Development of mathematical model for material removal and surface roughness in electrolytic magnetic abrasive finishing process

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Abstract: Electrolytic magnetic abrasive finishing is a hybrid machining process which takes into account both electrolytic & magnetic abrasive finishing process. It is a high efficiency finishing process which is used for advanced engineering materials like super alloys, metal matrix composites and ceramics. In this study mathematical modeling of material removal has been performed by considering the effect of electrode gap on material removal and then surface roughness model has been developed by assuming the surface profile as triangular. This research also investigates the interaction between various input process and their effect on process output characteristics like MRR and surface finish. The simulated data has been validated with the previous literature result which were found to be in good agreement.

1. Introduction

The need for high accuracy and high efficiency machining of difficult to cut materials is making the applications of abrasive finishing technologies increasingly important. The most labor intensive, uncontrollable area is the manufacture of precision parts involves final finishing operation because the cost of surface finish increases sharply for a roughness value of less than one micron. In the field of manufacturing industry it is not only the demand to obtain the surfaces with high quality but it is also the urgent demand to fulfill this demand along with high efficiency also. However it is not possible to obtain these present demands by using single traditional machining processes only for both high quality and high efficiency. Thus, there need a compound finishing process which consist of several process and meets the current demand in the field of finishing having high quality and high finishing. Electrolytic magnetic abrasive finishing is a hybrid machining process which is used for high efficiency and high quality surface. It consist of Magnetic abrasive finishing process and electrolytic process in which magnetic abrasive particles form magnetic abrasive brush in the presence of magnetic field and then perform the finishing process by abrasion. Material is removed in the form of small micro-chips as given by Jain et al
In electrolytic process material is removed due to the formation of passive layer formed on the surface of workpiece which is kept at anodic potential.

Yan et al. [2] have performed experiments on the electrolytic magnetic abrasive finishing process and describes the principles of the process, the finishing characteristics of the surface roughness and material removal, and the associated mechanism. Mischler et al. [3] has found out the role of oxide (passive) layer formed due to electrochemical reaction on the steel surface which has significant effect and found out that the formation of passive layer has significant on the increased wear. Garcia et al. [4] have introduced the concept of active wear track area to consider the corrosion wear process on passive material. Jayswal et al. [5] deals with the theoretical investigation of MAF process and a finite element model of this process has been developed to evaluate the distribution of magnetic forces on the workpiece surface. Kim and Choi [6] had developed a mathematical model of surface roughness to find out surface roughness as a function of finishing time which is based on the amount of material removed in magnetic abrasive machining. Kim and Choi [7] have carried out magneto-electrolytic-abrasive-polishing of newly developed Cr coated rollers and their finishing characteristics have been analyzed which were used in video-tape manufacturing industries and also they have theoretically studied the effect of magnetic field on electrolytic process and give the theoretical basis behind the modification of electrolytic ion motion caused by magnetic field. Kim et al. [8] in another research have developed a non woven abrasive pad, which is a kind of efficient machining polishing material which has been used in magneto-electrolytic-abrasive -polishing system. Judal and Yadava [9] has developed response surface methodology model for the prediction of material removal and surface roughness during the machining of non-magnetic stainless steel in cylindrical electrochemical magnetic abrasive machining process (C-EMAM). Though significant work has been reported to simulate the magnetic abrasive finishing process numerically but very little effort has been made toward the modeling of electrolytic magnetic abrasive finishing process.

In the present work a mathematical model of material removal and surface roughness of EMAF process has been done by considering abrasion, electrolytic action considering the effect of electrode gap on material removal. Derivational mathematical model of material removal has been derived then the final surface roughness has been derived by considering total volume of material removed by considering uniform triangular surface profile.

2. Modeling of material removal rate in EMAF process

The total amount of material removed during EMAF process is equal to the sum of material removed during MAF process and electrolytic process.

2.1 Modeling of magnetic abrasive finishing system

For the purpose of brevity the assumptions made during modelling are not listed here and can be referred from [1,2,3,5]. In magnetic abrasive finishing since abrasives are distributed randomly and the primary cutting action is performed by abrasives while ferromagnetic particles supplies abrasion pressure. The number of abrasives taking part in abrasion action beneath each FP may vary from one instance to another instance. It has been assumed that cross-sectional area of magnetic brush is same as that of air gap, therefore the number of magnetic abrasive that are in actual contact with workpiece are [3]:

\[ N = \frac{A_0}{(\pi/4)D^2} \]  \hspace{1cm} (1)

The force acting on a magnetic abrasive is

\[ f = \frac{F}{N} \]  \hspace{1cm} (2)
The force acting on cutting edge is

\[ \Delta f = \frac{f}{n} \]  

(4)

where \( n \) = number of cutting edges participating in the machining for a magnetic abrasive

\[ \Delta f = \frac{D^2}{4n} p \]  

(5)

\( P \) = machining pressure applied on the surface of workpiece due to ferromagnetic particles [13]

\[ p = \frac{\mu_0 H^2 (1 - \frac{1}{\mu_a})}{2} \]  

(6)

\( \mu_a \) = relative permeability of abrasive particles [1]

\[ \mu_a = \alpha \mu_{fp} + (1 - \alpha) \mu_{abr} \]  

(7)

The characteristic shape of magnetic abrasive particle which have been considered during modeling is shown in Fig.1

Fig 1 Characteristic shape of magnetic abrasive particle [3]

The total length of workpiece which has to be finished is \( l_{tot} = v \times t \)

Actual length of contact between workpiece and magnetic abrasive within total finishing length from the above Fig.2

\[ l = (1 - \frac{R_v}{R_w}) vt \]  

(8)

Stock of material removed due to MAM by cutting edge in time \( t = \)

actual length of contact X area of grain on which force is acting

actual length of contact X total force acting/force acting on grain on unit area
\[ W_{i} = \pi DNr(1 - \frac{R_{a}}{R_{w}})[\frac{\Delta f}{H_{m} \pi \tan \theta_{a}}] \]

Fig. 2. Shape of scratched machined surface

Fig. 3. Wedge shaped abrasive

2.2 Calculation of material removal due to electrolytic process considering electrode gap

In electrochemical dissolution process the gap between workpiece and electrode is filled with electrolyte. The electrode is connected to cathode while workpiece is connected to anode of the DC power source. The material is removed atom by atom from the workpiece kept at anodic potential. Material removal in term of volume can be calculated as [10]

\[ W_{2} = \frac{\eta itE}{F \rho} \]

In ECM process generally tool (cathode) is fed toward the workpiece (anode) at constant rate. During equilibrium, feed rate of cathode is equal to the rate at which the thickness of anode is being reduced i.e material removal along length. The inter-electrode gap between workpiece and electrode is given by [11]

\[ \gamma_{e} = \frac{(V - \Delta V) \eta k E}{\rho f F} \]

So, material removal by considering electrode gap is

\[ W_{2} = \frac{\eta iy_{e} f}{(V - \Delta V) k} \]

Thus, total material removed during EMAF process considering material removal due to magnetic abrasive finishing and electrolytic process considering electrode gap is

\[ W = W_{1} + W_{2} \]

3. Modeling of surface roughness during EMAF process

The quality of surface can be improved by reducing unevenness from the surface profile of workpiece. It is generally reduced by the normal magnetic force which applies machining pressure on the surface of workpiece through magnetic abrasive particles which results in the penetration of cutting edges of abrasive grains in the workpiece. Due to rotation of MAPs, grooves are formed on the workpiece surface which decides the surface profile after the EMAF. Surface roughness is determined on the basis of the
surface profile achieved by equating the volume of the material removed to the volume of groove produced. It has been assumed that the initial surface of the workpiece have uniform triangular profile as shown in Fig.2. It has been assumed that initial arithmetic mean surface roughness of workpiece is $2R_a^0$. After processing time of $T$ during EMAF process the final surface roughness achieved is $2R_a$. It has been assumed that the valleys of the surface irregularities are passivated initially, which prevents further electrolytic process. The passive film formed at valleys is inaccessible to magnetic abrasive brush during MAM, hence the major amount of material is removed from the peaks of the surface profile and the peaks get truncated as shown in Fig.2. The final surface roughness can be obtained from the volume of material removed during the EMAF process.

Thus total volume of material removed in a cell is

$$W = \frac{(R_a^0 - R_a)^2}{R_a^0} \times l_w \times \pi \times d_w$$

By re-arranging equation 17 we can found out final surface roughness of the workpiece. Thus the final surface roughness of workpiece is

$$R_a = R_a^0 - \sqrt{\frac{R_a^0 \times W}{\pi d_w \times l_w}}$$

From the above equation the final surface roughness of the workpiece can be calculated if the total volume of material removed from the machining zone is known. A critical surface roughness may exist in the machining region due to indentation of the cutting edge on the workpiece surface and due to the presence of this critical surface roughness the surface roughness of workpiece will not improve further. The shape of wedge shaped abrasive is shown in Fig.3.

Radius of conical shaped abrasive can be calculated as

$$r = h_c \tan \theta_a$$

Force acting on single cutting abrasive is [3]

$$\Delta f = H_m \pi r^2$$

$$\Delta f = H_m \pi (h_c \tan \theta_a)^2$$

Thus the value of critical depth of penetration is

$$h_c = \frac{1}{\tan \theta_a} \sqrt{\frac{\Delta f}{H_m \pi}}$$

Since the critical surface roughness is the mean of depth of penetration

$$(R_a)_{cr} = \frac{h_c}{2}$$

Higher the value obtained from both the (18) and (23) will be taken as final surface roughness.
4. Results and Discussion

In the present work, a MATLAB code has been written for the material removal and surface roughness model of EMAF process. The simulation result of EMAF has been compared with the experimental result [9] of material removal and surface roughness with respect to machining time. The process parameters which have been used for the validation of EMAF model have been given in the table 1. Fig. 4 shows the simulation result of material removal at 0.5 A electrolytic current at different workpiece rotational speed of 200 and 500 rpm as shown in Fig. 4 (a) and (b) respectively. It can be observed that material removed at 200 rpm is 22 mg while it is 35 mg at 500 rpm for a finishing time of 5 min for a given electrolytic current of 0.5 A. Higher material removal at higher rotational speed is due to the reason that higher rotational speed can cause the easy removal of passive film formed on the workpiece surface. The simulation result is close to the experimental result [9] and also follow nearly similar trend. Fig. 5 shows the simulation result of surface roughness 0.5 A electrolytic current for 200 and 500 rpm of workpiece rotational speed. It can be observed from Fig. 5 (a) that at 200 rpm the surface roughness can be improved to 0.03 µm Ra after the finishing time of 5 min while it can be seen from Fig. 5(b) that at 500 rpm surface roughness can be improved to 0.017 µm Ra. This is due to the reason that at smaller rate of rotation less amount of material is removed. Thus higher rate of rotation is associated with better surface roughness. The trend of simulated result of surface roughness is same as the experimental result [9].

Fig. 4. Variation of material removal with finishing time for various rate of workpiece rotation (a) for 200 rpm (b) for 500 rpm at electrolytic current of 0.5 A

Fig. 6. (a) and (b) shows the simulation result of material removal at an electrode gap of 3 mm and 5 mm respectively, it can be observed that smaller the electrode gap is more will be the material removal however the difference is not much more. During the processing rate of workpiece rotation is kept at 500 rpm while electrolytic current is kept at 0.5 A. Due to more material removed at smaller electrode gap surface roughness obtained at smaller electrode gap is better than that obtained at larger electrode gap Fig. 7 (a) and (b) shows the surface roughness obtained after the finishing time of 5 min at an electrode gap of 3 mm and 5 mm respectively, the surface roughness obtained at the electrode gap of 3 mm is 0.017 µm and 0.021 µm at an electrode gap of 5 mm. The reason of less material removal and poor surface roughness at higher electrode gap is when the electrode gap increase, ions are acted upon by Lorentz force...
and under this effect the anion cannot reach the electrode surface to participate in the reaction and thus electrolytic reaction decreases and thus material removal also decreases. It can also be seen that surface roughness decreases rapidly at the start of the process and then the decrease in roughness is quite slow, this is due to the reason that the peak of the surface roughness before the start of the process is much higher so that they can be removed.

![Surface Roughness Variation](image1)

Fig.5. Variation of surface roughness with finishing time for various rate of workpiece rotation (a) for 200 rpm (b) for 500 rpm at an electrolytic current of 0.5A

![Material Removal Variation](image2)

Fig.6. Variation of material removal with finishing time at different electrode gap (a) for 3mm of electrode gap (b) with 5mm of electrode gap at 500 rpm and an electrolytic current of 0.5A easily, but once the peaks get removed then the height of roughness peaks get smaller so it becomes quite difficult to remove the roughness peaks latter. Thus, surface roughness improves rapidly at beginning and less at the end of the process. The simulation result is close to experimental result [9] and follow nearly similar trend. Fig 8(a) and 8(b) shows the simulated result of material removal at an electrolytic current of 0.5A and 1.5A respectively at 200 rpm and 500 rpm respectively. It can be observed that higher the electrolytic current more will be the material removal. From Fig. 8 (a) when the workpiece revolution is 200 rpm, EMAF with electrolytic current of 1.5 A will cause 55 mg of material removal while it is only 35 mg at 0.5 A of electrolytic current. This is due to the fact that higher the electrolytic current, more will be the formation of passive film at the workpiece surface and easier will be the material removal. From Fig.8 (b) it can be observed that when the workpiece revolution is 500 rpm, material removal at 0.5A
current and 1.5 A current is more as comparison to that at 200 rpm. Reason behind the removal of more material at higher workpiece rotation is, at higher speed it's much easier to remove the passive film which is formed on the surface in comparison to lower rate of rotation. The computed result of material removal follows the same trend and agrees with the experimental result.

![Fig.7](image-url) Variation of surface roughness for various inter electrode gap (ieg) (a) for 3mm (b) for 5mm at N=500 rpm, 0.5A of electrolytic current.

![Fig.8](image-url) Effect of electrolytic current a) at 200 rpm, b) at 500 rpm on material removal

5. Conclusions

A model for material removal by considering the electrode gap has been developed and its effect on the surface roughness has been considered by developing a surface roughness model considering triangular profile. The effect of electrode gap has been captured in the model of material removal. From result and discussion following points have been drawn.

1. EMAF is a hybrid machining process which improves material removal and surface roughness drastically in comparison to the constituent process when they are applied individually.
2. Material removal becomes more when higher rate of workpiece revolution is used in comparison to lower rate of revolution.

3. Using higher electrolytic current more material removal and better surface finish is obtained in comparison to lower electrolytic current because of more formation of passive film at higher electrolytic current.

4. Lower inter-electrode gap will cause more material removal while higher inter-electrode gap will cause less material removal, however the difference is not much more.

5. Simulation result of the model being used agreed with the previous literature result and follows the same trend.

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