IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Effect Of Electrochemical And Magnetic Helical Assistance On Abrasive Flow Machining Performance

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Abstract: Abrasive flow machining (AFM) is a popular fine finishing process for polishing hidden internal surfaces, radii and other areas of components during the current manufacturing scenario. This consists of a media containing abrasive particles forced to flow back and forth, through the workpiece under pressure, allowing for consistent finishing even in complex internal geometries. In the present study, a brass workpiece is held securely within a nylon fixture, and a two-way AFM setup is employed, where the media reciprocates between two chambers through the workpiece to achieve effective surface finishing. The abrasive-laden media typically consists of Guar gam as carriers mixed with magnetic abrasive particles and is extruded under controlled pressure. Although the process is highly effective for precision finishing, it generally has a low material removal rate and is relatively time-consuming. To improve the surface finishing of AFM, a modified technique called Electrochemical assisted Magnetic Helical Abrasive Flow Machining (ECMHAFM) was employed to finish the internal surface of a brass workpiece. The present investigation focuses on analysing the effect of electrochemical machining combined with magnetic assistance using helical profile rods on key quality characteristics, including material removal and the percentage improvement in surface roughness.

Index Tems: Abrasive flow machine, Guar gam, Electrochemical assisted magnetic helical abrasive flow machine.

I. Introduction

Abrasive Flow Machining (AFM) is considered one of the most effective non-traditional finishing processes for achieving high-quality surface finish, especially in complex and hard-to-reach internal geometries. One of its key advantages is the ability to uniformly polish intricate features such as internal passages, cavities, and radii that are difficult or impossible to finish using conventional methods. The process provides excellent control over surface roughness while maintaining dimensional accuracy. Additionally, AFM is highly versatile, as it can be applied to a wide range of materials including metals, alloys, and composites.

It is also possible to finish several surfaces at the same time with the process enhancing productivity [1]. The media employed in the process is abrasive but very deformable such that it flows easily when passing through passages of different shapes and sizes. In operation, a workpiece is placed between two opposite cylinders (an upper and lower cylinder) which are hydraulically driven. A preprogrammed amount of abrasive media is added to the lower cylinder, and forced through the workpiece into the upper cylinder at a controlled pressure. When the forward stroke has ended the flow direction is reversed and the media is forced back through the workpiece to the lower cylinder. This is an upward and downward step which results in a one cycle [2]. In recent years, AFM has gained an even greater ability with the development of magnetic assistance, electrochemical integration and hybrid methods, it has become an even more desirable choice in such industries as aerospace, automotive and biomedical manufacturing [3].

Literature review:

In the new manufacturing procedures, Hybrid machining procedures have received close attention since they can be used to meet the demands of high surface quality, tight tolerances, and high production rates, and in particular to components with complex geometries and contours. These processes are also effective in finishing hard materials. In the development of hybrid Abrasive Flow Machining (AFM) processes, researchers have successfully combined AFM with various non-conventional machining techniques to enhance material removal rates—addressing one of the primary limitations of the conventional AFM process—and to achieve superior surface finishes in a shorter processing time [3]. Malik and Pandey proposed the integration of two non-traditional machining processes-Magnetic Abrasive Finishing (MAF) and Ultrasonic Finishing Machining (UFM) to develop a highly precise Ultrasonic Assisted Magnetic Abrasive Finishing (UAMAF) process. This hybrid technique was introduced to improve the surface morphology within a short processing time [4]. Singh and Walia developed a novel method that integrates magnetic force with the AFM process in order to enhance the material removal rate and improve overall machining efficiency [5]. Dabrowski et al. (2006) investigated the Electrochemical Assisted Abrasive Flow Machining (ECAFM) process; however, their study was limited to the fine finishing of flat surfaces The study reported enhanced material removal, which resulted from a combination of anodic dissolution at the atomic scale and mechanical abrasion caused by the cutting action of abrasive particles. Various types of electrolytic pastes were tested, and the findings indicated that cyanide-based pastes led to comparatively higher material removal rates. [6]. Later, Brar et al. developed the Electrochemical Aided Abrasive Flow Machining (ECA^{2}FM) process by integrating Abrasive Flow Machining with electrochemical machining, and successfully applied it for finishing the internal surfaces of hollow cylindrical workpieces. The combination of ECM and AFM was found to provide superior surface finish along with an increased material removal rate. In a subsequent study, Brar et al. reported that parameters such as applied voltage, salt molal concentration, number of cycles, and abrasive-to-media concentration ratio significantly influence the improvement in surface roughness and material removal rate [7,8]. Furthermore, M. Shankar et al. conducted experiments on Abrasive Assisted Electrochemical Machining (AECM). In their work, graphite was used as a solid lubricant to enhance the tribological properties of Al–B_4C composites, while SiC abrasive particles (50 µm) were used along with a NaCl electrolyte. The results of the study indicated that machining is better with the presence of abrasive particles, which leads to higher rate of material removal and better surface roughness than conventional ECM [9]. Likewise, Pankaj et al. (2014) found that the rate of material removal is higher when electrochemical machining is combined with abrasive flow machining. They also pointed out that the surface is likely to become irregular at higher voltages causing deep cuts on the workpiece surface [10]. Subsequently, Gupta et al. indicated that the ECA ^{2}FM process enhances machining ability, surface finish and material removal rate significantly. The abrasive slurry used in their study was made up of Al_2O_3 abrasives, silicon-based polymer, hydrogen gel, and sodium chloride salt. It was noted that, voltage made the most significant contribution to the enhancement of the material removal rate, followed by molal concentration, the number of cycles and rod diameter [11]. Walia et al. proposed a technique called centrifugal force assisted abrasive flow machining (CFAAFM). In this method, the abrasive media is rotated and extruded through the workpiece by means of geometrical dissimilarity rods. The synergistic effect produced by the combination of rotational and extrusion action causes intensified interaction between the abrasive particles and the work surface, and leads to greater aggressive finishing action [12-14]. Singh et al. Guar gum-based media demonstrated superior performance in the abrasive flow machining process compared to other organic media. It provided effective finishing while maintaining controlled material removal. Guar gum achieved the maximum percentage improvement in surface roughness [15]. Shergill et al. also used guar gam as media which are organic in nature, cost effective and easily available. Its result show that most significant parameter is media which contribute 59.38% for material removal [16]. Kumar et al. The newly developed electrochemical magneto-abrasive finishing (ECMAF) setup effectively addresses the issue of abrasive particles being washed away from the machining zone. Experimental results indicate that a maximum improvement in surface roughness of 0.239 mm was achieved at a signal-to-noise ratio of 12.34, while the highest material removal of 47.4 mg was obtained at a signal-to-noise ratio of 36.48 [17]. Vahdati et al. investigated the influence of magnetic abrasive machining parameters on freeform aluminium surfaces with computer numerical control (CNC) technology. The experimental setup incorporated a hemispherical tool mounted on flat magnetic surfaces, along with curved magnetic field configurations to enhance finishing performance [18]. In the present investigation effect of voltage has been studied in the finishing of internal cylindrical shape of brass workpiece. Special fixture is designed for electrochemical assisted magnetic helical abrasive flow machine. The different parameters have been optimised to achieve optimal material removal and percentage improvement in the surface finish.

Experimental Setup:

The experimental design is according to One-factor-at-a- time approach. This method consists of selecting a starting point or baseline set of levels, for each factor, and then successively varying each factor its ranges with the other factors held constant at baseline level.

The main process parameter for the current experimentation is voltage (V, in volt), the other factors of the experiment have been kept constant. 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:

$$\text{Material Removal (MR)} = (\text{Initial Weight- Final Weight}) * 1000\ (\text{mg})$$

Percentage Improvement in Surface Roughness is calculated by using:

$$\text{Surface Roughness Improvement } (\%\Delta Ra) = \frac{Initial\ Ra - Final\ Ra}{Initail\ Ra} * 100$$

In the present ECMHAFM setup, an axially cylindrical helical profile rods made as cathode and workpiece as anode. A Scientech DC power supply with voltage range 0-30V is used on the already developed basic AFM setup to supply the DC current to the electrode. The current setup employs the hydraulic system for the back-and-forth extrusion of the electrolytic abrasive (mixture of ferromagnetic and aluminium oxide) laden media through the hollow cylindrical brass workpiece. A nylon fixture is used which contain a hollow cylindrical workpiece of brass material (yellow brass: 65 % Cu, 35%Zn having BHN hardness 156) is made in three parts. In this setup helical geometries 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 as well as surface finish. An electromagnet is also used with range of 0.2 to 2 Tesla to produce magnetic field by using an electric current. These electromagnetic poles are used on the left and right side of the workpiece in such a way that to provide maximum magnetic field around the workpiece.

Media used for present investigation consist of electrolytic salt NaCl, ferromagnetic particles and Al_2O_3 as abrasive and Guar Gam used as organic media which is low lost environment friendly media. In this experiment abrasive to media ratio is taken as 1:1, magnetic flux density is 0.6T, abrasive size 150µm and the work-piece is hollow cylindrical piece with I.D. 8mm, O.D. 12 mm and length is 16 mm.

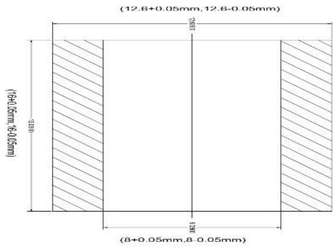

Fig. 1. Dimension of hollow cylindrical workpiece

During the experimentation, media is extruded through the recess between the copper cathode rod and the inner surface of the cylindrical hollow work-piece. A combination of upward and downwards stroke completes a cycle and the present set of experimentation the media has been extruded for five cycles. The stroke length is keeping fix at 100 mm. The required D.C. voltage is supplied and switch on just before the start of stroke and is also switch off in the middle of last stroke of the experimentation to achieve the final finishing. The experiments, process parameters shown in Table 1 and Table 2 to study the effect of only one factor of voltage on the output parameter of Material Removal and Percentage Improvement in Surface Roughness (%ΔRa).

Table 1: process parameters for material
Removal in the One-Factor- at- a- time- Approach

Mean Data of Material Removal (MR)				
Exp. No.	**Workpiece no**	**Response for Material Removal, MR (in mg)**		
		Voltage	**M1**	**Mean MR**
1	16	5V	23.1	19.633
2	14	5V	13.9	
3	5	5V	21.9	
Mean data of material removal (MR)				
Exp. No.	Workpiece no	**Response for Material Removal, MR (in mg)**		
		Voltage	M2	Mean MR
4	12	10V	41.2	34.633
5	19	10V	28.3	
6	9	10V	34.4	
	Mean data of material removal (MR)			
Exp. No.	**Workpiece no**	**Response for Material Removal, MR (in mg)**		
		Voltage	M3	Mean MR
7	3	15V	38.9	38.466
8	6	15V	34.8	
9	10	15V	41.7	

Table 2: Experimental result for Surface Roughness ΔRa

Mean data of Surface Roughness (ΔRa)				
Exp. No.	**Workpiece no**	**Response for Surface Roughness (ΔRa)**		
		Voltage	**R1**	**Mean of % improvement in ΔRa**
1	16	5V	52.33645	46.88
2	14	5V	34.35754	
3	5	5V	53.95833	
Mean data of Surface Roughness (ΔRa)				
Exp. No.	**Workpiece no**	**Response for Surface Roughness (ΔRa)**		
		Voltage	**R2**	**Mean of % improvement in ΔRa**

4	12	10V	27.31707	26.93
5	19	10V	24	
6	9	10V	29.4964	
	Mean data of Surface Roughness (ΔRa)			
Exp. No.	**Workpiece no**	**Response for Surface Roughness (ΔRa)**		
		Voltage	**R3**	**Mean of % improvement in ΔRa**
7	3	15V	35.12397	25.74
8	6	15V	17.9878	
9	10	15V	24.11924	

Analysis and Discussions:

Material Removal

The main effect for process parameter, voltage (V) is determined based on the average of the raw response data. The main effect for the voltage is plotted in the figure 2. The analysis of variance (ANOVA) is performed to find the significance of the voltage parameter (Table 3).

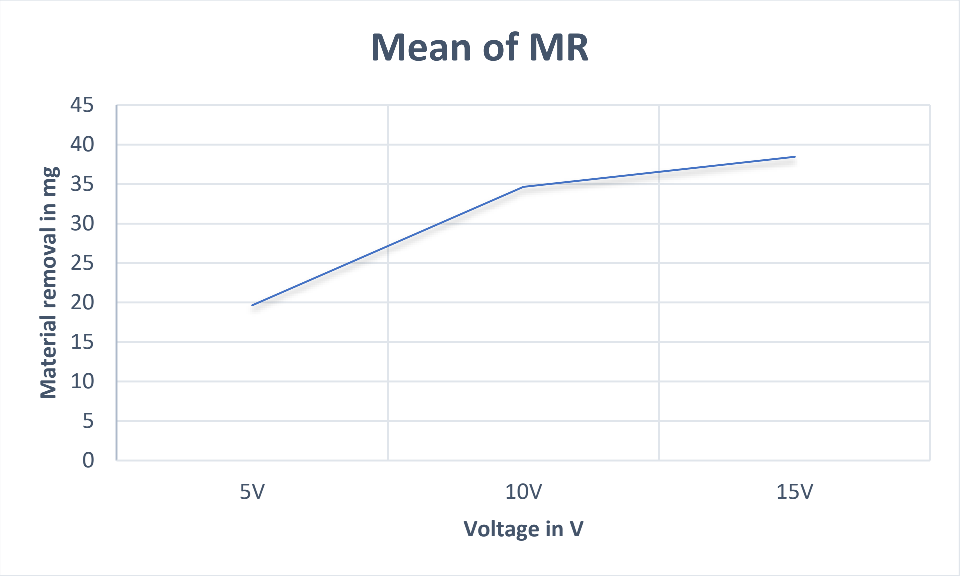

Fig. 2. Main Effect of Voltage in Material Removal

In this experimentation due to electrochemical action, 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. The main effect for material removal for the process parameter of voltage show that the material removal increases almost linearly with the increase voltage.

Table 3: Anova (Material removal)

Source	DOF	Sum of Square (SS)	Mean Square (V)	F-Ratio
Voltage	2	594.39	297.19	11.33*
Error	6	157.40	26.23	------------
Total	8			------------

*Significant at 95% confidence Level

F critical (2,6,0.05) = 5.14

Percentage Improvement in Surface Roughness

The influence of process parameters, particularly the Voltage is evaluated by calculating the average values of the observed response data. The relationship between the voltage and the percentage improvement in surface roughness is illustrated in Figure 3 through the main effects plot. Furthermore, an Analysis of Variance (ANOVA) is conducted to determine the statistical significance of the voltage as presented in Table 4.

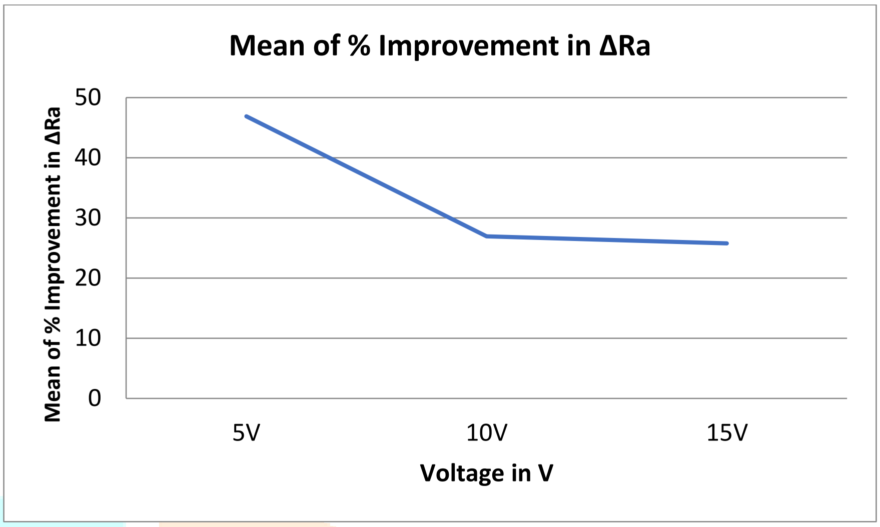

Fig. 3. Main Effect of Voltage in % Improvement in ΔRa

The main effect plot for surface roughness with respect to voltage indicates that surface roughness decreases as the applied voltage increases. At lower voltage levels, the electrochemical action removes micro peaks while abrasive smooth 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.

Table 4: Anova (Percentage improvement in Surface Roughness)

Source	**DOF**	**Sum of Square**	**Mean Square**	**F-Ratio**
Voltage	3-1=2	846.33	423.16	423.16/67.14=6.30*
Error	6	402.89	67.14	-----------
Total	9-1=8			-----------

*Significant at 95% confidence Level
F critical (2,6,0.05) = 5.14

Conclusions:

The main conclusions of this research work are:

- Material removal is enhanced through the synergistic coupling of electrochemical dissolution and magnetic field-assisted abrasive action. The incorporation of a helical profile rod induces complex axial, radial, and centrifugal force components, resulting in improved abrasive flow behaviour and intensified cutting efficiency in the Electrochemical Assisted Magnetic Helical Abrasive Flow Machining (ECMHAFM) process.
- The material removal goes on increasing with the increase in applied voltage.
- Better surface finish is achieved at 5V with this process, but at higher operating voltages 10V and 15V, the surface becomes rough due to more material dissolution resulting in deeper scratches on the surface.

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