WALAILAK JOURNAL

Applied Sciences

http://wjst.wu.ac.th https://doi.org/10.48048/wjst.2021.9885

Experimental Investigation of Process Parameters of Al-SiC-B_4C MMCs Finished by a Novel Magnetic Abrasive Flow Machining Setup

Gagandeep CHAWLA[1,*], Vinod Kumar MITTAL[1] and Sushil MITTAL[2]

[1]*Department of Mechanical Engineering, NIT, Kurukshetra, Haryana, India*
[2]*Department of Mechanical Engineering, Chandigarh University, Gharuan, Punjab, India*

([*]Corresponding author's e-mail: gagan1984mech@gmail.com)

Received: 17 April 2020, Revised: 20 March 2021, Accepted: 27 March 2021

Abstract

Abrasive flow machining (AFM) is one of the non-conventional finishing processes used to attain good surface quality and high material removal. However, limited attempts have been made to improve the performance of these processes. This paper presents a novel magnetic abrasive flow machining (MAFM) setup fabricated by adding a magnetization effect in which a nylon fixture and permanent magnets are replaced by a newly fabricated aluminium fixture and coil-type magnets, respectively. Inner cylindrical surfaces of hybrid Al/SiC/B_4C metal matrix composites (MMCs) are finished by the MAFM process. One variable at a time (OVAT) approach is used for studying the effect of 6 input parameters, extrusion pressure (E_p), the number of cycles (N), abrasives concentration (C), workpiece material (W_p), abrasive mesh size (M), and magnetic flux density (M_f) upon response parameters, material removal rate (MRR) and change in surface roughness (ΔRa). The experimental results obtained for MRR and ΔRa show a significant improvement from 3.92 to 7.68 µg/s and 0.49 to 0.74 µm, respectively due to the increase of the extrusion pressure from 1 to 9 Mpa. The MRR and ΔRa was reduced from 6.89 to 6.78 µg/s and 0.46 to 0.22 µm, respectively with an increase in mesh number of abrasives from 80 to 400. The variation in concentration of abrasives from 40 to 60 % shows an improvement in MRR from 4.51 to 6.42 µg/s; whereas, there is a negligible effect on ΔRa which comes out from 3.82 to 3.86 µm. The MMCs, which are used for the experimentation shows a decline in MRR and ΔRa from 5.12 to 3.85 µg/s and 0.77 to 0.42 µm, respectively. This happened because there was a percentage change of reinforcement of SiC from 9 to 7 % and B_4C from 1 to 3 % in Al-6063. An increase in the number of cycles from 50 to 250 shows a significant improvement in both MRR and ΔRa from 1.79 to 3.75 µg/s and 0.97 to 1.86 µm, respectively. Variation in magnetic effect also significantly improves MRR and ΔRa from 1.35 to 3.17 µg/s and 0.38 to 1.06 µm, respectively, when it is varied from 0.15 - 0.45 Tesla. The work carried out shows an overall significant improvement in MRR and ΔRa by using the MAFM process. The MAFM process finds a wide range of applications in finishing like surgical instruments, mechanical components, aerospace industry, electronics industry, etc.

Keywords: MAFM, OVAT, MRR, Al/SiC/B_4C-MMCs, ΔRa

Nomenclature

E_p	Extrusion pressure
N	Number of cycles
C	Abrasives concentration
W_p	Workpiece material
M	Abrasive mesh size
M_f	Magnetic flux density
MRR	Material removal rate

ΔRa	Change in surface roughness
MMC	Metal matrix composite
OVAT	One variable at a time approach
MAFM	Magnetic abrasive flow machining

Introduction

Achieving an improved surface finish for complex mechanical parts is a big concern in the manufacturing industries [1]. The cost of finishing operations is about 15 % of the total machining cost in the manufacturing cycle. In complex parts, conventional finishing methods like lapping, grinding, and honing, etc. are unable to finish multifaceted geometries and internal surfaces. Refining the surface quality of complex parts is very challenging. Hence, for obtaining the acceptable surface finish in the complex parts, AFM was introduced in the 1960s [2].

Abrasive media, machines, and tooling form the basic components of the AFM process. This process is mainly used to remove burrs and polish the surfaces by removing the material. The nature of AFM makes it suitable for interior surfaces, cavities, holes, and other areas that may be hard to reach with other polishing processes. Conventional AFM is flawed with low finishing rate as all the abrasive particles do not participate in material removal from the workpiece. As such, different models of AFM machines abbreviated as ultrasonic-assisted abrasive flow machining (UAAFM), centrifugal force assisted abrasive flow machining (CFAAFM), electro-chemical aided abrasive flow machining (ECAAFM) and rotational-abrasive flow finishing (R-AFF) have been proposed by various researchers to remove the irregularities like low finishing rate and inability to correct the form geometry [3]. In the present work, a modified AFM machine with a variable magnetic field generator arrangement is introduced and named as a magnetic abrasive flow machine (MAFM).

Rawangwong *et al.* [4] studied the effects of the key elements like speed, depth of cut and feed rate upon the surface roughness in aluminium semi-solid 2024 and revealed that surface roughness was mainly affected by feed rate and speed whereas there was no effect of depth of cut. Das *et al.* [5] performed simulation on achieving MR and Ra using the MRAFF process with magnetorheological polishing fluid (MRPF) and applying a magnetic field. Singh *et al.* [6] identified and optimized the magnetic-field-assisted AFM parameters that impact material removal by using the Taguchi method. Mamilla *et al.* [7] demonstrated the outcomes with response to a surface methodology and attained the best surface finish of 110 nm. The nano-finishing experiments were conducted on Al alloy/SiC (10 %) by preparing a media of SiC abrasive particles with a combination of soft styrene polymers and silicone polymers.

Mittal *et al.* [8] optimized the process variables using the Taguchi method. The study revealed that MRR and ΔRa were significantly affected by extrusion pressure. The AFM process was used to finish Al/SiC MMCs with a high proportion of SiC (20 to 60 %). Ghadikolaei *et al.* [9] used a hydro-mechanical device consisting of abrasive fluid containers, a power unit, a base frame, permanent magnets (Nd- Fe), and job fixtures. The study provided an experimental setup for investigating various parameters on surface roughness. The authors used the MRAFF process for conducting the experiments on aluminium (7075 alloys), copper (unalloyed), and austenitic stainless steel (AISI304) with different values of abrasive particle size, magnetic field strength, and finishing time cycles. It was reported that the surface roughness was decreased by decreasing the magnetic field strength while it was higher when the mesh number was increased.

Das *et al.* [10] analyzed the effects of parameters on finishing performance using a response surface regression analysis and reported a significant influence of rotational speed on surface roughness. The R-MRAFF process was used for polishing the stainless-steel workpiece with a 16 nm value of surface finish. Speculative surveys of the plane magnetic abrasive finishing were done and mathematical experiments were conducted by Jayswal *et al.* [11] to identify the influence of process variables upon produced surface quality. The authors casted-off the finite element model for simulating and measuring the magnetic field to confirm the theoretic outcomes and concluded that by enhancing the value of magnetic abrasive particle size and flux density, R_{max} (surface roughness) was decreased. Kanish *et al.* [12] reported the impact of machining gap, abrasive size, rotational speed, and the voltage applied to the electromagnet on SS316L material during magnetic field-assisted abrasive micro finishing. The authors tested the fuzzy model with different process variables value sets and reported a close correlation with the investigational value of 7.16 %.

Nagdeve *et al*. [13] designed a duplication of the knee joint implantation similar to a finished fixture using the RMRAFF method. The authors studied the pressure's effect upon the percentage variation in finishing rate and surface roughness. They observed that when there was an increasing extrusion pressure, both finishing rate and ΔRa were increased till a certain range, and beyond that pressure, negative results were reported. Nagdeve *et al*. [14] measured the yield stress with a rheometer and observed higher yield stress in the case of MR fluid and reported the lowest yield stress at 9 μm abrasive particle size. The authors used the magnetorheological fluid-based finishing (MRFF) method to study the influence of relative abrasive and magnetic particle size of MR fluid upon the finishing performance of the MRFF method.

Singh *et al.* [15] hybridized AFM with a magnetic force to improve the efficiency and optimized the value of MR to enhance the productivity and also to determine the impact of various factors upon performance measures. Singh *et al.* [16] improved the proficiency of AFM with the centrifugal force produced by rotating the CFG rod into the cylinder-shaped workpiece. They reported the parameters to effect upon process performance. The authors used hybrid centrifugal force assisted AFM processes to find the impact of key parameters on ΔRa. A deterministic process for developing an improved finish of diamond-turned surface was deliberated by Khatri *et al.* [17] with clubbing of single-point diamond turning and MRF. The authors identified the optimal combination of various factors with an analysis of variance, which revealed the effect of various parameters on the final surface finish.

In a rigorous literature survey, utmost work has been described upon finishing homogeneous materials (aluminium, stainless steel, brass, copper, mild steel, etc.) using different AFM processes [6,9,10-16,19-20,23-24], while little work is reported on heterogeneous materials (Al/SiC-MMCs) [7-8]. Although the heterogeneous material is used, the material (Al/SiC/B_4C-MMCs) used in the present study is not yet finished. The accomplishment of the fine finishing of such composites is a challenging task. Therefore, the present study uses the MAFM process for finishing the hybrid MMCs with different ratios of SiC and B_4C particulates reinforced with Al-6063 (as base material). The silicon carbide is hard and superior wear resistance, high strength, highest corrosion resistance, and good thermal properties. On the other hand, boron carbide also possesses good wear resistance, high specific strength, good thermal stability, and high elastic modulus. When these particulates are reinforced with aluminum composites, these abrasives certainly improve the overall strength and hardness of the composites. All these parameters motivated to work on such MMCs (Al/SiC/B_4C). The hybrid MMCs find a wide variety of industrial and medical applications such as surgical, aerospace, dies and moulds, tool manufacturing industries, which are used to make automotive components like cylinder heads, pistons, liners, and brake motors, etc.

In AFM, the workpiece fixture plays a significant role in guiding the media to pass through the workpiece surface, which requires machining. Many researchers have used the fixtures [8,14-15,20,23] made up of several materials like nylon, brass, and steel, etc. Further, most of the studies have shown that the material used for fabricating the fixtures is nylon. The fixture design should enable cleaning, loading, and unloading that can generate a maximum magnetic field around the workpiece surface. It is observed that the nylon fixture has a low magnetic permeability for the magnetic line of forces. This hinders the process of finishing the inner cavity of the workpiece. To prevent this, the present study sheds light on the newly fabricated aluminium fixture, in which the workpiece comes exactly in between the magnetic field produced by electromagnet coils. This enhances the effectiveness of the MAFM process, thus making this process an interesting field of research.

Materials and methods

The Experimental MAFM Setup

In the current investigation, a novel MAFM setup is designed and fabricated by modifying the existing AFM setup with the addition of an electromagnetic effect. The setup consists of 2 media cylinders, a hydraulic unit, an aluminium fixture, electromagnets, and a supporting frame. The media cylinders contain a sufficient quantity of media flowing from the lower to upper media cylinder under pressure with the help of a piston through the workpiece. A hydraulic unit containing a gear pump is designed to push the oil to the complete circuit by taking it from the tank. A novel aluminium fixture with a hole cut of the same size and outer shape of the workpiece is designed and fabricated for holding the workpiece. **Figures 1(a)** and **1(b)** show the geometrical representation and pictorial view of the aluminium fixture, respectively.

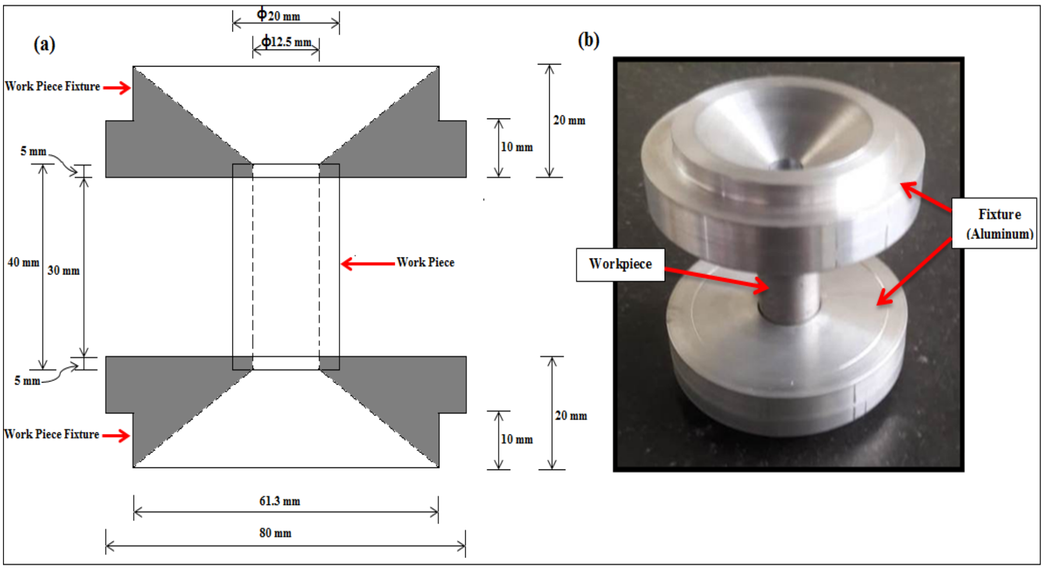

Figure 1 (a) geometrical representation (b) pictorial view of the aluminium fixture.

Two vertical plates were attached to hold the fixture strongly without any media leakage. To avoid the vibration during machining, the diameter of the aluminium fixture was reduced gradually. After finishing the appropriate number of cycles, the workpiece was detached from the fixture and another workpiece was placed in the slot. The abrasive media was prepared by mixing thoroughly the abrasive particles of silicon carbide (SiC), hydraulic oil number 68, liquid silicone rubber (carrier), and iron (Fe) powder and by passing it from a dummy workpiece. During the abrasion process, the media was expelled by the actuators and passed from upper to lower media cylinders through a cylindrical workpiece to complete a forward stroke. The reverse process was repeated for a backward stroke to complete the cycle. To finish the inner workpiece surface having a cylindrical shape, the abrasive laden media was extruded through the workpiece as shown in **Figure 2**.

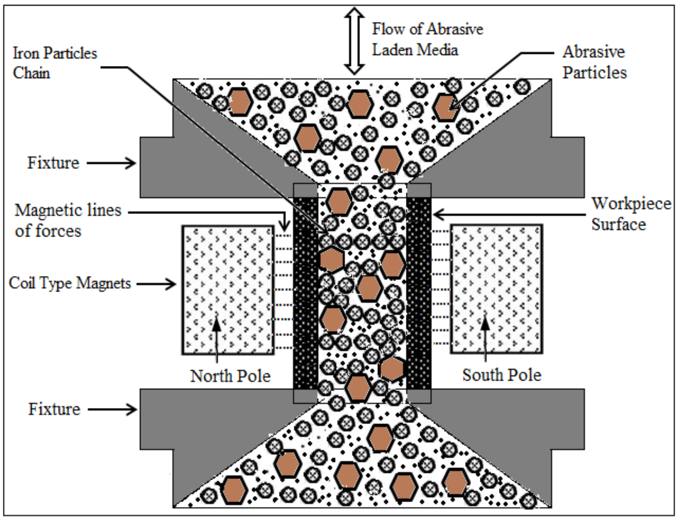

Figure 2 The finishing mechanism.

A magnetic field was applied causing the abrasion to take place only around the workpiece surface keeping other areas unaffected. Coil-type magnets wound by copper coils were used instead of permanent magnets to provide the maximum effect of magnetic field around the work-piece surface. **Table 1** shows the specifications of coil-type magnets.

Table 1 Specifications of the electromagnet.

Sr. No.	Constituents of electromagnet	Description of attributes
1)	Material used for core	Mild steel
2)	Size of core	Diameter of core rod = 35 mm Radius of core = 25 mm Core length = 175 mm
3)	Electromagnet coils	Coil material = 23-gauge copper wire Number of turns = 2,500 per coil Weight of each coil = 3.820 kg
4)	DC power supply to coils	0 - 240 Volts
5)	Magnetic flux density	0 - 2 Tesla

A digital counter meter was used to calculate the number of cycles. EN8 (unalloyed medium carbon steel) material was used for the fabrication of hydraulic cylinders. Extrusion pressure with a maximum value of 10 MPa, an internal cylinder diameter of 90 mm, hydraulic oil no. 68, the stroke length of a constant value 250 mm, media volume of 300 cc, and the magnetic flux density 0 - 2 Tesla were used. MAFM experimental setup with finished workpieces and job profile is shown in **Figure 3**. The finishing of inner cylindrical surfaces of Al/SiC/B_4C MMCs was done using MAFM setup. After finishing, every sample was cleaned with acetone. The weight and ΔRa of each specimen were measured before and after conducting the experiments.

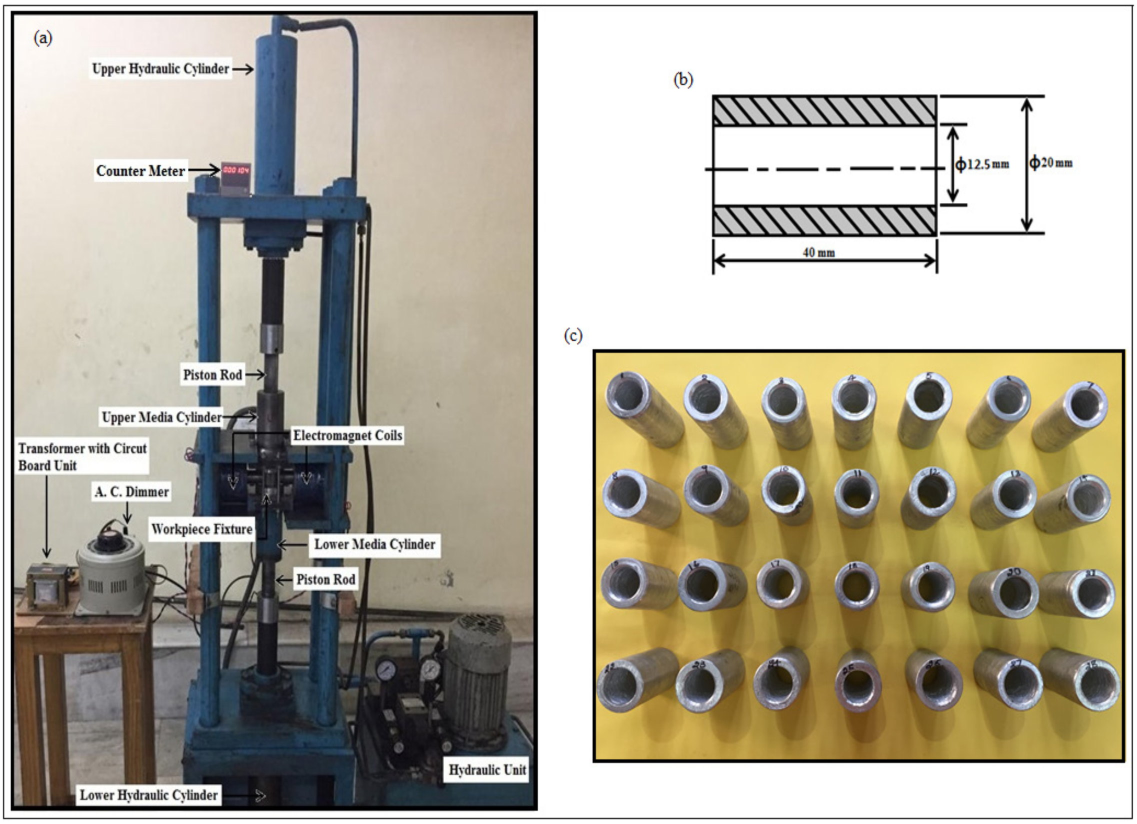

Figure 3 (a) Developed MAFM machining setup, (b) job profile, (c) finished workpieces.

Material used

In the current study, the hybrid Al/SiC/B_4C-MMCs with different ratios of SiC and B_4C abrasive particles having a mesh size 220 reinforced with Al-6063 (as base metal) was used as a work material.

Fabrication of hybrid Al/SiC/B_4C-MMCs

In the present experimental work, 3 different samples/workpieces of hybrid MMCs were prepared like {sample 1: 90 % of Al-6063 with 9 % of SiC and 1 % of B_4C}, {sample 2: 90 % of Al-6063 with 8 % of SiC and 2 % of B_4C} and {sample 3: 90 % of Al-6063 with 7 % of SiC and 3 % of B_4C}. The MMCs were fabricated using a stir casting technique in which a rectangular muffle furnace with a temperature controlling device and graphite stirrer was used for melting and stirring purposes respectively. **Figure 4** depicts the flow chart for the fabrication procedure of hybrid Al/SiC/B_4C-MMCs. Thereafter, the prepared samples were tested and analyzed using spectro and chemical analysis testing. The spectro analysis testing was used to carry out tests of the recognized elements of the periodic table. Moreover, the chemical analysis testing was used to find the percentage composition of various chemical compounds in the prepared samples as shown in **Tables 2** and **3** respectively.

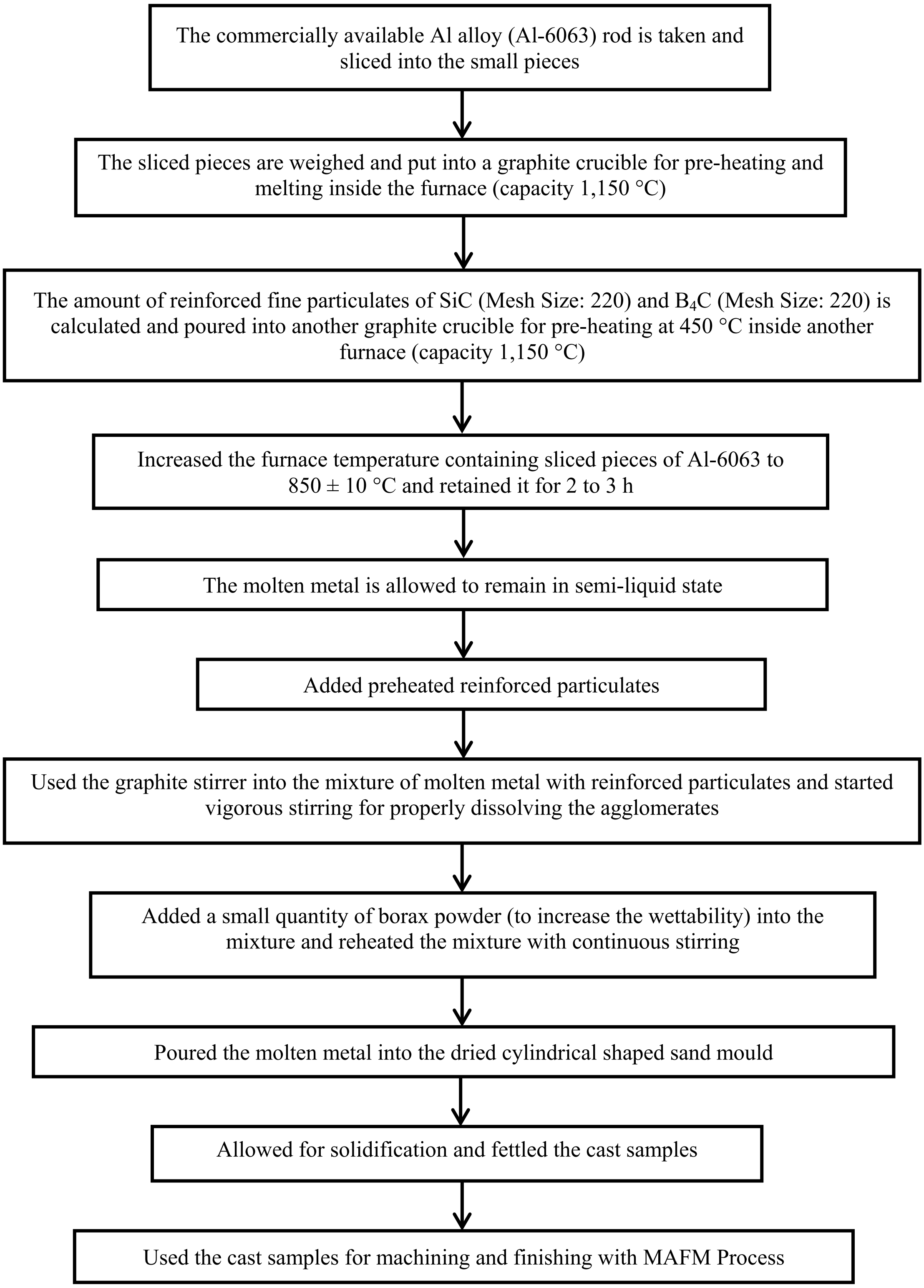

Figure 4 Flow chart for samples fabrication (Al/SiC/B_4C-MMCs).

Table 2 Spectro analysis testing results.

Element	Al	Fe	Mg	Cu	Si	Zn	Mn	Pb	B	Cr	Ti
Sample-1	Base material	0.28	0.76	0.03	9.15	0.0010	0.0064	0.0025	1.01	0.0016	0.0096
Sample-2	Base material	0.16	0.53	0.02	8.02	0.0012	0.0050	0.0026	1.96	0.0021	0.0090
Sample-3	Base material	0.18	0.72	0.04	6.82	0.0012	0.0068	0.0027	2.86	0.0021	0.0091

Table 3 Chemical analysis testing results.

Percentage in Samples	Aluminium (Al-6063)	Silicon Carbide (SiC)	Boron Carbide (B_4C)
Sample-1	89.96 %	9.06 %	0.98 %
Sample-2	90.13 %	7.95 %	1.92 %
Sample-3	90.21 %	6.87 %	2.92 %

Results and discussion

During the experimental study, different input parameters like the number of cycles (N), workpiece material (W_p), extrusion pressure (E_p), abrasive mesh size (M), the concentration of abrasives (C), and magnetic flux density (M_f) were deviated to find their influence upon the response parameters like MRR and ΔRa. One variable at a time approach [18] was used to analyze the experimental results. The values of different variables and constant parameters were selected on the basis of pilot experimentation and literature survey [8,11,20-24]. The experiments were conducted according to the plan, where values of variable and constant parameters are described in **Table 4**.

Table 4 Plan of experiments.

Variable Parameters	Constant Parameters	Count of Change in Media
Extrusion Pressure (Mpa) E_p = 1, 3, 5, 7, 9	M = 220, C = 50 %, W_p = sample 2, N = 150, M_f = 0.30	1 time
Mesh no. of abrasive M = 80, 150, 220, 325, 400	E_p = 5, C = 50 %, W_p = sample 2, N = 150, M_f = 0.30	5 times
Concentration of Abrasive (wt %) C = 40, 45, 50, 55 and 60 %	E_p = 5, M = 220, W_p = sample 2, N = 150, M_f = 0.30	5 times
Workpiece Material W_p = Sample 1, 2, 3	E_p = 5, M = 220, C = 50 %, N = 150, M_f = 0.30	1 time
No. of cycles N = 50, 100, 150, 200, 250	E_p = 5, M = 220, C = 50 %, W_p = sample 2, M_f = 0.30	1 time
Magnetic flux density (Tesla) M_f = 0.15, 0.25, 0.30, 0.35, 0.45	E_p = 5, M = 220, C = 50 %, W_p = sample 2, N = 150	1 time

Effect of extrusion pressure

The results of the present study revealed that both MRR and ΔRa get increased by augmenting the value of extrusion pressure as shown in **Figures 5(a)** and **6(a)**. This happens as more abrasion takes place using enabled abrasive particles with more extrusion pressure since these particles strike the surface with greater impact. These outcomes are in favour of the reported results by Jain et al. [19-20]. MRR and ΔRa increase from 3.92 to 7.68 µg/s and 0.49 to 0.74 µm by varying extrusion pressure from 1 to 9 Mpa and keeping other parameters constant at M = 220, C = 50 %, W_p= sample 2, N = 150 and M_f = 0.30 Tesla, respectively.

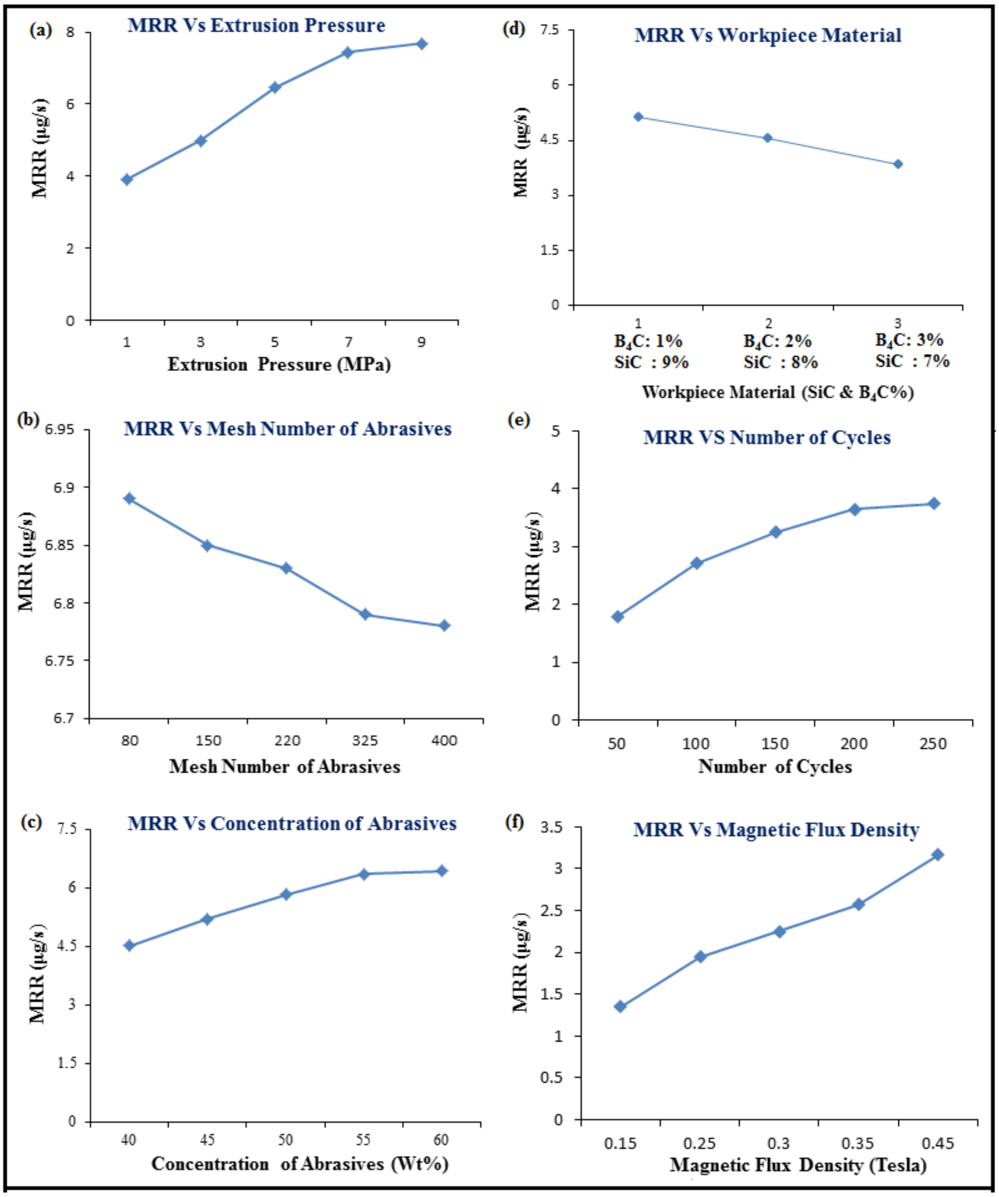

Figure 5 One factor plot for MRR.

Effect of mesh number of abrasives

It is demonstrated from **Figures 5 (b)** and **6 (b)** that MRR and ΔRa are decreased by increasing the mesh number. By increasing the mesh number, both width and depth of penetration also decreased. Hence, smaller abrasive size, leads to a lower value of MRR and ΔRa. The magnitude of MRR and ΔRa decreased from 6.89 to 6.78 µg/s and 0.46 to 0.22 µm by varying the mesh number from 80 to 400 while keeping other parameters constant at E_p = 5 Mpa, C = 50 %, W_p = sample 2, N = 150 and M_f = 0.30 Tesla, respectively.

Effect of concentration of abrasives

By increasing the value of abrasive concentration in the medium, the MRR and ΔRa increased as illustrated in **Figures 5(c)** and **6(c)**. Since at a higher concentration of abrasives in the media, a large number of abrasives interact with the surface of the workpiece because the media retains more cutting force causing more abrasion. The value of MRR and ΔRa increased from 4.51 to 6.42 µg/s and 3.82 to 3.86 µm respectively, by varying the abrasive concentration from 40 to 60 % while keeping other parameters constant at E_p = 5 Mpa, M = 220, W_p= sample 2, N = 150 and M_f = 0.30 Tesla.

Effect of workpiece materials

In the current research work, the Al/SiC/B_4C hybrid MMCs was taken as a workpiece material by taking aluminium as a base material and by varying the percentages of SiC and B_4C. The hardness of the workpiece was increased with the presence of boron carbide, as reported by the findings of Reddy and Bodukuri [21-22]. Therefore, by increasing the proportion of B_4C, the workpiece hardness increases making it harder to cut or finish. Because of this, the value of MRR and ΔRa decreases. **Figures 5(d)** and **6(d)** show that the value of MRR and ΔRa decreases from 5.12 to 3.85 µg/s and 0.77 to 0.42 µm by varying the workpiece composites value from (9 to 7 %) for SiC and (1 to 3 %) for B_4C while keeping other parameters constant at E_p = 5 Mpa, M = 220, C = 50 %, N = 150 and M_f = 0.30 Tesla, respectively.

Effect of the number of cycles

The value of both MRR and ΔRa increases from 1.79 to 3.75 µg/s and 0.97 to 1.86 µm by increasing the number of cycles from 50 to 250, while keeping other parameters constant at E_p = 5 Mpa, M = 220, C = 50 %, W_p = sample 2 and M_f = 0.30 Tesla, respectively as shown in **Figures 5(e)** and **6(e)**. These outcomes support the findings reported by Shan and Wang [23-24]. In the case of MRR, the slope decreases near 200 cycles after the lesser peaks and valleys were finished. On the other hand, ΔRa improves initially, due to the presence of more peaks and valleys in the early stages of machining. Further increment in the number of cycles results in lesser peaks getting machined and becoming somewhat flatter than before. Due to this ΔRa reduces.

The results also report that the required number of cycles to eradicate an equal amount of material reduces on the application of a magnetic field. The magnetic field generator results in the formation of a chain-like structure known as an iron particles chain between the electromagnetic poles as depicted in **Figure 2**. This in turn increases the bonding strength of abrasive particles. Thus, the maximum abrasive particles participate in the abrasion process and shear off more peaks along with deep penetration of these peaks. This causes more material removal from the workpiece surface during the finishing process.

Effect of magnetic flux density

In the MAFM setup, a magnetization effect is produced around the cylindrical workpiece leading to the finishing fluid becoming rigid. This is due to the formation of iron particles (IP) chains that wrap the micro-irregularities on the surface. The metal is removed from the asperities of the surface by the abrasives entrapped between the iron particles chain. The current passes through the coiled-type electromagnet to produce the magnetic flux density. By increasing the magnetization effect from 0.15 - 0.45 Tesla, more metal is eradicated by the abrasives from the surface asperities. Because of this MRR, increases from 1.35 to 3.17 µg/s and an improved value of ΔRa is achieved from 0.38 to 1.06 µm enhancing the quality of surface finish. **Figures 5(f)** and **6(f)** illustrate that with a magnetic field, a rapid increase is observed in MRR than in ΔRa. These outcomes support the findings stated by Shan *et al.* [23].

One factor plot is drawn for MRR and ΔRa at constant values of parameters E_p = 5 Mpa, M = 220, C=50%, W_p = sample 2 and N = 150.

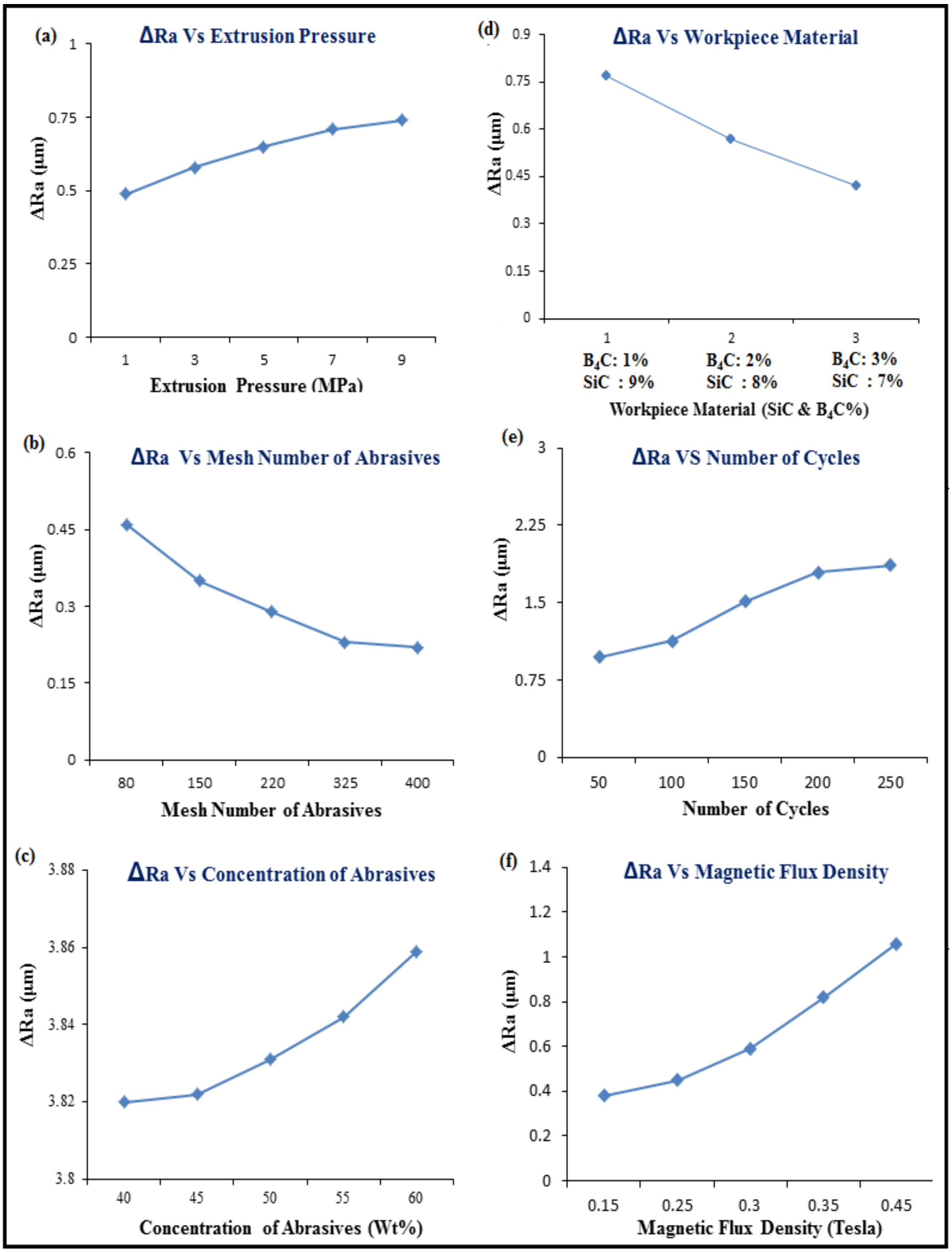

Figure 6 One factor plot for ΔRa.

Conclusions

Based on the experimental investigation, the parametric effect on MRR and ΔRa is analyzed by finishing Al/SiC/B_4C MMCs with a newly designed and fabricated MAFM setup. The 6 input parameters; extrusion pressure, the concentration of abrasives, mesh number, the number of cycles, workpiece material, and magnetic flux density were varied for studying their effect upon response parameters as MRR and ΔRa. By applying one variable at a time, it is found that extrusion pressure, the number of cycles, and magnetic flux density played a significant role in finding the improved value of MRR and ΔRa. Depending upon the outcomes, various conclusions can be outlined:

The results show a significant improvement in MRR and ΔRa by 95.92 and 51.02 %, respectively by varying the extrusion pressure from 1 to 9 MPa.

The increase in mesh number from 80 to 400 resulted in a percentage reduction of 1.62 and 109.09 % for MRR and ΔRa respectively.

The MRR and ΔRa increase by 42.35 and 1.05 %, respectively with a variation in the concentration of abrasives from 40 to 60 %.

The percentage change in the reinforcement of SiC and B_4C in Al-6063 reduces the MRR and ΔRa by 32.99 and 83.33 %, respectively.

A significant improvement of 109.50 and 91.75 % is observed in MRR and ΔRa by increasing the number of cycles from 50 to 250.

From the results, it is also observed that the most significant parameter is magnetic flux density since it improves MRR and ΔRa by 134.88 and 178.95 %, respectively for a change in its value from 0.15 to 0.45 Tesla.

References

[1] MS Cheema, G Venkatesh and A Dvivedi. Developments in abrasive flow machining: A review on experimental investigations using abrasive flow machining variants and media. *Proc. I Mech. Engineers, Part B: J. Eng. Manufact*. 2012; **226**, 1951-62.

[2] MR Sankar, VK Jain and J Ramkumar. Abrasive flow machining (AFM): An overview. *In:* Proceedings of the INDO-US Workshop on Smart Machine Tools, Intelligent Machining Systems and Multi-Scale Manufacturing, Indo-US Science and Technology Forum, New Delhi, India. 2008, p. 1-9.

[3] KS Santhosh and SH Somashekhar. A review on abrasive flow machining (AFM). *Proc. Technol.* 2016; **25**, 1297-304.

[4] S Rawangwong, J Chatthong, W Boonchouytan, C Homkhiew, W Cheewawuttipong and R Burapa. Influence of cutting parameters in face milling semi-solid AA 2024 using a carbide tool affecting the surface roughness and tool wear. *Walailak J. Sci. Tech*. 2017; **14**, 441-9.

[5] M Das, VK Jain and PS Ghoshdastidar. Analysis of magnetorheological abrasive flow finishing (MRAFF) process. *Int. J. Adv. Manuf. Technol.* 2008; **38**, 613-21.

[6] S Singh, HS Shan and P Kumar. Parametric optimization of magnetic-field-assisted abrasive flow machining by the taguchi method. *Qual. Reliab. Eng. Int.* 2002; **18**, 273-83.

[7] RS Mamilla, VK Jain and KP Rajurkar. Nano-finishing studies using elastically dominant polymers blend abrasive flow finishing medium. *In:* Proceedings of the 19th CIRP Conference on Electro Physical and Chemical Machining, Zurich, Switzerland. 2018, p. 529-34.

[8] S Mittal, V Kumar and H Rajurkar. Experimental investigation and optimization of process parameters of Al/SiC MMCs finished by abrasive flow machining. *Mater. Manuf. Process.* 2015; **30**, 902-11.

[9] AD Ghadikolaei and M Vahdati. Experimental study on the effect of finishing parameters on surface roughness in magneto-rheological abrasive flow finishing process. *J. Eng. Manufact*. 2015; **229**, 1517-24.

[10] M Das, VK Jain and PS Ghoshdastidar. Nano-finishing of stainless-steel tubes using rotational magnetorheological abrasive flow finishing process. *Mach. Sci. Technol.* 2010; **14**, 365-89.

[11] SC Jayswal, VK Jain and PM Dixit. Magnetic abrasive finishing process - a parametric analysis. *J. Adv. Manuf. Syst.* 2005; **4**, 131-50.
[12] TC Kanish, P Kuppan, S Narayanan and SD Ashok. A fuzzy logic-based model to predict the improvement in surface roughness in magnetic field assisted abrasive finishing. *Procedia Eng.* 2014; **97**, 1948-56.
[13] L Nagdeve, VK Jain and J Ramkumar. Experimental investigations into nano-finishing of freeform surfaces using negative replica of the knee joint. *Procedia CIRP* 2016; **42**, 793-8.
[14] L Nagdeve, VK Jain and J Ramkumar. On the effect of relative size of magnetic particles and abrasive particles in MR fluid-based finishing process. *Mach. Sci. Technol.* 2018; **22**, 493-506.
[15] R Singh and RS Walia. Hybrid magnetic force assistant abrasive flow machining process study for optimal material removal. *Int. J. Appl. Eng. Res.* 2012; **7**, 2121-4.
[16] R Singh, RS Walia and NM Suri. Study of parametric effect on surface roughness improvement for hybrid centrifugal force assisted abrasive flow machining process. *Int. J. Latest Sci. Res. Technol.* 2012; **1**, 198-201.
[17] N Khatri, S Tewary, V Mishra and RV Sarepaka. An experimental study on the effect of magneto-rheological finishing on diamond turned surfaces. *J. Intell. Mater. Syst. Struct.* 2013; 1-13.
[18] DC Montgomery. *Design and Analysis of Experiments*. 5^{th} eds. John Wiley & Sons, New York, 2002, p. 60-119.
[19] RK Jain, VK Jain and PM Dixit. Modeling of material removal and surface roughness in Abrasive flow machining process. *Int. J. Mach. Tools Manuf.* 1999; **39**, 1903-23.
[20] VK Jain, and SG Adsul. Experimental investigations into abrasive flow machining (AFM). *Int. J. Mach. Tools Manuf.* 2000; **40**, 1003-21.
[21] PS Reddy, R Kesavan and BV Ramnath. Investigation of mechanical properties of aluminium 6061-silicon carbide, boron carbide metal matrix composite. *Silicon* 2017; **10**, 495-502.
[22] AK Bodukuri, K Eswaraiah, K Rajendar and V Sampath. Fabrication of Al-SiC-B4C metal matrix composite by powder metallurgy technique and evaluating mechanical properties. *Perspect Sci*. 2016; **8**, 428-31.
[23] HS Shan and S Singh. Development of magneto abrasive flow machining process. *Int. J. Mach. Tools Manuf.* 2002; **42**, 953-59.
[24] AC Wang and SH Weng. Developing the polymer abrasive gels in AFM Process. *J. Mater. Process. Technol.* 2007; **192-193**, 486-90.