A Review on Parametric Analysis of Magnetic Abrasive Machining Process

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Abstract: The magnetic abrasive machining (MAM) process is a highly developed unconventional machining process. It is frequently used in manufacturing industries for nanometer range surface finishing of workpiece with the help of Magnetic abrasive particles (MAPs) and magnetic force applied in the machining zone. It is precise and faster than conventional methods and able to produce defect free finished components. This paper provides a comprehensive review on the recent advancement of MAM process carried out by different researcher till date. The effect of different input parameters such as rotational speed of electromagnet, voltage, magnetic flux density, abrasive particles size and working gap on the performances of Material Removal Rate (MRR) and surface roughness (Rₐ) have been discussed. On the basis of review, it is observed that the rotational speed of electromagnet, voltage and mesh size of abrasive particles have significant impact on MAM process.

1. Introduction

High quality and limited dimensional tolerance parts used in the aircraft, automobile, and shipbuilding industries require excellent surface finish. Conventional methods such as filling, lapping, honing, super finishing, grinding, polishing and buffing are used to modify the surface texture produced by manufacturing process[1-2]. To further optimize the finishing operation unconventional machining processes like MAM are gaining attention owing to their ability to provide better surface finish than the conventional processes. Magnetic abrasive machining (MAM) is a process in which a magnetic power is employed as a machining force. This force is directing the abrasive particles towards the target surface. The efficiency of the process is easily controllable by the electric current. To prevent the over-finishing of surface roughness, careful monitoring of the process automation is needed [3]. Therefore, MAM has been used for accuracy of surface finishing because of many advantages such as self-adaptability, controllability and self-sharpening [4].

2. Literature Review

The work done by several researchers signify the feasibility, effectiveness and economic aspect of MAM in various manufacturing domains.

Ramesh babu et al. (1998) investigated the effect of various input parameters on the surface quality of stainless steel workpiece. They observed preliminary roughness and hardness of the workpiece influencing the surface finish significantly [5]. Yamaguchi and Shinmura proposed an internal magnetic abrasive finishing process for quality finishing of inner surface of the tubes. They observed
surface texture is full of micro-scratches and this feature exhibits that the MAF process is a pressure-copying process. The MAF process provides smoothing with high MRR [6].

It is studied that different researchers had done experiment for understanding the result of different input parameters on surface finishing during MAM process. In 2001, Khairy developed the magneto abrasive finishing process and overcome the disadvantages of rigid shaped and grinding wheels on the magneto abrasive finishing process. They studied the main features of the MAM process to make the model for kinematic process. They investigated outcome of input parameters like rotational speed of electromagnet, abrasive particles size and current intensity in output parameters namely edge and surface finishing. They also compared the conventional grinding and super finishing method to explain the nano machining capabilities of MAM process [7]. Biing-Hwa et al. analyzed the principle and property of the unbounded MAPs on Stainless Steel (SUS 304) by cylindrical Magnetic Abrasive Finishing (MAF) processes. They explained how \( R_e \) and MRR are impact by the process parameters as well as their mechanism. They also explained that steel grit produce superior finishing than that of iron grit when mixed with SiC abrasive [8].

Biing et al. discussed the principle of electrolytic magnetic abrasive finishing (EMAF) in 2003. They also analyzed the impact of different process parameters with different range as shown in (Table 1) in \( R_e \) and MRR. This experimental result also shows that with a high electrolytic current EMAF process produces excellent finishing characteristics [9]. In 2004, Sing et al. conducted experiments on stainless steel during MAM process using Taguchi design experiment and found the optimum input parameters. They explained how \( R_e \) is impact by input parameters namely voltage, revolution speed of the electromagnet, abrasive particles size and working gap. They also designed force transducer for inspection of the finishing process and fabricated to calculate the force during MAM process [10].

In 2012, Yadava and Judal introduced a hybrid machining known as cylindrical electrochemical magnetic abrasive machining(C-EMAM), which is used in cylindrical work surface for effective surface finishing which is tough by other machining processes. Experiment was performed on self developed C-EAMM process setup of magnetic stainless steel (AISI-420) using unbounded MAPs. They explained the impact of process parameters on MRR and finishing. They also observed that for magnetic steel, how \( R_e \) and MRR are influenced with the electro-chemical dissolution and magnetic abrasion respectively [11]. Judal et al. designed and developed cylindrical MAF setup to produce high grade of surface finish quality which are needed on advanced manufacturing industries. They explained how current on electromagnet influenced the magnetic field. In this experiment they also studied the effect of main critical parameters which effect on the finishing quality. \( R_e \) decrease from 1.3 \( \mu m \) to 0.24 \( \mu m \) after machining process in their experiment. They observed that to improve the finishing quality, magnetic poles are rotated [12].

Madarkar and Jain investigated the new technique namely magnetic abrasive deburring (MADe) method. They studied the effect of input parameters with different range as shown in (Table 1) on output parameters such as surface finishing. They also explained that magnetic abrasive deburring method had most effective improvement on hole-edge quality and burr reduction [13]. In 2016, Jeinzhong et al. explained the new novel of ultra precision MAF process and studied how output parameters are influenced by the effect of different input parameters. They compare the study between silicon and water soluble cutting fluids, neat cutting oil. They also observed that by enhancing the frequency of current there is decrease in the angle of difference of MAPs [14].

kanish et al. investigated an experiment setup of Magnetic field assisted abrasive finishing (MFAAF) which depend in Taguchi methods. They studied how there is enhancement on MRR and \( R_e \) with the different range of process parameters. They selected different workpiece materials and conduct experiment on that by using developed models with the help of experimentation records. It is found that prediction errors of 4.16\% and 6.96\% on \( R_e \) and MRR respectively. The surface topography obtained by this process is analyzed using scanning electron microscopy (SEM) [15]. Moro et al. stated the principle of polishing of plane type workpiece which is of non-ferromagnetic particles in 2003. They discussed three kind of summation of energy, how abrasive particles are magnetized. They also explained that if MAPs drift against the balance point of magnetic than the tangential force fabricated
returning force, by that magnetic abrasives polish the workpiece surface smoothly which should be less than 0.3 µm after finishing of inner surface [16]. Wang and Hu developed MAF Technology for analyzing the work surface of different materials and it show negative impact in Rₚ and material removal with different process parameters. The imperative application of MAM process in the field of modern manufacturing industries are aerospace parts, medical instruments, atomic energy parts etc. [17].

Moreover, Sing et al. studied the principle of MAF process where work surface is finished by removing materials with the help of MAPs (SiC and ferromagnetic particles). In this mechanism, force has direct impact on the finished surface and accuracy of the workpiece. They also found that with the increment of current in electromagnetic and decrement in working zone there is increment in Rₚ [18]. Wang and Lee elaborated a novel on abrasive medium using the abrasive gel with abrasive particles to improve the disadvantage of MAF process. They studied and found that the surface finishing of the workpiece is three times better by magnetic finishing with gel abrasive than MAF process. They studied about the effect of mesh size of silicon carbide and Silicon gel, quantity of abrasive gel, current, vibration frequency and rotational speed on Rₚ and MRR of workpiece. They also found that surface roughness improvement was about 90% when the same abrasive medium was used about 15 times to surface finish 15 different workpiece, thereby proving that gel abrasive had excellent ability for recycling [19].

Jain et al. explained MAF process where MAPs are joined to each other and forms a flexible brush when magnetic field is generated. They studied parametric effects on Rₚ. As compared to the measured force in developed set up which is use in this experiment they found that magnetic force is more in magnetic materials than non-magnetic materials. They also found that there is no crucial change in tangential cutting force [20].

Sathua et al. stated that MAF is an effective technique. It is capable to get desired finishing of nonferromagnetic materials because of its new ball-ended tool developed. They explained the mechanism of variation and surface production acting during the finishing operation using different process parameters with different range as shown in (Table 1) [21]. Liu et al. investigated the smooth surface finishing with high efficiency which are needed in manufacturing industries. They explained that EMAF is capable to produce desired Rₚ and MRR than MAF, which are arrangement of both MAF and ECM (Electrochemical machining). With the optimal used of input parameters, Rₚ reduces from 1.3 µm to 0.2 µm within a few minute when EMAF process is applied to AL 6061 [22].

Shanbhag et al. developed analytical model and explained the principle of MAF process. The purpose of this developed model was to find Rₚ with the effect of different process parameters. Experimental results are verified with theoretical results achieved from developed model [23]. In 2016 Verna et al. explained the principle based on a novel tool of MAF process. They study the impact of process parameters used in MAM process on Rₚ [24]. Choopani et al. developed experiment setup. They studied how MRR and Rₚ are affected by input parameters with different range as shown in (Table 1) during MAF process. They also stated that FMAB and magnetic force act on the MAPs rely on the shape, type and size of it and Rₚ is obtained up to the range of 0.207 µm [25].

3. Fundamental of Magnetic Abrasive Machining Process

In MAM process, MAPs are formed by the combination of abrasive and ferromagnetic particles. It is used for the purpose of cutting tool where finishing operation is carried by magnetic field produce by electromagnet [3]. Abrasive particle used during MAM process may be SiC (which is used for hard materials), Al₂O₃ (which is used for soft materials) [27-29].
MAPs may be bonded and unbounded. Bounded are simply mixing of abrasive and ferromagnetic particles whereas unbounded are mixing of abrasive and ferromagnetic particles with small amount of lubricant [28-30]. MAPs connect to each other through the lines of magnetic force. By that, FMAB will form and it acts as multipoint cutting tool for surface finishing performance. While revolving the magnetic pole, FMAB also revolves than desired surface finishing characteristics is obtained with the performance of magnetic force on MAPs [31]. It is useful for both internal and external surface finishing on a cylindrical workpiece. In external surface finishing process, the cylindrical workpiece rotates between the magnetic poles with MAPs filled at each side of both the gap as given in Figure 1 [26].

**4. Analysis of Process Parameters**

The impact of various input parameters on process characteristics namely $R_a$ and MRR of MAM during machining of different engineering materials has been analyzed using the experiment and are discussed below:

4.1. *Influence of Voltage on $R_a$ and MRR.* With the increment in voltage supplied to the electromagnet, the $R_a$ and MRR rate are also increases [10]. It creates much line of magnetic force so there is increase in magnetic flux density on the working zone. With the decrement of working area the strength and contact area of FMAB with workpiece increase. By that there is increment in $R_a$.

4.2. *Influence of Mesh Size of Abrasive Particles on $R_a$ and MRR.* With the increment in abrasive particles size there is decrease in surface finish [10, 32, 33]. With the decrease in abrasive particle size, there is increase in a contact area of workpiece with abrasive particles size. So, much surface got sheared off so that there is increase in surface finish but it is not possible to larger abrasive particle size because in FMAB it is hard to trap between abrasive particles size. Thereby, it impact in finishing, result on improper $R_a$ and MRR.
4.3. **Influence of Rotational Speed of Electromagnet on $R_a$ and MRR.** Surface roughness and MRR increase which guide to the better surface finishing due to increment of Rotational speed [10, 18]. Furthermore Rotational speed supply additional energy to abrasive to penetrate workpiece, thereby there is better $R_a$ and MRR. But there is decrement in surface roughness with increment in rotational speed. Increment of centrifugal force is corresponding to the increment of rotational speed. The mixtures of MAP is cast away from the machining zone with increment of force, thereby magnetic flux density decrease in the machining zone as well as there is available of less MAP used for the shearing with the surface of workpiece. So, there is reduction in $R_a$ with more increase in rotational speed of electromagnet.

4.4. **Influence of Magnetic Flux Density on $R_a$ and MRR.** There are improvement in $R_a$ and MRR of workpiece, when there is increase in magnetic flux density [34-35]. $R_a$ and MRR are increased due to the increment in flux density of magnetic; thereby increase in tangential finishing force which is the crucial cutting force required for smoothening of surface by removing materials as microchips. Magnetic flux density and different parameters should be used according to the properties of operating workpiece materials.

4.5. **Influence of Working Gap on $R_a$ and MRR.** Due to decrement of working zone percentage of $R_a$ and MRR increases [20, 26, 35]. But with the increment of working zone, surface finish is decreased because magnetic field generated is minimum so that ferromagnetic particle is weakly magnetized therefore it produce lesser amount of pressure force in FMAB during workpiece boundary by that abrasive particle size doesn’t have exact indentation with large working zone. So, $R_a$ and MRR are decreased.

5. **Discussion**

MAM is one of the finest surfaces finishing unconventional machining process for all types of engineering materials and it is suitable for the surface finishing with high accuracy and efficiency. It is always not necessary that there should be significant contribution of input parameters on output parameters like surface finish and MRR. Some of the parameters are significant as compared to others. In this section, different working input parameter, output parameters workpiece and abrasive particles related to MAM process have been summarized in the Table 1.

| Table 1. Summarized machining parameters of MAM process |
|---------------------------------------------------------|
| **Workpiece** | **Abrasive Particles** | **Input Parameters With Range** | **Output parameters** | **Major Finding** | **Ref.** |
| Stainless steel (AISI 440C) | SiC | Workpiece circumferential speed: 45-160 rpm, Magnetic flux density: 0.3-0.5 T, Abrasive grain size: 53-106 µm, Workpiece hardness: 45-55 HRC and Working gap: 0.002-0.004 m | Surface finish | Experiment was designed with the involvement of QA experimentation. | 5 |
| Stainless steel (SUS 304) | Fe₂O₃ | Workpiece revolution: 50-400 rpm, Disk revolution: 0-2500 rpm, Current: 1-2 A, Magnetic flux density: 1.04 T and clearance: 3 mm | $R_a$, MRR | MAF removes more material to get better $R_a$ as compared to magnetic jig finishing, $R_a$ measurement, SEM, Atomic force are used to distinguish MRR process and gives idea to process mechanism. | 6 |
| Stainless Steel (SS304) | Al₂O₃ | Rotational speed: 100-400 rpm, Magnetic flux density: 0.15-0.45 T, Feed: 0.0005 mm/sec, Diameter of MAP: 75E-0.6 - 150E-0.6 mm, Feed: 0.0005 mm/sec, Size of workpiece: 50x50x1.2 mm and Hardness of workpiece: 5.5 GPa | Surface finishing | Analytical model is prepared to obtain $R_a$. $R_a$ from Expt. is close enough with Theoretical. $R_a$ is affected by speed, feed, diameter of magnetic abrasive, number of active magnetic abrasives. |
|------------------------|-------|-------------------------------------------------|------------------|--------------------------------------------------|
| SKD11, HRC61 (WA)      | Al₂O₃ | Rotational speed: 200–800 rpm, Magnetic flux density: 0.85 T, Electrolytic current: 0.5-2.5 A, Frequency of axial vibration: 2–8 Hz, Working gap: 1 mm and Flow rate of electrolyte: 1.5 ml/sec | MRR, $R_a$ | Surface finishing characteristic of EMAF has better than MAF. Electrolytic current is the major parameter. |
| Stainless Steel (SUS 304) | Al₂O₃ | Rotational speed: 250 rpm and Current: 0.5-5.0 A | $R_a$ | A polishing mechanism as well as formation of FMAB was explained in this expt. |
| Flat Stainless Steel (SUS 304) | SiC, Al₂O₃ | Rotational speed: 90-180 rpm, Voltage: 7.5-11 V, Working gap: 1.25-1.75 mm, Grain size: 400-1200 μm and Time 1200 sec | $R_a$ | Voltage is the most significant parameter among other used parameters. A high voltage 1.5V, Rotational speed 180 rpm, working gap 1.25mm and grain mesh size numbers are useful to enhance $R_a$. Rotational Speed, Vibration frequency, a high current could achieve a smooth $R_a$ and MRR. Recycling efficiency is good and reusing of MAP is practicable. |
| SKD11                  | SiC   | Rotational Speed: 700-1300 rpm, Current: 1-3 A, Mesh size of silicon carbide: 2000-8000 μm and Silicone gel: 50-100 g, Quantity of abrasive gel: 10 g, Vibrational frequency: 4-6 Hz and working gap: 1 mm. | $R_a$ and MRR | MAM process has better contribution in MRR because of maximum magnetic permeability of Stainless Steel-magnetic (AISI-420). The main critical parameters which effect on MRR are rotational speed to electromagnet and electrolytic current. |
| Stainless Steel-magnetic (AISI-420) | SiC | Rotational Speed: 150-710 rpm, Electrolytic current: 0.5-2.5 A, Excitation current: 0.5-2.5 A, Frequency of vibration: 2-6 Hz and Working gap: 1 mm. | $R_a$ and MRR | The main input parameters during finishing of workpiece are MAPs as well as frequency of vibrations. Due to high rotational speed there is unfavorable effect on MRR and $R_a$. |
| Stainless Steel AISI304 (non-magnet) | SiC | Rotational speed: 250-1200 rpm, Excitation current: 0.5-2 A, Frequency of vibration: 2-6 Hz, Magnetic flux density: 0.34 – 0.68 T, Abrasive particle mesh size: 10.13-25.33 μm, Ferromagnetic material: 152 μm and Working | Surface finishing | The main input parameters during finishing of workpiece are MAPs as well as frequency of vibrations. Due to high rotational speed there is unfavorable effect on MRR and $R_a$. |
Stainless steel (SS304)  
SiC, Al₂O₃ and diamond paste  
Rotational speed: 200-600 rpm, Magnetic flux density: 0.4-0.8 T, Abrasive weight: 20-30 % and Abrasive mesh number: 400-1200  
Rₐ change up to 89.6% and 56 nm of surface finish in this experiment. Magnetic flux density is the most effective parameter followed by Rotational Speed for surface finishing. They use same magnetic pole (N-N).

Stainless steel (AISI 440C)  
SiC, Al₂O₃ and diamond paste  
Workpiece Rot. speed: 250-500 rpm and Working gap: 1 mm  
Rₐ and MRR Input parameter had significant effect on Rₐ according to the ANOVA. With abrasive tool, diamond paste at 2mm working gap and 355 rpm Rotational speed Rₐ obtained is 0.207 µm.

Brass  
SiC, Al₂O₃  
Rotational speed: 500-2050 rpm and Time: 45-180 sec  
Edge finishing, Surface finishing  
Rₐ decrease from 9.6 µm to 0.24 µm. The critical factor which affect MRR in dry and wet finishing process are cutting machinability of the work surface and chemical reaction respectively. Decrement of burr height as well as enhancement in hole edge grade can be obtained by deburring operation. Deburring time is the major component to percentage decrement of burr height.

Brass  
SiC  
Rot. speed of magnet: 100-200 rpm, Abrasive mesh size: 80-160, Working gap: 6.8-12 mm and Deburring time: 360-1320 sec  
Burr height of workpiece  
Rₐ should not exceed 0.3 µm after surface finishing. Finishing the different variety of materials, MAF experiment set-up was made.

Aluminum Alloy, Stainless Steel, Brass  
Al₂O₃, Titanium Chloride (TiC)  
Rotational speed: 1120 rpm and Time: 120 sec  
MRR, Surface finishing  
The ECM and MAF processes must collaborate to enhance surface quality. As compared to surface quality EMAF process is better than MAF process. Rₐ decrease from 1.3 µm to 0.24 µm with EMAF process.

AL 6061  
SiC (unbounded abrasive)  
Rotational speed: 400-2000 rpm, Current: 20 A, Voltage: 12V, Working gap: 2 mm, Pulse frequency: 5 KHz and Machining time: 600 sec  
Surface quality, MRR  
6. Conclusions
In this review paper, it is theoretically analyzed that the impact of various processing parameters such as rotational speed of electromagnet, working gap, flux density of magnetic, voltage and abrasive particles size on MRR and Rₐ in MAM process. In this article, an overview on critical parameters and application of MAM process during machining of advanced engineering material has also been given. Based on the above discussion following conclusion are made from the present work:
1. It has been concluded that, voltage and rotational speed of electromagnet are observed to be the effective parameters thereafter size of abrasive particles, magnetic flux density and working gap.
2. It is found that during studying of two abrasive particles Sic and Al₂O₃ on MAM process, Sic gives better surface finish than Al₂O₃.

3. Surface finish increases with the increments in abrasive particle size, voltage, rotational speed of electromagnet and magnetic flux density but due to the decrease in working gap, surface finish increases.

4. It has also been concluded that there is measurable increase in surface finishing with increment of electrolyte current.

5. It has been debated that, magnetic force is influenced by the shape, size of the workpiece, working gap and composition of magnetic abrasives particles during MAM process.

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