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Experimental Investigations of the Process Parameters in the Magnetic Assisted Abrasive Flow Machining

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Abstract- **The non-conventional machining is the present demand of the time in advanced finishing of complex and hard components in minimum time duration with superior accuracy which is not possible with conventional machining. Magnetically assisted abrasive flow machining has the potential to finish tough and hard components in the field of automobiles, aerospace and medical. Present research work focuses on the optimizing the process parameters for Al/SiC/B_4C metal matrix composites (MMCs) using magnetically assisted abrasive flow machining process. The process parameters used such as extrusion pressure, magnetic flux density, no. of cycles etc. and the experiments conducted using Taguchi's L27 Orthogonal array. ANOVA technique used to predict the relative significance of the process parameters and their contribution level. The magnetic field and extrusion pressure were turned out to be highly significant factors affecting surface roughness (R_a) and MRR. Microstructure analysis carried out using Scanning Electron Microscope (SEM). The present research work shows flexibility based on the product application could be validated.**

Index Terms: **Magnetically Assisted Abrasive Flow Machining (MAFM), Material Removal Rate (MRR), Surface roughness (R_a), Response surface methodology (RSM), Metal matrix composites (MMCs).**

1. INTRODUCTION

MAFM is a process to finish the hard and complex geometry profiles with superior finishing and accuracy. High quality and limited dimensional tolerance parts utilized in the aircraft, automobile, and shipbuilding industries require excellent surface finish. Conventional methods like filling, lapping, honing, super finishing, grinding, polishing and buffing are used to modify the surface texture produced by manufacturing process [1-2].

Abrasive flow machining (AFM) process came into existence in 1960. It is used for finishing internal or external surfaces which are complex in shape and geometry. It patented by extrude hone corporation in 1970. It is widely used in different industries. The major applications of AFM are found in inner finishing of turbo engines, aerospace and tool engineering. It also found applications in edge rounding, de-burring and finishing diesel motor components of rail. The application of AFM on these components showed the improvement of R_a from 2 µm to 0.2 µm within 2 minutes [3]. To further optimize the finishing operation unconventional machining process like MAFM is gaining attention due to their ability to supply better surface finish than the conventional processes. MAFM is a process in which a magnetic flux is used as a machining force. This force directs the abrasive particles towards the target surface. The efficiency of the method is controllable by the electrical current to stop the over-finishing of surface roughness with careful monitoring of the process [4].

Therefore, MAFM has been used for accuracy of surface finishing due to many advantages like self-adaptability, controllability and self-sharpening [5]. Wani et. al. [6] studied the effect of varied magnetic field around the workpiece and found that using MAFM, the MRR increased and the surface roughness decreased. Sadiq et. al. [7] investigated MAFM process and found that using MAFM, the MRR increased upto 44% and the surface roughness decreased upto 83%.

MAFM process used for the aluminium workpieces helped in increasing MRR [8]. MAFM process was used in machining of AISI 1019 steel. The RSM technique with Box-Cox transformation was used. Mathematical modeling obtained for determining the cutting force and torque. It was found that the MAFM significantly improved the MRR and minimized the surface roughness [9]. Using MAFM on complex geometry, hard and tough workpieces, it was found that, the MRR maximized, surface roughness decreased [10].

The main purpose to use the magnetic field around the work piece is to enhance the material removal rate and surface finishing of the work piece. Research studies showed that the MAFM process significantly improved the surface finishing of Al/SiC MMCs and also increases the MRR [11].

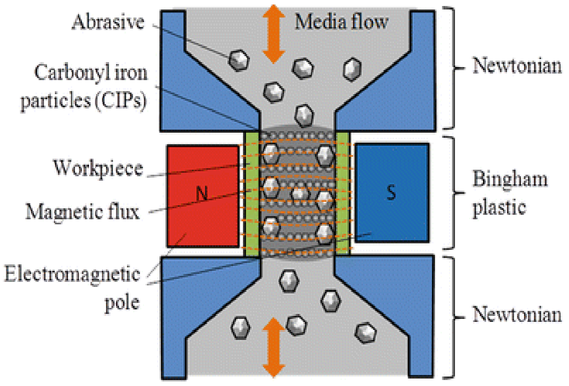

Fig. 1 MAFM process [12]

In MAFM process, the abrasive powder is fabricated by sintering mixture of iron and abrasive powder. The sintered mixture is crushed and sieved for getting suitable particle size. The lubricants also used for giving strength to the mixture [13].

The work done by several researchers signify the feasibility, effectiveness and economic aspect of MAFM in various

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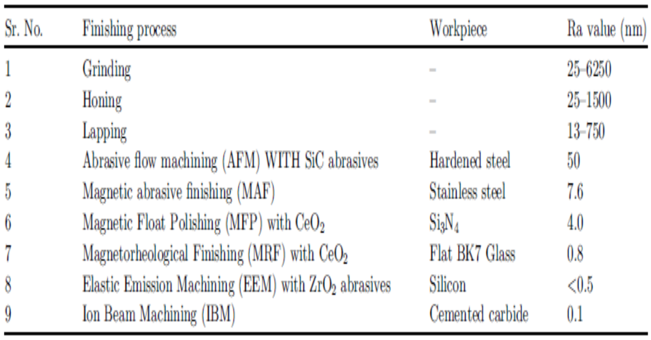
manufacturing domains. Ramesh babu et al. (1998) investigated the effect of varied input parameters on the surface quality of chrome steel workpiece. They observed roughness and hardness of the workpiece influencing the surface finish significantly [14]. Yamaguchi and Shinmura proposed an indoor magnetic abrasive finishing process for quality finishing of inner surface of the tubes. They observed surface texture is filled with micro-scratches and this feature exhibits that the MAFM process provides smoothing with high MRR [15].

It has been studied that different researchers had done experiment for understanding the results of different input parameters on surface finishing during MAFM 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 most features of the MAFM process to form 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 traditional grinding and super finishing method to elucidate the nano machining capabilities of MAFM process [16].

Table 1 Surface finish achievable with different finishing processes [17]



Sr. No.	Finishing process	Workpiece	Ra value (nm)
1	Grinding	-	25-6250
2	Honing	-	25-1500
3	Lapping	-	13-750
4	Abrasive flow machining (AFM) WITH SiC abrasives	Hardened steel	50
5	Magnetic abrasive finishing (MAF)	Stainless steel	7.6
6	Magnetic Float Polishing (MFP) with CeO_2	Si_3N_4	4.0
7	Magnetorheological Finishing (MRF) with CeO_2	Flat BK7 Glass	0.8
8	Elastic Emission Machining (EEM) with ZrO_2 abrasives	Silicon	<0.5
9	Ion Beam Machining (IBM)	Cemented carbide	0.1

Biing-Hwa et al. analyzed the principle and property of the unbounded MAPs on chrome steel (SUS 304) by cylindrical MAFM process. They explained how Ra and MRR are impact by the method 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 [17]. Biing et al. discussed the principle of electrolytic magnetic abrasive finishing (EMAF) in 2003. They also analyzed the impact of various process parameters with different range in R_a and MRR. This experimental result also shows that with a high electrolytic current EMAF process produces excellent finishing characteristics [18].

In 2004, Sing et al. conducted experiments on stainless steel during MAFM process using Taguchi design experiment and located the optimum input parameters. They explained how Ra is impact by input parameters namely voltage, revolution speed of the electromagnet, abrasive particles size and dealing gap. They also designed force transducer for inspection of the finishing process and fabricated to calculate the force during MAFM process [19].

In 2012, Yadava and Judal introduced a hybrid machining referred to as cylindrical electrochemical magnetic abrasive machining(C-EMAM), which is employed in cylindrical surface for effective surface finishing which is hard by other machining processes. Experiment was performed on self developed C-EAMM process setup of magnetic chrome steel (AISI-420) using unbounded MAPs. They explained the impact of process parameters on MRR and finishing. They also observed that for magnetic steel, R_a and MRR were influenced with the electro-chemical dissolution and magnetic abrasion respectively [20].

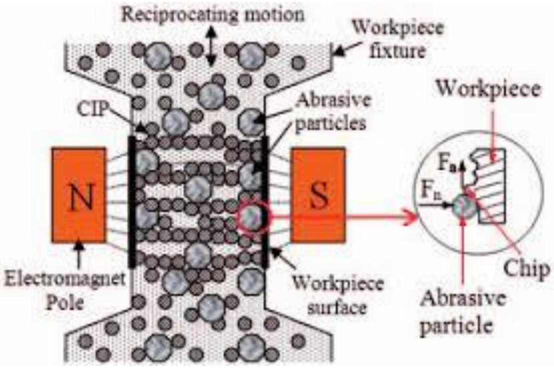


Fig. 2 MAFM Process [21]

Judal et al. designed and developed cylindrical MAFM setup to supply high grade of surface finish quality which are needed on advanced manufacturing industries. They explained how current on electromagnet influenced the magnetic flux . during this experiment they also studied the effect of main critical parameters which effect on the finishing quality. Ra decrease from 1.3 µm to 0.24 µm after machining process in their experiment. They observed that to enhance the finishing quality, magnetic poles are rotated [21].

Chahal et al. [22] investigated the abrasive flow machining of Al-6061 alloy assisted with the electrochemical machining. The Al_2O_3 abrasive particles, silicon based polymer, hydrocarbon gel and sodium iodide as electrolyte solution were used for machining Al-6061 alloy work piece. The mathematical modeling was conducted using Taguchi L27 orthogonal array and ANOVA techniques. The experiments were conducted using process parameters such as number of cycles, abrasive concentration and diameter of rod. It was found that the surface finishing of the Al-6061 alloy was considerably increased after abrasive flow machining. The MRR was found increased with increase in the abrasive concentration. It was also recommended to use hybrid abrasive flow machining to finish complex geometrical shapes for obtaining the super finishing.

Shabgard et al. [23] reported the magnetic assisted abrasive flow machining of H13 tool steel. The cutting tool used was SiC, Al_2O_3 abrasive particles with hydraulic oil. The mathematical modeling was conducted using the ANOVA and regression model technique. The magnetic field intensity and the number of abrasive particles were increased during the experimentation. It was found that the increase in the magnetic field intensity and number of abrasive particles increases MRR and surface finishing of the H13 tool steel. It was recommended that the magnetic assisted abrasive flow machining should be used for finishing harder materials. Mittal et al. [24] investigated the machining of MMCs using AFM process and found that surface defects in the inner and outer sides were successfully removed after AFM process.

2. EXPERIMENTATION

The machining/finishing of the material is a very important part of the manufacturing process. The selection of the appropriate machines, materials and input parameters is necessary to obtain optimal solution of the research problem. Metal Matrix Composites (MMCs) such as Al/SiC/B_4C are taken for experimentation. In the experimentation, the input parameters are changed to observe their effect on the MRR and R_a. On the basis of the outcomes of the experimentation, the process parameters with their levels are finalized. L27 Orthogonal array has been used for the experimentation. Taguchi method/ANOVA technique used for obtaining significance of the process parameters.

PROCESS PARAMETERS

In the present research, the following process parameters are selected for experimentation:

- i) Magnetic Flux Density.
- ii) Workpiece material.
- iii) No. of cycles.
- iv) Extrusion pressure.
- v) Mesh number.
- vi) Concentration of abrasives.

RESPONSE PARAMETERS

In the present research, the following process parameters are selected for experimentation:

- i) Material Removal Rate (MRR).
- ii) Surface Roughness (Ra).

EXPERIMENTAL SETUP

Magnetic Abrasive Flow Machining (MAFM) setup has designed and developed in the laboratory in such a way that the process parameters can be varied as per the process requirements.

Components of Experimental setup

The various components of experimental setup are as following:

- i) Electromagnets.
- ii) Media cylinders and pistons.
- iii) Workpiece fixtures.
- iv) Hydraulic unit.

Electromagnets

The primary job of an electromagnet is to produce the magnetic field by using an electric current. Electromagnet poles are used on the left and right side of the workpiece. Electromagnets are designed and placed in such a way that to provide the maximum magnetic field around the workpiece. The main advantage of the electromagnet over permanent magnet is that the intensity of the magnetic field can be changed in case of electromagnets. The poles of electromagnets can be reversed by reversing the flow of the electricity. The magnetic field created by the electromagnet is proportional to NI where N = No. of turns in the winding and I is the current in the wire. In the present research, the intensity of the magnetic field can be varied from 0.2 to 1 Tesla.

Media cylinders and pistons

The objective of the media cylinders is to guide the piston and containing the sufficient media for operation. The reciprocating movement of the piston inside the cylinder moves the abrasive particles and oil through the inside of the workpiece surface.

The volume of cylinders = 350 cc
Maximum permissible pressure = 10 MPa.
Cylinder material = EN8.

Properties of EN8 material

- i) Medium carbon steel.
- ii) Tensile strength.

Table 2: Chemical Composition of EN8

Carbon	0.36 - 0.44 %
Silicon	0.10 - 0.40 %
Manganese	0.60 - 1 %
Sulphur	0.050 max
Phosphorus	0.050 max

Piston material = Grey cast iron.
Stroke length = 250 mm.
Piston diameter = 90 mm.

Workpiece fixtures

The workpiece fixtures holds significant role in the machining process for holding the workpiece. Nylon fixture has been taken to hold the workpiece through a slot which is cut through the nylon fixture. To decrease the machining vibrations, the diameter is gradually decreased in the nylon fixture.

Hydraulic Unit

Hydraulic unit is designed to withstand the pressure upto the limit of 10 MPa. The various components of the hydraulic unit are as following:

- i) Hydraulic cylinders.
- ii) Hydraulic gear pump.
- iii) Direction control (DC) valves.
- iv) Pressure relief (PR) valves.
- v) Hydraulic tank.
- vi) Pressure gauges.

Fig. 3 Experimental Setup for Magnetic Abrasive Flow Machining (MAFM)

Experimentation is done using L27 orthogonal array. Workpiece material has been taken as Al/SiC/B_4C hybrid MMC (10, 20, 30 percent SiC and 3, 5 and 7 percent B_4C in Al as base material). Input parameters such as workpiece material, magnetic flux density, no. of cycles, extrusion pressure, grain size, concentration of abrasives were altered at three levels each to obtain their effect on the output parameters. The deviations in the results were minimized by taking three readings for each run. The significance and % contribution of input parameters were established. Experimental setup has been shown in Fig. 3 and the machined workpieces with Magnetic Abrasive Flow Machining (MAFM) have been shown in Fig. 4.

Fig. 4 Machined workpieces with MAFM

Fig. 5 Prepared abrasive putty

MATERIALS

Workpiece material has been taken as Al/SiC/B_4C hybrid MMC (10, 20, 30 percent SiC and 3, 5 and 7 percent B_4C in Al as base material). Specimens are prepared using micro EDM and then machined using Magnetic abrasive flow machining (MAFM).

Table 3: Percentage composition of materials

Workpiece 1	10% SiC and 3% B_4C in Al/SiC/B_4C
Workpiece 2	20% SiC and 5% B_4C in Al/SiC/B_4C
Workpiece 3	30% SiC and 7% B_4C in Al/SiC/B_4C

In the experimentation, one factor at a time approach is used for studying the effect of process parameters such as workpiece material, magnetic flux density, no. of cycles, extrusion pressure, mesh number of abrasives, concentration of abrasives on the MRR and Surface roughness.

EFFECT OF PROCESS PARAMETERS

Effect of process parameters on MRR

Magnetic Flux Density

Fixing other parameters as constant, the magnetic flux density is increased from 0.2 to 1 Tesla. From the plot, it has been observed that MRR increases with increase in the magnetic flux density as shown in the fig. 6. It is also observed that the slope of the curve gets decreased gradually at 0.6 T and keep on decreasing upto 1 T. This is due to the fact that, initially, the total peaks on the workpiece surface were more. The greater are the no. of peaks on the workpiece, greater will be the MRR. As the surface is subjected to repeated cycles, there occurs decrease in the no. of peaks and their respective heights on the workpiece surface. So, the MRR decreases after the certain value of magnetic flux density.

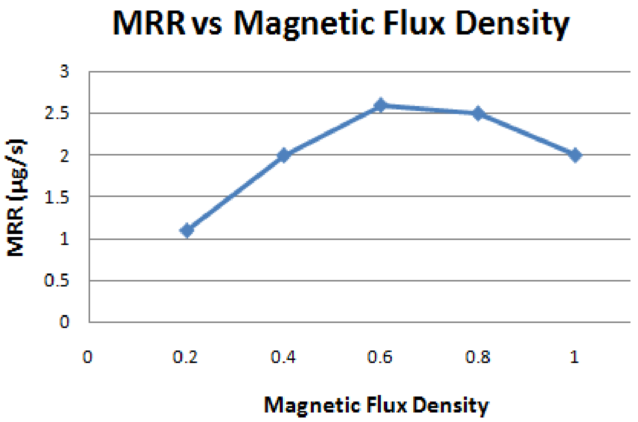


Fig. 6 Effect of the Magnetic Flux Density on MRR, at the concentration of abrasives = 55%, no. of cycles = 200, workpiece material (SiC % and B_4C %) = 20 and 5, mesh number = 150, extrusion pressure = 5 MPa.

Workpiece Material

Workpiece material has been taken as Al/SiC/B_4C hybrid MMC (10, 20, 30 percent SiC and 3, 5 and 7 percent B_4C in Al as base material). Specimens are prepared using micro EDM and then machined using Magnetic abrasive flow machining (MAFM). With the increasing percentage of SiC (10-30) and B_4C (3-7) in the Al/SiC/B_4C MMCs, the MRR gets decreased as shown in the fig. 7 and 8. This is because due to the addition of SiC and B_4C in the workpiece, the workpiece gets harder. So, the MRR decreases with increase in the hardness of the material.

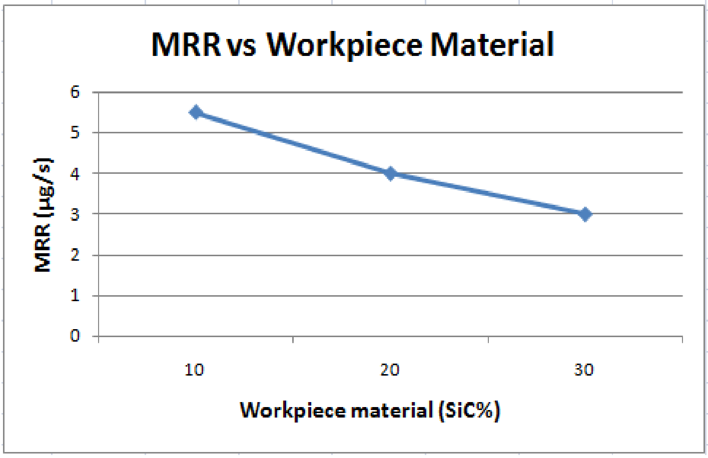


Fig. 7 Effect of the Workpiece material (SiC%) on MRR, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, no. of cycles = 200, mesh number of abrasives = 150, extrusion pressure = 5 MPa.

Number of cycles

With the increase in the number of cycles, the MRR also increases as shown in the fig. 9, but when the number of cycles reached at 300, the MRR began to decrease because after 300 cycles, the peaks and valleys are lesser to be finished on the workpiece. Hence, it can be concluded that MRR varies non-linearly with number of cycles. Because, initially more number of peaks and valleys to be finished but in the later stage, most of the peaks and valleys gets disappeared, thus, MRR gets decreased with increase in the number of cycles.

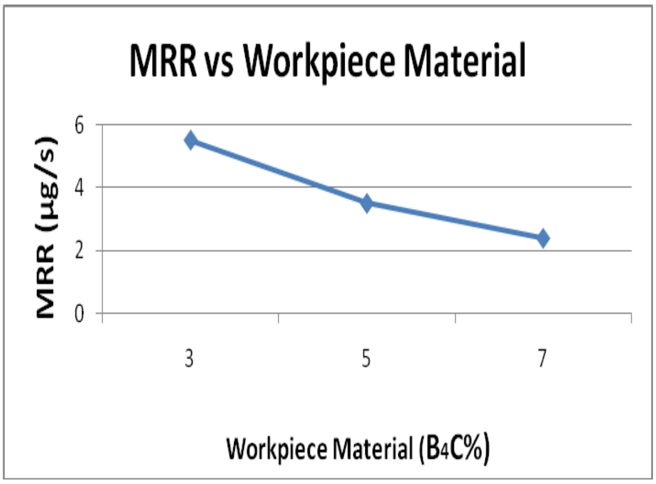


Fig. 8 Effect of the Workpiece material (B_4C%) on MRR, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, no. of cycles = 200, mesh number of abrasives = 150, extrusion pressure = 5 MPa.

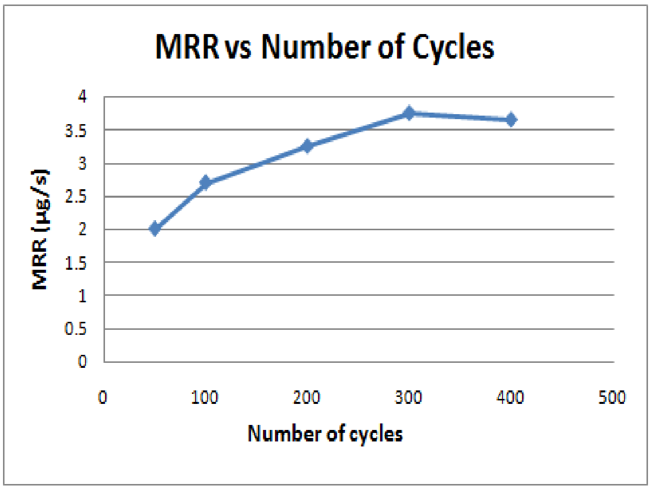


Fig. 9 Effect of number of cycles on MRR, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, workpiece material (SiC % and B_4C %) = 20 and 5, mesh number of abrasives = 150, extrusion pressure = 5 MPa

Extrusion Pressure

Extrusion pressure is varied from 2 to 10 MPa. It was observed from the fig. 10 that the MRR increases with increase in the extrusion pressure. At the extrusion pressure of 7 MPa, the MRR decreases, because at 7 MPa and onwards, the active grain density decreases. The active grain density increases with increase in the extrusion pressure upto 7 MPa but after 7 MPa, the active grain density decreases.

Mess number of Abrasives

It has been observed from the fig. 11 that MRR decreases with increase in the mess number of abrasives. The grit size decreases with increase in the mesh number. So, MRR decreases with decrease in the grit size because area of penetration of grit decreases with decrease in the grit size. So, volume of material removed decreases.

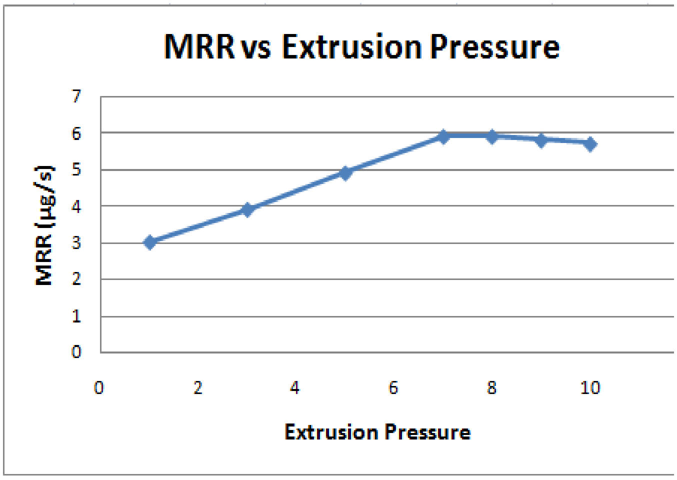


Fig. 10 Effect of Extrusion pressure on MRR, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, workpiece material (SiC % and B_4C %) = 20 and 5, no. of cycles = 200, mesh number of abrasives = 150.

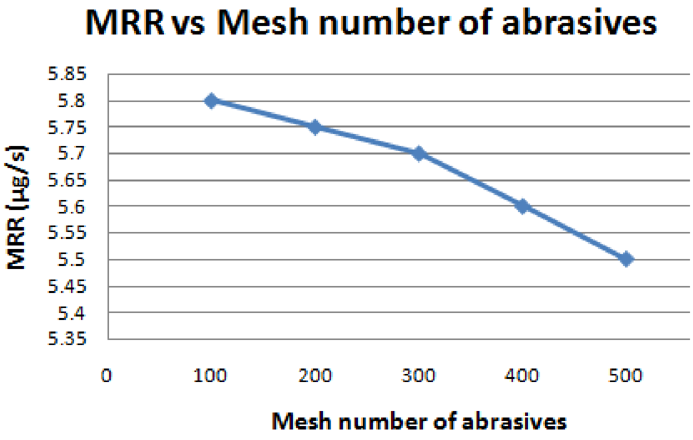


Fig. 11 Effect of Mesh number of abrasives on MRR, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, workpiece material (SiC % and B_4C %) = 20 and 5, no. of cycles = 200, extrusion pressure = 5 MPa

Concentration of Abrasives

MRR increases with increase in the concentration of abrasives as shown in the fig. 12. This is due to the fact that, high number of abrasive particles in the medium results in the more number of particles to come in contact with the workpiece surface which results in the increase in the cutting force.

Effect of process parameters on ΔR_a

Magnetic Flux Density

Fixing other parameters as constant, the magnetic flux density is increased from 0.2 to 1 Tesla. From the plot, it has been observed that ΔR_a increases with increase in the magnetic flux density as shown in the fig. 13. This is due to the fact that, when magnetic flux density increases, more number of peaks get disappeared or dissolved, thus, ΔR_a increases. It is also observed that the slope of the curve gets decreased gradually at 0.6 T. As the surface is subjected to repeated cycles, there occurs decrease in the no. of peaks and their respective heights on the workpiece surface. So, the ΔR_a decreases after the certain value of magnetic flux density.

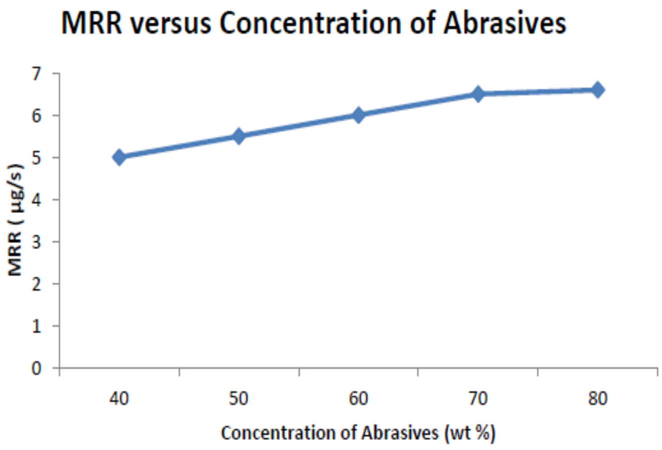


Fig. 12 Effect of concentration of abrasives on MRR, at the magnetic flux density = 0.4T, workpiece material (SiC % and B_4C %) = 20 and 5, no. of cycles = 200, extrusion pressure = 5 MPa, mesh number of abrasives = 150.

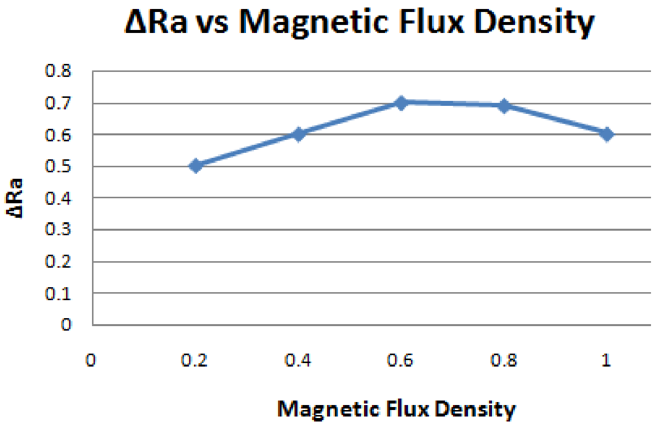


Fig. 13 Effect of Magnetic Flux Density on ΔR_a, at concentration of abrasives = 55%, workpiece material (SiC % and B_4C %) = 20 and 5, no. of cycles = 200, mesh number of abrasives = 150, extrusion pressure = 5 MPa.

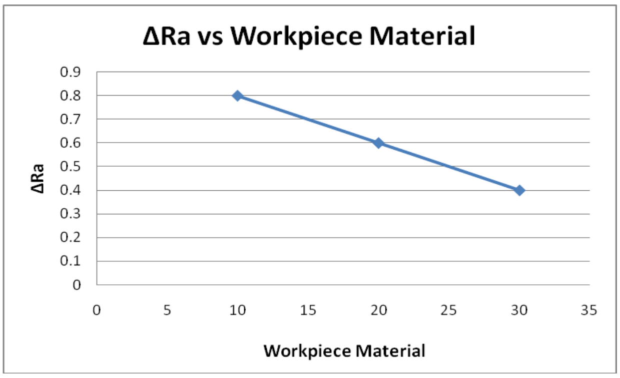


Fig. 14 Effect of the Workpiece material (SiC%) on ΔR_a, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, no. of cycles = 200, mesh number of abrasives = 150, extrusion pressure = 5 MPa.

Workpiece Material

Workpiece material has been taken as Al/SiC/B_4C hybrid MMC (10, 20, 30 percent SiC and 3, 5 and 7 percent B_4C in Al as base material). Specimens are prepared using micro EDM and then machined using Magnetic abrasive flow machining (MAFM). With the increasing percentage of SiC (10-30) and B_4C (3-7) in the Al/SiC/B_4C MMCs, the ΔR_a gets decreased as shown in the fig. 14 and 15. This is because due to the addition of SiC and B_4C in the workpiece, the workpiece gets harder. So, the ΔR_a decreases with increase in the hardness of the material.

Number of cycles

With the increase in the number of cycles, the ΔR_a also increases as shown in the fig. 16, but when the number of cycles reached at 300, the ΔR_a began to decrease because after 300 cycles, the peaks and valleys are lesser to be finished on the workpiece. Hence, it can be concluded that ΔR_a varies non-linearly with number of cycles. In the starting, ΔR_a increases with increase in the number of cycles because initially there are more number of peaks and valleys to be finished but in the later stage, most of the peaks and valleys gets disappeared, thus, ΔR_a gets decreased with increase in the number of cycles.

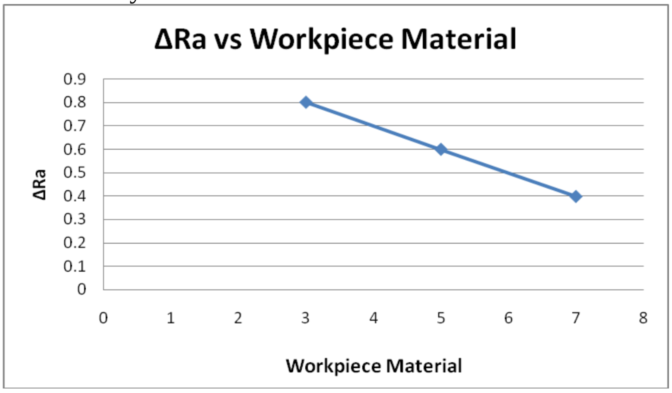


Fig. 15 Effect of the Workpiece material (B_4C%) on ΔR_a, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, no. of cycles = 200, mesh number of abrasives = 150, extrusion pressure = 5 MPa.

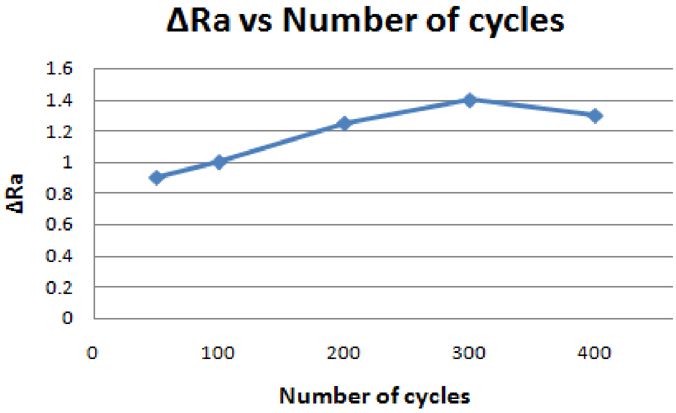


Fig. 16 Effect of the Number of cycles on ΔR_a, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, mesh number of abrasives = 150, workpiece material (SiC % and B_4C %) = 20 and 5, extrusion pressure = 5 MPa.

Extrusion Pressure

Extrusion pressure is varied from 2 to 10 MPa. It was observed from the fig. 17 that ΔR_a increases with increase in the extrusion pressure. At the extrusion pressure of 7 MPa, the ΔR_a decreases, because at 7 MPa and onwards, the active grain density decreases. The active grain density increases with increase in the extrusion pressure upto 7 MPa but after 7 MPa, the active grain density decreases.

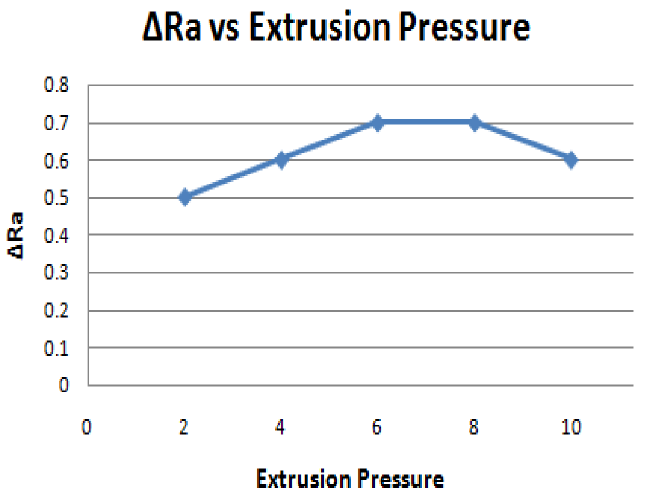


Fig. 17 Effect of the Number of cycles on ΔR_a, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, mesh number of abrasives = 150, workpiece material (SiC % and B_4C %) = 20 and 5, no. of cycles = 200.

Mess number of Abrasives

It has been observed from the fig. 18 that ΔR_a decreases with increase in the mess number of abrasives. The grit size decreases with increase in the mesh number. So, ΔR_a decreases with decrease in the grit size because area of penetration of grit decreases with decrease in the grit size. So, volume of material removed decreases.

Concentration of Abrasives

ΔR_a increases with increase in the concentration of abrasives as shown in the fig. 19. This is due to the fact that, high number of abrasive particles in the medium results in the more number of particles to come in contact with the workpiece surface which results in the increase in the cutting force.

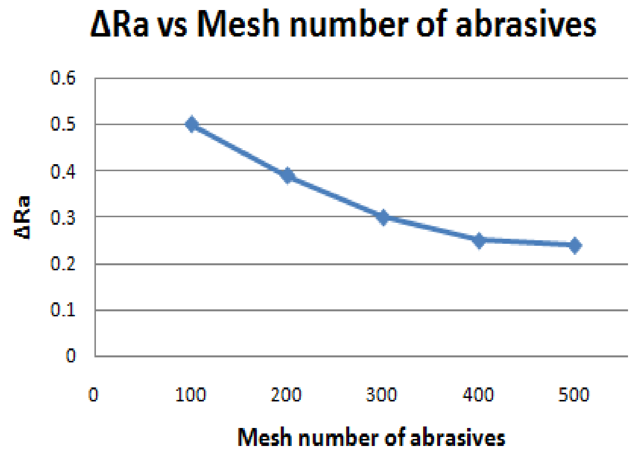


Fig. 18 Effect of the Number of cycles on ΔR_a, at the magnetic flux density = 0.4T, concentration of abrasives = 55%, extrusion pressure = 5 MPa, workpiece material (SiC % and B_4C %) = 20 and 5, no. of cycles = 200.

3. Selection of Process/Input Parameters

The Taguchi method has been adopted for the experimentation, the process/input parameters are finalized with their levels as shown in the Table 4.

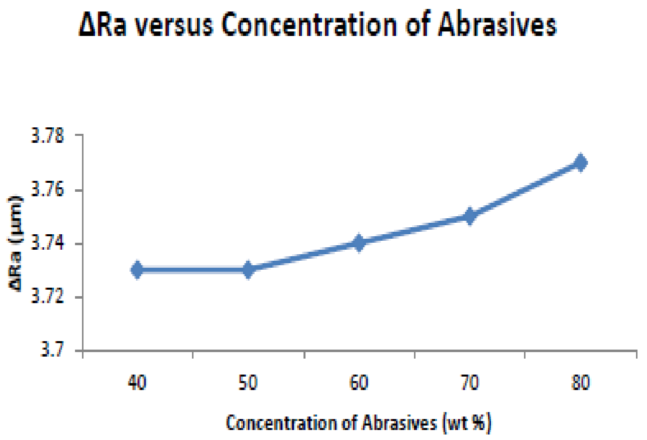


Fig. 19 Effect of the Concentration of abrasives on ΔR_a, at the magnetic flux density = 0.4T, extrusion pressure = 5 MPa, workpiece material (SiC % and B_4C %) = 20 and 5, mesh number of abrasives = 150, no. of cycles = 200.

Table 4 Process Parameters with levels

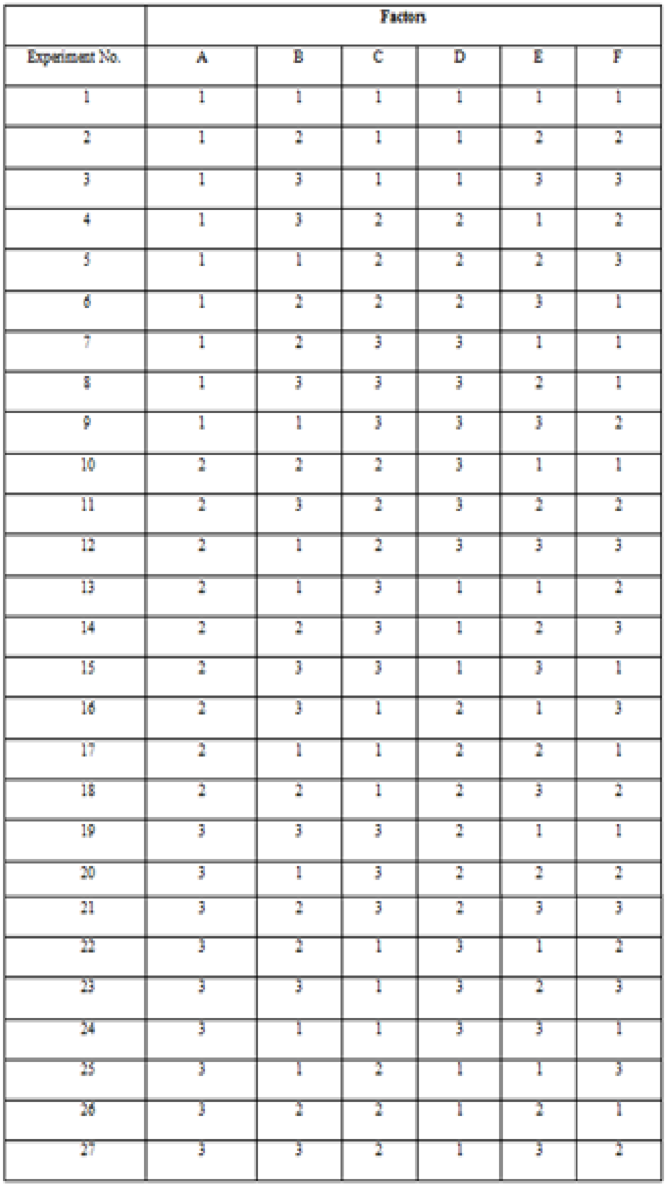
Symbol	Factors	Level 1	Level 2	Level 3
A	Magnetic Flux Density (T)	0.2	0.4	0.6
B	Workpiece Material (percentage of SiC in Al/SiC/B_4C)	10	20	30
	Workpiece Material (percentage of B_4C in Al/SiC/B_4C)	3	5	7
C	Number of Cycles	100	200	300
D	Extrusion pressure (MPa)	3	5	7
E	Mesh Number	100	150	200
F	Concentration of abrasives (weight %age of abrasives)	50	55	60

In the present research, total six process parameters are selected. The selected process parameters have three levels each and the degree of freedom of three levels factor is 2, so, total degree of freedom for experiments is 12. As we know that, degree of freedom of selected orthogonal array must be greater or equal to the total degree of freedom for that experiment. So, Taguchi's method with L27 Orthogonal array has been selected as shown in the Table 5.

4. Analysis of Variance (ANOVA)

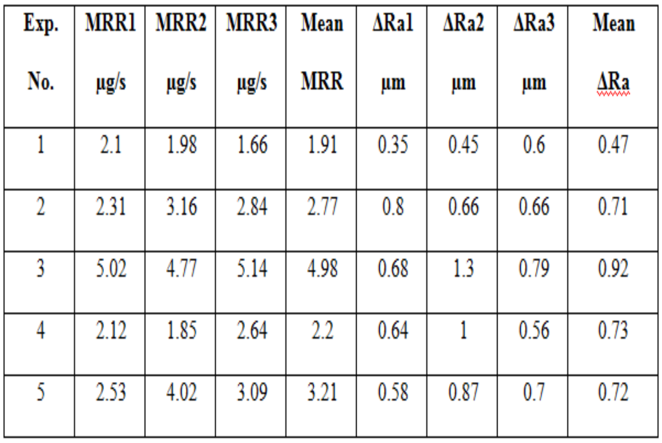
ANOVA is a collection of statistical models and their associated estimation procedures (such as the "variation" among and between groups) used to analyze the differences among group means in a sample. ANOVA was developed by statistician Ronald Fisher. An ANOVA test is a way to find out if survey or experiment results are significant. In other words, they help us to figure out if we need to reject the null hypothesis or accept the alternate hypothesis. ANOVA method is used to check the significance of the process/input parameters. ANOVA is used to establish whether the process/input parameters have any significance on the response/output parameters.

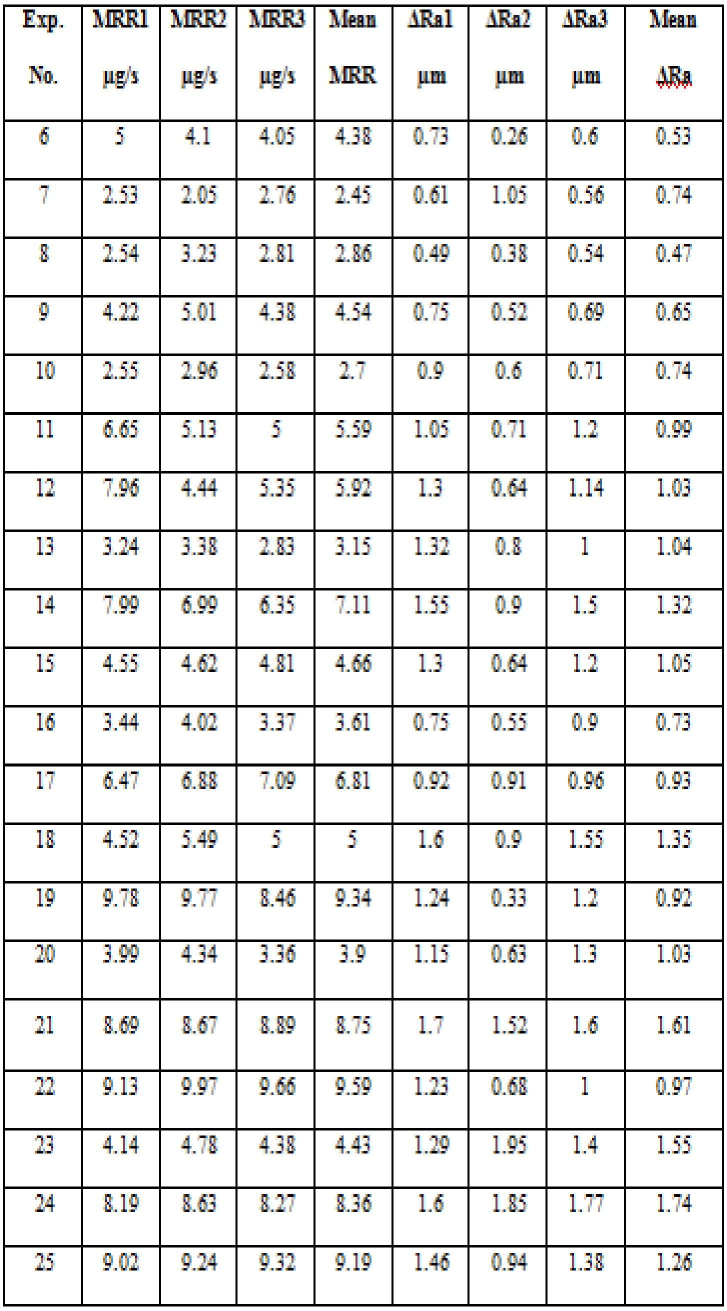
Table 5: L27 Orthogonal array



	Factors					
Experiment No.	A	B	C	D	E	F
1	1	1	1	1	1	1
2	1	2	1	1	2	2
3	1	3	1	1	3	3
4	1	3	2	2	1	2
5	1	1	2	2	2	3
6	1	2	2	2	3	1
7	1	2	3	3	1	1
8	1	3	3	3	2	1
9	1	1	3	3	3	2
10	2	2	2	3	1	1
11	2	3	2	3	2	2
12	2	1	2	3	3	3
13	2	1	3	1	1	2
14	2	2	3	1	2	3
15	2	3	3	1	3	1
16	2	3	1	2	1	3
17	2	1	1	2	2	1
18	2	2	1	2	3	2
19	3	3	3	2	1	1
20	3	1	3	2	2	2
21	3	2	3	2	3	3
22	3	2	1	3	1	2
23	3	3	1	3	2	3
24	3	1	1	3	3	1
25	3	1	2	1	1	3
26	3	2	2	1	2	1
27	3	3	2	1	3	2

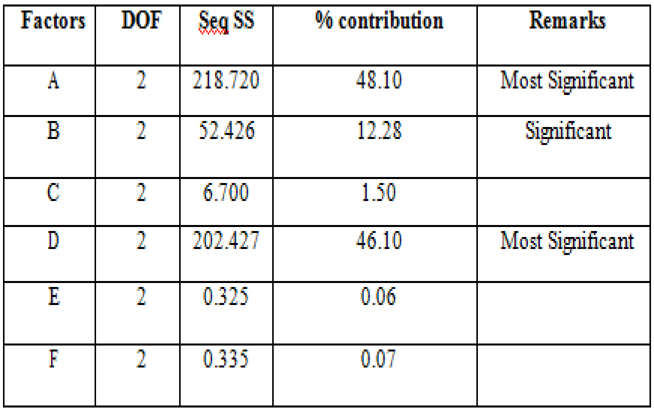
Table 6: Observation table for MRR and ΔRa, after each experiment





Exp. No.	MRR1 µg/s	MRR2 µg/s	MRR3 µg/s	Mean MRR	ΔRa1 µm	ΔRa2 µm	ΔRa3 µm	Mean ΔRa
1	2.1	1.98	1.66	1.91	0.35	0.45	0.6	0.47
2	2.31	3.16	2.84	2.77	0.8	0.66	0.66	0.71
3	5.02	4.77	5.14	4.98	0.68	1.3	0.79	0.92
4	2.12	1.85	2.64	2.2	0.64	1	0.56	0.73
5	2.53	4.02	3.09	3.21	0.58	0.87	0.7	0.72
6	5	4.1	4.05	4.38	0.73	0.26	0.6	0.53
7	2.53	2.05	2.76	2.45	0.61	1.05	0.56	0.74
8	2.54	3.23	2.81	2.86	0.49	0.38	0.54	0.47
9	4.22	5.01	4.38	4.54	0.75	0.52	0.69	0.65
10	2.55	2.96	2.58	2.7	0.9	0.6	0.71	0.74
11	6.65	5.13	5	5.59	1.05	0.71	1.2	0.99
12	7.96	4.44	5.35	5.92	1.3	0.64	1.14	1.03
13	3.24	3.38	2.83	3.15	1.32	0.8	1	1.04
14	7.99	6.99	6.35	7.11	1.55	0.9	1.5	1.32
15	4.55	4.62	4.81	4.66	1.3	0.64	1.2	1.05
16	3.44	4.02	3.37	3.61	0.75	0.55	0.9	0.73
17	6.47	6.88	7.09	6.81	0.92	0.91	0.96	0.93
18	4.52	5.49	5	5	1.6	0.9	1.55	1.35
19	9.78	9.77	8.46	9.34	1.24	0.33	1.2	0.92
20	3.99	4.34	3.36	3.9	1.15	0.63	1.3	1.03
21	8.69	8.67	8.89	8.75	1.7	1.52	1.6	1.61
22	9.13	9.97	9.66	9.59	1.23	0.68	1	0.97
23	4.14	4.78	4.38	4.43	1.29	1.95	1.4	1.55
24	8.19	8.63	8.27	8.36	1.6	1.85	1.77	1.74
25	9.02	9.24	9.32	9.19	1.46	0.94	1.38	1.26

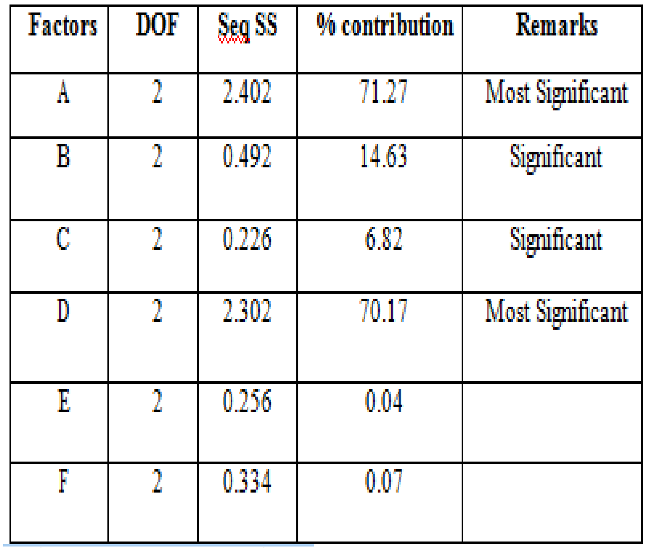
Table 7: ANOVA for MRR



Factors	DOF	Seq SS	% contribution	Remarks
A	2	218.720	48.10	Most Significant
B	2	52.426	12.28	Significant
C	2	6.700	1.50	
D	2	202.427	46.10	Most Significant
E	2	0.325	0.06	
F	2	0.335	0.07	

R^2 = 98.172% *R^2 = 98.13%*
R^2 (adj.) = 52.64 *R^2 (adj.) = 51.40*
R^2 (pred.) = 0.00 *R^2 (pred.) = 0.00*

Table 8: ANOVA for ΔR_a



Factors	DOF	Seq SS	% contribution	Remarks
A	2	2.402	71.27	Most Significant
B	2	0.492	14.63	Significant
C	2	0.226	6.82	Significant
D	2	2.302	70.17	Most Significant
E	2	0.256	0.04	
F	2	0.334	0.07	

R^2 = 98.172% *R^2 = 98.13%*
R^2 (adj.) = 52.64 *R^2 (adj.) = 51.40*
R^2 (pred.) = 0.00 *R^2 (pred.) = 0.00*

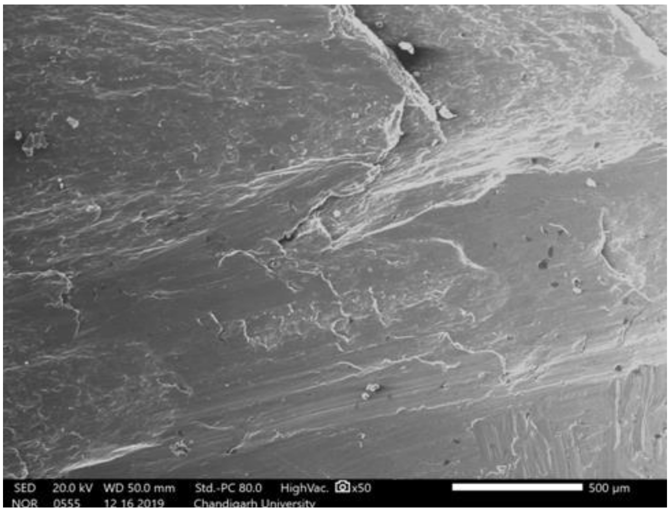


Fig. 20 SEM image before machining

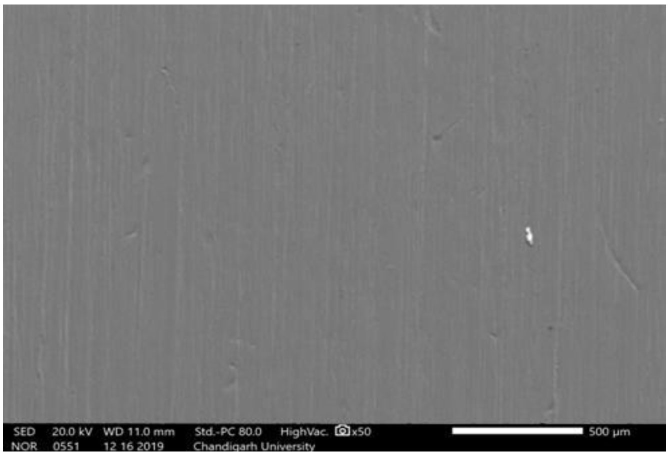


Fig. 21 SEM image after machining

CONCLUSIONS

Based on the experimental results, following results are concluded:

1. MAFM is a process which is used to finish the workpieces machined with EDM process.
2. Using ANOVA technique, it was found that Magnetic flux density and extrusion pressure are the most significant factors in MAFM process. MRR and ΔRa both increases with increase in extrusion pressure.
3. It was observed that MRR increases with increase in the magnetic flux density. As the surface is subjected to repeated cycles, there occurs decrease in the no. of peaks and their respective heights on the workpiece surface. So, the MRR decreases after the certain value of magnetic flux density.
4. It was observed that ΔR_a increases with increase in the magnetic flux density. This is due to the fact that, when magnetic flux density increases, more number of peaks get disappeared or dissolved, thus, ΔR_a increases. It was also observed that the slope of the curve gets decreased gradually at 0.6 T. As the surface is subjected to repeated cycles, there occurs decrease in the no. of peaks and their respective heights on the workpiece surface. So, the ΔR_a decreases after the certain value of magnetic flux density.
5. With the increasing percentage of SiC (10-30) and B_4C (3-7) in the Al/SiC/B_4C MMCs, the MRR gets decreased. This is because due to the addition of SiC and B_4C in the workpiece, the workpiece gets harder. So, the MRR decreases with increase in the hardness of the material.
6. It can be concluded that ΔR_a varies non-linearly with number of cycles, because initially there are more number of peaks and valleys to be finished but in the later stage, most of the peaks and valleys gets disappeared, thus, ΔR_a gets decreased with increase in the number of cycles.
7. The SEM images showed that the defects on the surface that produced after μ-EDM process were successfully removed and significantly improving the surface finishing of the work piece.

8. From the present research, it is suggested that the MAFM process is suitable for finishing hybrid MMCs such as Al/SiC/B_4C.

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