A Study of Material Removal during Electrical-Discharge Drilling of Hybrid Metal Matrix Composites

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In this paper, the machinability behavior of hybrid metal matrix composites (HMMCs) has been experimentally investigated. The experiments were performed at different level of (i) discharge current, (ii) pulse-on-time, (iii) pulse-off-time, and (iv) tool rotational speed. The intrinsic influence of these parameters on the material removal rate (MRR) has been investigated during electrical-discharge drilling (EDD) of developed HMMCs using copper electrode and quenched copper electrode. The influence of powder-mixed dielectric on MRR has also been investigated. The results of the experimental investigation indicated that the MRR is increased with discharge current (6 to 30 A) and pulse-on-time (60 to 500 µs) and decreased with pulse-off-time (8 to 90 µs) and tool rotational speed (400 to 1200 RPM).

Keywords: HMMCs, EDD, and MRR

Introduction

The application of EDD for making of hole is seen in several manufacturing areas as shown in Figure 1. Extensive researches have been conducted to improve the material removal during EDM of MMCs. But little research has been conducted in the context of EDD of MMCs. Yan and Wang¹ investigated the performance of rotary-EDM for Al₂O₃/Al 6061. The influence of pulse duration, discharge current, volume fraction of reinforced particles, electrode rotation, and flushing pressure on MRR, TWR, and (surface roughness) SR has been investigated. Wang and Yan² optimized the same parameters effect for blind-hole drilling using rotary-EDM. It was found that the blind-hole drilling of MMCs with an eccentric through-hole electrode is better than the solid electrode in terms of improved MRR. The effects of parameters such as concentration of SiC particles, discharge current, speed of tube electrode, and pulse duration on MRR have been investigated during EDM of MMCs.³,⁴ Chattopadhyay et al.⁵ evaluated the performance of disc type copper tool electrode with an objective to increase the MRR and decrease the TWR during rotary-EDM of EN-8. Jahan et al.⁶ studied micro-EDM of cemented carbide using tungsten tool electrode. The influence of major machining parameters has also been studied. Singh et al.⁷ studied the EDM of EN-31 tool steel using copper, aluminum, brass, and copper tungsten tool electrodes at different level of pulsed current. Singh et al.⁸ used a square and rectangular shaped tool electrode for EDM of Al 6061/Al₂O₃ composites. It was showed that the shape of the tool electrode significantly affects the tool wear. Khan⁹ studied the influence of different parameters on MRR and TWR during EDM of conventional materials. Puthumana and Joshi¹⁰ developed a slotted tool electrode. The performance of the developed tool electrode on material removal,

Fig. 1 — Application of EDD process
tool wear, oversize, and depth of machining was evaluated during dry-EDM of SS304. Yilmaz and Okka\textsuperscript{11} investigated the influence of operating parameters on MRR and TWR during EDD of Inconel and Ti 6Al-4V using two different tool electrode geometries such as single and multi-channel tubular tool electrode. Rajesha \textit{et al.}\textsuperscript{12} investigated the effect of copper hollow tool electrode on MRR and TWR. The performance of rotary-EDM has also been studied for hard materials such as titanium, titanium alloy, and die steel\textsuperscript{13,14}. The research attempt has also been made to access the performance of rotary-tool-electrode during EDM of MMCs\textsuperscript{15,16}. From the discussion, it is clear that few studies have been conducted on powder-mixed EDD using rotary tool electrode. Also the behavior quenching of tool electrode has not been investigated in the context of EDD or powder-mixed EDD. The EDD has been investigated for machining of hard alloys but its applicability for MMCs has to be explored. Therefore, the drilling of HMMCs with EDD and powder-mixed EDD have been attempted in this present work.

**Materials and Methods**

**Fabrication of HMMCs**

The stir and squeeze casting method have been applied to develop the hybrid MMCs. The melting of Al 6063 alloys and heating of SiC/Gr/Al\textsubscript{2}O\textsubscript{3} particles were carried out in two different furnaces. The composition of Al 6063 base metal was Cu 0.1%, Si 0.3-0.7%, Mn 0.3%, Fe 0.6%, Mg 0.4-0.9%, and balance Al. Reinforcements such as 5% SiC, 2.5% Gr and 2.5% Al\textsubscript{2}O\textsubscript{3} were preheated at around 800-900\degree C for 3 hours. The size of the reinforcement particles was 15-25 µm. Graphite particles were added because of its self-lubricating properties and thus can be used for tribological applications. The melting of matrix material was carried out in a stainless steel crucible in a resistance furnace under argon atmosphere. Al 6063 was heated at around 800-850\degree C to make their mushy phase. The preheated reinforcement particles were mixed in the matrix by stir casing process. The stirring was carried out at speed of 150-300 RPM and temperature of 750\degree C for 10 minutes. Finally, the hybrid mixture is squeezed to get the HMMCs.

**Development of EDD Setup**

The ZNC-EDM was used to carry out the experimental work. A rotary setup was designed and fabricated to perform the EDD. Rotary setup was retrofitted to the servo mechanism of the EDM machine. The different components of the EDD setup are shown in Figure 2. Table 1 neatly summarizes the important parameters and their levels. The spark gap of 0.05 mm was maintained during the machining using a computer controlled positioning system. The depth of the hole was 3 mm. The experimental time and other observations were directly measured by the control panel. The weight loss of the workpiece was measured using an electronic balance (least count of 0.1 mg). MRR (mm\textsuperscript{3}/min) was calculated using Eq. (1).

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MRR = \frac{(W_f - W_i) \times 1000}{\rho_w T}
\]

where, \(W_i\) and \(W_f\) is the initial and final weight of the workpiece (gm), \(T\) is the machining time (min), and \(\rho_w\) is the density of workpiece (gm/cm\textsuperscript{3}).

**Results and Discussion**

The intrinsic influence of input process parameters on MRR has been studied by changing the level of one input parameter at a time while keeping other input parameters constant at lowest level. The variation in MRR also studied by considering copper electrode,
quenched copper electrode, and copper electrode with powder-mixed dielectric. The mechanisms of materials removal during EDD is shown in Figure 3. The variation in MRR with discharge current for various tool electrodes is shown in Figure 4(a). The discharge current is a significant parameter as it is proportional to the spark energy\(^1\). It is quite clear from the figure that the MRR increases linearly with increase in discharge current from 6 to 30 A. The increase in discharge current results in increased heat density within the spark gap which helps in achieving higher MRR. Machining with quenched copper electrode showed the maximum MRR followed by copper electrode with powder-mixed dielectric. The hardness of the copper electrode is increased after quenching. Thus the quenched copper tool electrode is better than the unquenched copper tool electrode in removing material from the work surface. The powder-mixed dielectric shows slight improvement in MRR when compared one-on-one with unmixed dielectric.

In Figure 4(b), it is evident that MRR increases gradually as the pulse-on-time increases. Pulse-on-time is defined as the duration for which the voltage is applied. The maximum energy can be reached depending upon the pulse duration. The maximum spark energy is converted into heat energy which results in formation of bigger crater. Thus the larger pulse duration results in higher material removal. However, the copper electrode without powder-mixed dielectric may not generate high pressure to flush the debris particles. This directly reduces the MRR. The controlled spark erodes more amount of material as the quenched copper electrode is used during machining. From the figure, it is

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![Fig. 3 — Process mechanism during (b) pulse-on-time and (b) pulse-off-time](image)

![Fig. 4 — Variation in MRR with (a) discharge current, (b) pulse-on-time, (c) pulse-off-time, and (d) tool rotational speed](image)
also evident that the MRR initially increases with an increase in the pulse-on-time and then followed a decreasing trend as the pulse-on-time is further increased. Figure 4(c) shows the effect of pulse-off-time on MRR for different electrodes. MRR decreases as the pulse-off-time is increased from 8 to 90 µs. Pulse-off-time allows dielectric fluid to remove eroded particles because once the sparking process is culminated the work surface is cooled by the pressurized dielectric and the eroded particles are flushed out. During the pulse-off-time, the debris is removed from the machining zone and facilitates to continue the material removal. Additionally, the debris consists of non-conductive SiC particles those left loose after the vaporization of matrix material which may results in erratic discharge. MRR obtained with powder-mixed copper electrode is greater because carbon layer accumulated on electrode surface is flushed by the SiC particle during pulse-off-time. Figure 4(d) represents the effect of tool rotational speed on MRR. The tool rotational speed has significant effect on the flushing of debris particles accumulated in the spark gap. The debris mainly consists of eroded metallic particles and products of dielectric decomposition. It is clear from the figure that the maximum MRR can be obtained with quenching copper electrode irrespective of tool speed. The tool rotation produces centrifugal force that imparts whirl and effectively flushes the debris. However, increase in tool rotational speed shows a decreasing trend of MRR. The flow of dielectric is difficult through the spark gap as the tool rotational speed is increased. This resulted in accumulation of debris in the spark gap and may lead to short circuit. The instability of spark at higher tool rotational speed may also results in low material removal.

Conclusions

From the present experimental investigation, it was observed that the quenched copper electrode is relatively better than the unquenched copper electrode as it gives better MRR during making of hole in HMMC by means of EDD. It was also observed that the performance of the powder-mixed dielectric is better than the unmixed dielectric for same type of tool electrode. Both pulse-on-time and discharge current exert a significant influence on MRR. MRR increases as both pulse-on-time and discharge current is increased. The MRR is decreased with both types of tool electrodes with an increase in the pulse-off-time. The MRR tend to decrease as the rotational speed of the tool electrode is also increased.

References


