Improvement in Machined Surface with the use of Powder and Magnetic Field Assisted on Machining Aluminium 6061 Alloy with EDM

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Abstract. Surface characteristics are the major challenges faced by the manufacturing industry when materials are machined with electrical discharge machining. Magnetic Field assisted powder mixed electrical discharge machining (MFAPM-EDM) is hybrid machining process which has shown the good potential of improving the surface characteristics. In this present paper, machining of aluminium 6061 alloy was carried out with aluminium powder mixed in EDM oil and in presence of magnetic field using EDM process Magnetic field, spark on duration, spark off duration, pulse current and powder concentration were selected as variable machining parameters and surface roughness as a response. Box-Behnken design approach based on response surface methodology was used for performing the experiments. In the present analysis, current was observed as the most significant parameter followed by spark on duration, powder concentration and magnetic field on surface roughness. Improvement in surface roughness with lesser voids and craters were observed under the influence of magnetic field and aluminium powder mixed in EDM oil.

1. Introduction

The uses of aluminium 6061 alloy (AA6061) in industrial applications are increasing at present context owing to enticing properties such as light weight, high corrosion resistance, high strength, and better machinability. AA6061 contains magnesium and silicon as principal elements in addition to aluminium. The use of AA6061 was found to be suitable in automobile, marine, aerospace industries and also structural as well as architectural applications [1-2]. Burr formation, adhesion between tool and workpiece, dimensional inaccuracy are some of the problems faced on conventional machining of AA6061 [3, 4]. Owing to certain difficulties faced on conventional machining, researchers have tried to machine the AA6061 by non-conventional machining process. However, electrical discharge machining (EDM) was found suitable which can machine the hard conductive materials irrespective of materials hardness and in the absence of cutting force [5, 6]. In this process, thermal energy is responsible for generating the spark which melts the materials from the surface of workpiece in the form of small debris. At present context, EDM is used in the manufacturing of complex dies, molds and also in aerospace, military, automobile industry for making critical parts. The EDM process, however posses certain limitations such as low machining rate, longer lead time and surface finish limit the use of this process in its applications [7-9]. Thus, researchers have focused their attention on such difficulties by developing new hybrid processes which can improve the process productivity and surface quality. Thus, for effective machining with enhanced machining rate and better surface quality was obtained with the machining of materials with new hybrid machining process known as magnetic
field assisted powder mixed electrical discharge machining (MFAPM-EDM). The mechanism of material removal in this process is by melting and evaporation with the assistance of powder in dielectric media and in the presence of magnetic field. The material removal occurs by multiples discharge due to bridging of powder particle under the sparking area instead of single spark combined with Lorentz force developed due to magnetic field coupled electric field which assists in removing material faster to improve the MRR, TWR and better surface integrity [10-12].

Bhatt et al. [10] used powder mixed in EDM oil and in presence of magnetic field for machining of AISI D3 and H13 steel. Pulse on time was the most significant parameter for TWR, overcut, microhardness (MH) and surface roughness (SR) followed by powder concentration and peak current. Kant [13] observed higher MRR and lower TWR at 2 g/l of graphite powder mixed in dielectric and copper as tool on machining EN-19 steel using EDM process in presence of fixed magnetic field (0.1 T). Bains et al. [14] noticed an improvement in MH, SR and recast layer thickness with the use of SiC powder and magnetic field in EDM on machining Al-Si MMCs. Rouniyar and Shandilya [12] fabricated MFAPM-EDM setup and was successfully used for performing the machining of AA6061. One factor approach was used for experimental design and improvement in TWR and MRR was observed. Hienz et al. [15] machined non-magnetic material i.e. Ti-6Al-4V alloy using the EDM process under the influence of external magnetic field. Effect of process parameter on erosion efficiency, debris field and plasma temperature was studied. Rouniyar and Shandilya [16] used Taguchi coupled with GRA to determine the optimum machining parameters on machining Ti-6Al-4V alloy with graphite powder mixed in dielectric for minimum SR and maximum MRR.

Most of the literature on machining of difficult to cut materials were available on machining using either powder mixed in dielectric or magnetic field assisted EDM. Handful works was explored using magnetic field assisted powder mixed EDM on machining of conductive materials. In this paper, the effect of machining parameters on SR, and surface morphology of machined AA6061 with MFAPM-EDM process was studied. Magnetic field (MF), spark on duration (S\text{ON}), and surface roughness (SR) were selected as variable machining parameters for this study. Second order regression model was developed to predict the SR and surface morphology using Scanning Electron microscope (SEM).

2. Experimental Details
Aluminium 6061 alloy (40 x 40 x 10 mm) as workpiece material and electrolytic copper (dia-12 mm) as tool material, EDM oil (grade 5) as dielectric, aluminium (0.074 mm particle size) as powder and NdFeB as ring magnet were selected for this experimental work. Elemental composition (wt %) of Al6061 alloy before machining was measured using EDX test is given as Al (97.87), Mg (0.8), Si (0.4), Ti (0.10), Cr (0.04), Mn (0.12) Fe (0.65), Cu (0.15) and Zn (0.07) [12]. The major properties of Al6061 alloy such as density 2.7 g/cm³, modulus of elasticity 80 GPa, thermal conductivity 173 W/m K, ultimate tensile strength 270 MPa and hardness 96 BHN respectively. A circular hole of 12 mm diameter was machined on the Al6061 alloy workpiece. Fabricated MFAPM-EDM setup as shown in Figure 1 was used for carrying out experiments. To avoid settlement of powder particles in the tank and for quick removal of debris particle from the spark zone, stirring system and magnetic system were used respectively. Experiments were performed as per Box Behnken design approach of response surface methodology with 5 machining parameters all at three levels. The experimental design consists of total 46 runs (40 factorial points and 6 center point) [17]. The parameters selected for the experimental work were magnetic field, spark on duration, spark off duration, pulse current and powder concentration as illustrated in Table 1. Surface roughness was measured and recorded at three different locations using surface roughness tester with sample length of 4 mm and cutoff length of 0.8 mm and the average of three readings was used for analysis purpose. Surface Morphology at different machining conditions was analyzed using SEM.
Figure 1. Pictorial View of MFAPM-EDM setup

Table 1. Machining Parameters and Their Levels

| Sl. No. | Machining Parameters        | Symbol | Level | Response          | Fixing Criteria                      |
|---------|------------------------------|--------|-------|-------------------|--------------------------------------|
| 1       | Magnetic field (T)          | MF     | 0.15  | 0.30              | 0.45                                 |
| 2       | Spark on duration (µs)      | S_ON   | 30    | 50                | 70                                   |
| 3       | Spark off duration (µs)     | S_OFF  | 35    | 43                | 51                                   |
| 4       | Pulse current (A)           | I_P    | 1     | 4                 | 7                                    |
| 5       | Powder concentration (g/l)  | P_C    | 6     | 8                 | 10                                   |

3. Results and Discussion
Total 46 experiments were performed on machining of AA6061 by MFAPM-EDM process. The average SR observed corresponding to the combinations of experimental runs for machining parameters was used for analysis. Analysis of variance (ANOVA) for SR was carried out at 95% confidence level using design expert V10.0.1 software as illustrated in Table 2. As observed from Table 2, F-value of 92.45 showing the significance of the developed model. Among linear term I_P, S_ON, P_C and MF observed were significant as p<0.05 was observed. As observed from ANOVA table I_P was most significant parameter which has effect on SR followed by S_ON, P_C and MF. Interaction effect was observed for I_P-P_C and MF-S_ON, while, for quadratic terms significant were observed for I_P, S_OFF and P_C.

Table 2. ANOVA for SR

| Source        | SS    | dof | MS   | F-Value | p-value | % Contribution |
|---------------|-------|-----|------|---------|---------|----------------|
| Model         | 40.23 | 10  | 4.02 | 92.45   | < 0.0001|                |
| MF            | 2.53  | 1   | 2.53 | 58.11   | < 0.0001| 6.52           |
| S_ON          | 6.25  | 1   | 6.25 | 143.52  | < 0.0001| 16.11          |
| I_P           | 18.86 | 1   | 18.86| 433.24  | < 0.0001| 48.63          |
| P_C           | 3.55  | 1   | 3.55 | 81.54   | < 0.0001| 9.15           |
| T_ON-MF       | 0.19  | 1   | 0.19 | 4.26    | 0.0465  | 0.59           |
| I_P-P_C       | 0.23  | 1   | 0.23 | 5.31    | 0.0273  | 0.52           |
| S_OFF^2       | 0.20  | 1   | 0.20 | 4.57    | 0.0396  | 0.52           |
| I_P^2         | 4.98  | 1   | 4.98 | 114.44  | < 0.0001| 12.84          |
| P_C^2         | 1.91  | 1   | 1.91 | 43.88   | < 0.0001| 4.92           |
Using ANOVA, regression coefficient corresponding to linear, quadratic and interaction terms were calculated at 95% confidence level. Thus, second order model to predict the SR was developed in terms of significant machining parameters (actual factors) as illustrated in Equation (1). The pred. $R^2$ for SR was found to be 0.9222, while Adj. R$^2$ was observed as 0.9531 and the difference between them was less than 0.2, signifying the relation good agreement of predicted results with the experimental data.

$$SR = + 6.47520 + 0.93708 \times MF + 0.052766 \times S_{on} + 0.67255 \times I_p - 2.15402 \times PC - 0.071750 \times S_{on} \times MF + 0.040042 \times I_p \times PC - 0.078878 \times I_p^2 + 2.21633 \times 10^{-3} \times S_{off}^2 + 0.109900 \times PC^2$$ (1)

Figure 2(a) depicts the surface plot showing the effect of PC and $I_p$ on SR. Increase in SR was observed with increase in $I_p$ and decrease in PC. The increase in SR with increase in $I_p$ was due to increase in energy per pulse in the spark region. A discharge energy associated with high current is capable of removing a chunk of material leading to formation of deep and wide crater with rougher surface. However, decrease in SR with increase in PC was mainly attributed to dispersion of impulsive force among the powder particles. Due to this, spark with less impulsive force strikes the surface with multiple discharges instead of single discharge generating smoother surface. However, decrease in SR with increase in PC was mainly attributed to dispersion of impulsive force among the powder particles. Decrease in SR with increase in PC was mainly attributed to dispersion of impulsive force among the powder particles. Figure 2(b) illustrates the surface plot showing the effect of MF and $S_{on}$ on SR. Increase in SR was noticed with increase in $S_{on}$ and decrease in MF. As $S_{on}$ increases, higher spark energy is available for machining the workpiece due to longer time duration. Thus, deeper and wide craters were observed leading to poor surface finish. However, decrease in SR with increase in MF was attributed to confinement of plasma causing the increment in depth and reduction in crater size as well as expelling the machining debris from the machining area effectively clearing the gap under sparking area due to Lorentz force developed due to magnetic along with electric field causing proper removal of material leading to lower SR.

|                | Residual | Lack of Fit | Pure Error | Cor Total |
|----------------|----------|-------------|------------|-----------|
|                | 1.52     | 1.32        | 0.20       | 41.70     |
|                | 35       | 30          | 5          | 44        |
|                | 0.085    | 0.044       | 0.041      |           |
|                | 0.22     | 1.07        | 0.5258*    |           |

| SS- Sum of Square, MS- Mean Square, dof- Degree of Freedom, *-Significant, #-Non significant |

|                | 0.0        | 30         | 0.44       | 0.21      |
|----------------|------------|------------|------------|-----------|
|                | 0.09635    | 0.9531     |            |           |

|                | 6.47520    | 0.93708    | 0.052766  | 0.67255   |
|----------------|------------|------------|-----------|-----------|
|                | 0.040042   | 0.078878   | 2.21633   | 10^{-3}   |
|                | 0.109900   | 0.071750   | 2.15402   |           |
|                | 0.044       | 0.071750   | 2.15402   |           |
|                | 0.0         | 0.078878   | 2.21633   |           |
|                | 0.09635    | 0.9531     |            |           |

**Figure 2.** Surface plot of (a) PC and $I_p$ (b) MF and $S_{on}$ vs. SR

The surface morphology of different machining conditions was analyzed using SEM as shown in Figure 3. Figure 3(a) illustrates the surface morphology of machined sample at higher spark on
duration and pulse current ($I_p$-7A, $S_{ON}$-70 µs, $S_{OFF}$-43 µs, PC-8 g/l, MF-0.3 T) where presence of large number of re-solidified debris particles, voids and smaller crater was observed. This was observed due to higher pulse duration available and high pulse current for producing the high discharge energy resulting in higher melting of molten materials from the surface which is unable to flush due to lower pulse off duration resulting in re-solidified layer on the surface. Figure 3(b) depicts the surface morphology at higher magnetic field and powder concentration ($I_p$-4A, $S_{ON}$-50 µs, $S_{OFF}$-43 µs, PC-10 g/l, MF-0.45 T) where the surface appears smoother with presence of lesser voids and re-solidified debris on the machined surface. This was because of effective expulsion of debris at higher magnetic field and due to multiple discharges resulting in shallow crater at higher powder concentration.

Figure 3. Surface morphology at (a) $I_p$-7A, $S_{ON}$-70 µs, $S_{OFF}$-43 µs, PC-8 g/l, MF-0.3 T (b) $I_p$-4A, $S_{ON}$-50 µs, $S_{OFF}$-43 µs, PC-10 g/l, MF-0.45 T

4. Conclusions
In this study, detailed experimental investigation was carried out to evaluate and identify the effect of machining parameters on surface roughness while machining AA6061 using MFAPM-EDM process with aluminium powder mixed in EDM oil. To check the effectiveness of developed hybrid process scanning electron microscope was used to examine the surface morphology of machined AA6061. Based on experimental observations following findings were derived from the present works.
1. Pulse current was observed as most significant machining on surface roughness at 95% confidence level followed by spark on duration, powder concentration and magnetic field.
2. Second order RSM model has been developed was developed to predict the surface roughness in terms of significant machining parameters.
3. Improvement in surface roughness was observed with the addition of aluminium powder and in presence of magnetic field.
4. SEM image depicts the lesser crack, voids and re-solidified debris on surface when machined at higher magnetic field and powder concentration.

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