiece-gap: 5mm Rotation Speed:200,400,600 Ultrasonic Frequency time (s):2,4,6 Working Gap:5mm Finishing-Time:15 min	Rotation speed and % of abrasive contribute the maximum for finishing, with 82% improvement recorded.
Dhull S et al. [67]	(mathematical model)	Brass aluminium mild steel	Al_2O_3 SIC Al_2O_3+SiC	Extrusion pressure:15,30,45 ECM Voltage:6,12,18 Mesh size:100,200,300 No.of cycles: 3,6,9	Silicone rubber-based media gave maximum MRR and polyborosiloxane gave less material removal as compared to other media
Farwaha H.S et al. [68]	UEMAM (mathematical model)	Stainless Steel SS 316L	$NaNO_3$ electrolyte, magnetic abrasive particles, diamond abrasive	Rotation Speed:200,400,600 Ultrasonic Frequency time (s):2,4,6 Working Gap:1,2,3 mm Finishing-Time:5,10,15 min	UEMAM gave a better result than the traditional process, this mathematical model, the maximum value of MRR error is 7.351 and which is appropriate.
Sun Xu et al. [69]	EMAF	SUS 304	$NaNO_3$ Electrolyte Iron particles & WA particles Oily grinding fluid	Working gap:1mm The rotational speed of tool:450 voltage:8,10,12 V finishing time of ECM:4 min	Finishing efficiency is improved by more than 75% with EMAF process and the material removal rate was about seven times higher than in the MAF process

6. EMERGING APPLICATIONS OF THE ELECTROCHEMICAL AFM PROCESS

This process has an application to enhancing the finishing of micro-hole, turbine blades, automobile components, textile equipment, defence, chemical and space industries also. The inaccessible area in components, which are challenging to finish with traditional techniques, can be finished by this process with up to 90% improvement in the original roughness [20,21, 29]. The electrochemical process with magnetic abrasive machining also has many applications in finishing the turbine blade, cutting tool, optics, sanitary pipes, airfoils, food industry and medical lines (Fig. 26).

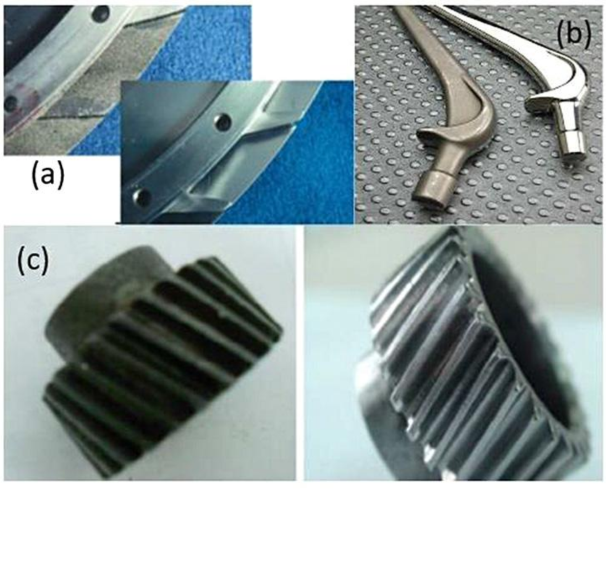


Fig. 26. Shows the improvement in the surface finish before and after (a) internal passage within the turbine engine diffuser [67], (b) medical implants [68], (c) finishing of helical gear [27] and (d) knee joint implant before and after finishing [23].

Recently, wear resistant thermal spray coating is also playing a significant role to improve the quality of parts [70-73]. Low Pressure Abrasive Flow Machining (LP-AFM) setup was created by Wan et al. [74] to close a small hole created by wire EDM using a low viscosity abrasive medium. They found that the surface finish and material removal rate (MRR) are strongly influenced by normal stress differences. It also takes certain finishing procedures to create a coating system that will shield the surface from harsh environments (oxidation, corrosion, erosion, wear and rust etc.). Different protective coatings have been utilized by different authors [75–80] to shield the surface from harsh environments. According to the authors, Ni-Cr-based coatings provided superior outcomes.

7. CONCLUSIONS

ECA²FM process has prominent superior finishing methods that are used in a wide range of materials to finish complex geometry. This paper presents an in-depth review of current developments in the ECA²FM process area. The following conclusions are drawn:

1. ECA²FM process is applied successfully to finish the portion of complex external and internal surface profiles. The MRR will be increased up to 84% when compared with the simple AFM process.
2. This process also helps to reduce about 15% manufacturing cost as compared to the AFM process.
3. The various parameter used in the ECA²FM process like abrasive type, abrasive size, salt molal concentration and RPM significantly affect the response parameter of MRR and SR.
4. The MRR of the ECA²FM process has increased with the rise of applied voltage. The surface becomes rough at more operating voltages due to more material dissolution, resulting in deeper scratches on the workpiece surface.
5. The EMAF method makes surface morphology denser and more uniform, thus improving the performance of the processing parameter as compared to sample MAF.
6. In the EMAF process, ECM makes the formation of an oxidation film and MAF removes it as a simultaneously ongoing process. So, this process is time-consuming and also effectively improved the machining efficiency.
7. In the EMAF process, the magnetic force is affected by different parameters like current, voltage, magnetic abrasive particle size, work-pole gap and no of cycles. Also, the increasing current effect the electromagnet which leads to more machining pressure and this pressure has a significant effect on the MRR and decreases the SR.

From the above article, it has been observed that SR and MRR can be enhanced by clubbing the ECM with the AFM process. Furthermore, a better result can be obtained by clubbing this process with another process like magnetic and also varying some parameters at a different level.

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Abbreviations

AFF	Abrasive Flow Finishing
AFM	Abrasive Flow Machining
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
BR	Butyl Rubber
CBN	Cubic Boron Nitride
CFAAFM	Centrifugal Force Assisted Abrasive Flow Machining
CFD	Computational Fluid Dynamics
CFG rod	Centrifugal Force Generating rod
CIP	Carbonyl Iron Powder
CMP	Chemical Mechanical Polishing
CNT	Carbon Nanotube
DBG-AFM	Drill Bit Guided Abrasive Flow Machining
DTA	Differential Thermal Analysis
ECAFM	Electrochemical Aided Abrasive Flow Machining
EC2 A2 FM	Electrochemical and Centrifugal Force Assisted Abrasive Flow Machining
ECM	Electrochemical Machining
EDM	Electric Discharge Machining
EPDM	Ethylene Propylene Diene Monomer
FDM	Fused Deposition Modeling
FTIR	Fourier Transform Infrared Spectroscopy
HLX-AFM	Helical Abrasive Flow Machining
MAF	Magnetic Abrasive Finishing
MAFM	Magnetic Abrasive Flow Machining
MFD	Magnetic Flux Density
MFP	Magnetic Float Polishing
MMC	Metal Matrix Composite
MR	Material Removed
MRAFF	Magnetorheological Abrasive Flow Finishing
MRF	Magnetorheological Finishing
MRR	Material Removal Rate
MVRA	Multi-Variate Regression Analysis
NR	Natural Rubber
OOR	Out of Roundness
R-AFF	Rotational Abrasive Flow Finishing
R-MRAFF	Rotational Magnetorheological Abrasive Flow Finishing
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
SiC	Silicon Carbide
SBR	Styrene-Butadiene Rubber
SLA	Stereolithography
SLM	Selective Laser Melting
TACAFM	Thermal Additive Centrifugal Abrasive Flow Machining
TGA	Thermogravimetric Analysis
UAAFM	Ultrasonic Assisted Abrasive Flow Machining
UFP	Ultrasonic Flow Polishing
USM	Ultrasonic Machining
WEDM	Wire Electric Discharge Machining