Effect of process parameters on material removal rate in magnetic abrasive flow machining of Al/SiC/B₄C metal matrix composites

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Abstract. In the recent times, the necessity for magnetic abrasive flow machining (MAFM) process in the industry arises as it is superior to conventional machining processes. MAFM is used to obtain high surface finishing and materials removal rate for the cylindrical, complex and intricate profiles. In this paper, the effect of process parameters has been studied on the material removal rate in MAFM process of metal matrix composites of Al/SiC/B₄C prepared by stir casting process. The process parameters are magnetic field, extrusion pressure, no. of cycles, mesh size of abrasives, workpiece material and concentration of abrasives. Taguchi design of experiments has been used for design of experiments and the analysis of variance technique has been used to check the significance level of each input parameter. The results show that the intensity of magnetic field has a dominant effect on the material removal rate.

1. Introduction

Metal Matrix Composites (MMCs) have excellent mechanical properties and are widely used in aerospace, structural and automotive fields [1-2]. To meet the standard industrial requirements, various processes such as Magnetic Abrasive Flow Machining (MAFM), grinding, laser polishing, lapping etc. are used for surface finishing operations [3-4]. In MAFM process, the abrasive particles are used in combination with iron powder and lubricant solution to obtain machining of inner surface and provide lubrication [5]. AFM process can provide the significant improvement in the surface finishing of the aerospace, automobile and rail locomotive components in just few minutes which show that this process is suitable for advance manufacturing [6]. MAFM process uses magnetic field to enhance the cutting force and obtain superior surface finishing as compared with conventional machining processes [7]. Therefore, MAFM process provides accuracy and significant surface finishing of the materials [8]. Shabgard et al. [9] reported the MAFM of H13 tool steel. It was found that the MAFM process provides good surface finishing of hard materials. Mittal et al. [10] found that AFM process increases the surface finishing of Al/SiC MMCs.

Using the magnetic field in the abrasive flow machining process, the surface finishing greatly improved in difficult to machine work pieces [11]. The reinforcement of SiC in the hybrid composites showed significant improvement in the wear resistance [12]. Research study showed that the surface roughness was significantly reduced using MAFM process for Inconel 718 work piece [13]. The magnetic field helped in improving the surface finishing of the Al-6061 hybrid composites using MAFM process [14]. The wear rate and coefficient of friction of Al/SiC/B₄C MMCs are lower as compared to Al/SiC MMCs. SEM images study showed uniform distribution of materials and no defect due to SiC and B₄C reinforcement in the aluminium [15]. MAFM process may not be suitable for drilling holes in the work pieces. However, the in some cases, it also offers little high cost [16]. The
metallurgical and hardness properties of aluminium are greatly improved with reinforcement of SiC and B₄C particles [17]. MAFM process improves the surface finishing unto 95 nm for achieving nano-finishing in case of Ti-6Al-4V flat discs [18]. MAFM process helps in improving the tool life by 50-60% in case of Ti-6Al-4V work piece [19-20]. MAFM process is also suitable for achieving nano-finishing of bio-titanium alloys [21-22]. It was reported that the machining efficiency can be increased by 40% using MAFM process assisted with ultrasonic vibration [23].

In the field of precision engineering, various processes such as magnetic float polishing [24], magnetorheological abrasive flow machining [25], magnetic abrasive finishing [26], magnetorheological finishing [27] are available for achieving better surface finishing with good flexibility and controllability [28-29]. Al/SiC/B₄C MMCs are used in aerospace, industries, rail locomotives, automobile and medical sector. The magnetic field, work piece materials, no. of cycles and extrusion pressure has the significant effect on the MRR in magnetic field abrasive flow machining. The magnetic field beyond certain value showed decrease in the MRR for the work piece as the rough peaks vanishes after certain level of machining [30].

2. Materials and Methods

In the present paper, Al/SiC/B₄C MMCs is prepared using stir casting method. The main advantage of preparing the Al/SiC/B₄C MMCs with stir casting is the lower cost as compared to other available methods and stir casting allows uniform distribution of the materials. The Al/SiC/B₄C MMCs are fabricated using micro-EDM process and then machined using MAFM process.

The various process parameters taken in the present research are magnetic field density, extrusion pressure, no. of cycles, mesh size of abrasives, workpiece material and concentration of abrasives. The response parameter taken is MRR. The effect of process parameters on response parameter was investigated. The magnetic field distribution is investigated using simulation software. The XRD analysis used to check the uniform distribution of materials and SEM used to compare the machined surfaces before and after machining.

2.1. Experimental Setup

The experimental setup for MAFM process consists of the electromagnets, media cylinders, pistons, workpiece fixtures and hydraulic unit. The electromagnets provide the magnetic field using the electric current. The cylinders used to guide the reciprocating pistons. Nylon fixtures with a hole used to hold the workpiece in the right position. Hydraulic unit with the capacity of withstanding pressure of 10 MPa was used for the experimentation. Hydraulic unit consists of direction, pressure control valves, hydraulic cylinders, tank, pressure gauges and gear pumps.

2.2. Experimentation
The work pieces of Al/SiC/B₄C MMCs were prepared using the stir casting process. The process parameters used are magnetic field, extrusion pressure, no. of cycles, mesh size of abrasives, workpiece material, concentration of abrasives as given in Table 1. The response parameter is material removal rate (MRR). The hydraulic oil was used in addition to the abrasive mixture and iron powder to provide the lubrication to the inner surface. The abrasive mixture with varying concentration was made up of Al, SiC and B₄C particles for machining the work pieces. The experiments were carried out by varying the process parameters to achieve the optimal material removal rate. The response parameter MRR was calculated using the following expression:

$$\text{MRR} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Time}}$$

**Table 1. Level of Input Parameters**

| Symbol | Factors                                         | Level 1 | Level 2 | Level 3 |
|--------|------------------------------------------------|---------|---------|---------|
| A      | Magnetic Field (T)                              | 0.2     | 0.4     | 0.6     |
|        | Workpiece Material                             | 10      | 20      | 30      |
| B      | (percentage of SiC in Al/SiC/B₄C)              | 3       | 5       | 7       |
|        | Workpiece Material                             |         |         |         |
|        | (percentage of B₄C in Al/SiC/B₄C)              |         |         |         |
|        | Mesh Number                                     | 100     | 150     | 200     |
| D      | Abrasives concentration                         | 50      | 55      | 60      |
| E      | Extrusion pressure (MPa)                        | 3       | 5       | 7       |
| F      | No. of Cycles                                   | 100     | 200     | 300     |

The specimens were fabricated using the micro-EDM process. After fabrication, the specimens were machined using MAFM process. Carbonyl iron particles used with the abrasive mixtures and hydraulic oil to finish the inner surface of Al/SiC/B₄C hybrid MMCs. Hydraulic oil acts as lubricant and binder for the abrasive mixture passing through the hollow inner surface of the work piece.

The significance of each process parameter was analyzed using the ANOVA technique. The distribution of the magnetic field in the machining region was analyzed using the simulation software as shown in the Figure 3.
3. Results and Discussion

Experiments were performed using Taguchi’s L27 Orthogonal array. Three repetitions of the experiments were done. The obtained values of MRR are given in Table 2. The experiments were performed using different values of input parameters as given by Taguchi L27 array.

Table 2. Experimental Observations for MRR

| Exp. No. | MRR1 (in µg/s) | MRR2 (in µg/s) | MRR3 (in µg/s) | Mean MRR (in µg/s) |
|----------|----------------|----------------|----------------|-------------------|
| 1        | 2.10           | 1.98           | 1.66           | 1.91              |
| 2        | 2.31           | 3.16           | 2.84           | 2.77              |
| 3        | 5.02           | 4.77           | 5.14           | 4.98              |
| 4        | 2.12           | 1.85           | 2.64           | 2.20              |
| 5        | 2.53           | 4.02           | 3.09           | 3.21              |
| 6        | 5.00           | 4.10           | 4.05           | 4.38              |
| 7        | 2.53           | 2.05           | 2.76           | 2.45              |
| 8        | 2.54           | 3.23           | 2.81           | 2.86              |
| 9        | 4.22           | 5.01           | 4.38           | 4.54              |
| 10       | 2.55           | 2.96           | 2.58           | 2.70              |
| 11       | 6.65           | 5.13           | 5.00           | 5.59              |
| 12       | 7.96           | 4.44           | 5.35           | 5.92              |
| 13       | 3.24           | 3.38           | 2.83           | 3.15              |
| 14       | 7.99           | 6.99           | 6.35           | 7.11              |
| 15       | 4.55           | 4.62           | 4.81           | 4.66              |
| 16       | 3.44           | 4.02           | 3.37           | 3.61              |
| 17       | 6.47           | 6.88           | 7.09           | 6.81              |
| 18       | 4.52           | 5.49           | 5.00           | 5.00              |
| 19       | 9.78           | 9.77           | 8.46           | 9.34              |
| 20       | 3.99           | 4.34           | 3.36           | 3.9               |
| 21       | 8.69           | 8.67           | 8.89           | 8.75              |
| 22       | 9.13           | 9.97           | 9.66           | 9.59              |
| 23       | 4.14           | 4.78           | 4.38           | 4.43              |
| 24       | 8.19           | 8.63           | 8.27           | 8.36              |
| 25       | 9.02           | 9.24           | 9.32           | 9.19              |
| 26       | 4.33           | 3.99           | 4.37           | 4.23              |
| 27       | 8.35           | 8.23           | 8.20           | 8.26              |
The values of MRR obtained in Table 2 have been used for calculation signal to noise ratio. For this purpose, ‘higher the best’ approach has been used. The graphs for signal to noise ratio have been shown in Figure 4 and response values for means are given in Table 3. To get the percentage contribution of each input parameter the analysis of variance has been shown in Table 4.

![Figure 4. S/N ratio plots for process parameters](image)

### Table 3. Response Table for Means

| Level | A   | B   | C   | D   | E   | F   |
|-------|-----|-----|-----|-----|-----|-----|
| 1     | 3.256 | 3.856 | 5.14 | 5.096 | 5.273 | 4.904 |
| 2     | 4.95  | 4.852 | 5.244 | 5.232 | 5.076 | 4.546 |
| 3     | 7.339 | 6.537 | 5.16  | 5.217 | 5.196 | 6.094 |
| Delta | 4.083 | 2.881 | 0.104 | 0.137 | 0.198 | 1.549 |
| Rank  | 1    | 2    | 6    | 5    | 4    | 3    |

### Table 4. ANOVA for MRR

| Source | D.F. | Seq. SS | Contribution | Adj. SS | Adj. MS | F-Value | P-Value |
|--------|------|---------|--------------|---------|---------|---------|---------|
| A      | 2    | 75.755  | 49.97%       | 75.7546 | 37.8773 | 23.86   | 0.001   |
| B      | 2    | 41.455  | 27.34%       | 41.4552 | 20.7276 | 13.05   | 0.007   |
| C      | 2    | 0.179   | 0.12%        | 0.1787  | 0.0893  | 0.06    | 0.945   |
| D      | 2    | 0.055   | 0.04%        | 0.0533  | 0.0247  | 2.76    | 0.041   |
| E      | 2    | 11.832  | 7.80%        | 11.8319 | 5.9159  | 4.55    | 0.030   |
| F      | 2    | 0.101   | 0.07%        | 0.1008  | 0.0504  | 7.64    | 0.013   |
| Error  | 4    | 22.228  | 14.66%       | 22.2281 | 1.5877  |         |         |
| Total  | 16   | 151.605 | 100.00%      |         |         |         |         |

R-Sq = 99.59% \quad R-Sq(adj) = 98.66%

Table 4 represents that the mesh size of abrasives has little effect on the MRR. It can be clearly observed that the magnetic field density is the major process parameter having most significant effect on the MRR of the Al/SiC/B4C hybrid MMCs in case of MAFM process. The percentage contribution
shows that the Magnetic field density, work piece materials, extrusion pressure and no. of cycles has a significant effect on MRR. The surface finishing was visibly improved after the machining.

3.1. Optimization for MRR using Taguchi Method

Overall MRR (M) = 5.18 µ g/s

Optimum MRR considering most significant factors as per Taguchi combination

\[ = A_3 + B_3 + F_3 - 2M \]
\[ = 7.33 + 6.53 + 6.09 - 2 \times 5.18 \]
\[ = 9.59\mu g/s \]

Now, Confidence Interval, \( CI = \pm \sqrt{F(1, n_e)Ve/ne} \)

\( F = F \) – ratio, \( \alpha = \) risk
\( n = \) degree of freedom for error
\( V_e = \) Variance
\( n_e = \) no. of replications

At 95%, Confidence Interval

\[ F(1, 2, 0.05) = 18.50 \]

\[ n_e = \frac{N}{1 + \text{dof of all the factors}} \]
\[ n_e = \frac{27}{1+6} = 3.80 \]

\[ V_e = 0.051 \]

\[ CI = \pm \sqrt{18.50 \times 0.051 / 3.80} = \pm 0.494 \]

Mean experimental value after confirmation experiments = 9.81 µg/s

\% error = \( \frac{9.81 - 9.59}{9.81} \times 100 = 2.24 \% \)

3.2 XRD and SEM analysis

The XRD graph in Figure 5 shows that there are no unwanted compounds present in the Al/SiC/B_{2}C MMCs. Most of the peaks are of Al, SiC and B_{2}C only. So, the uniform distribution of the materials achieved using the stir casting process. The surface defects, cracks and irregularities were significantly improved from the work piece using MAFM. It was observed that the magnetic field around the work piece in the machining region enhanced the MRR of the Al/SiC/B_{2}C MMCs.
SEM images were captured before and after machining of MAFM process. The surface defects, cracks and irregularities were significantly removed from the workpiece using MAFM. Figure 6 shows SEM surface before machining and Figure 7 shows a work piece after machining.

**Figure 5.** XRD graph for the Al/SiC/B$_4$C hybrid MMCs

**Figure 6.** SEM before MAFM process

**Figure 7.** SEM after MAFM process
4. Conclusions

1. In the present study it has been found that the significant factors in MAFM process are: magnetic field, work piece materials, no. of cycles and extrusion pressure.
2. It has been found that MRR increases with the increase in the magnetic field, no. of cycles and extrusion pressure.
3. The intensity of magnetic field has strong correlation with MRR. The MRR increases with increased magnetic field intensity. Also, the MRR decreased with increasing the hardness of the material.
4. The SEM and XRD images confirm the results of increased surface finish and removed material.

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