Chapter 30
Investigation on the Performance of Copper-Coated 6061 Aluminium Alloy Electrode in Electric Discharge Machining

P. Mandal and S. C. Mondal

Abstract Electric Discharge Machining (EDM) is one of the most popular non-traditional machining processes applied for machining very hard conductive materials with desired shape, size and dimensional accuracy. In this paper, copper-coated 6061 aluminium alloy is applied as EDM electrode instead of copper. Electrodeposition, simple and economical process, was used for preparation of copper coating on 6061 Aluminium alloy. The method of anodization was applied in order to get a strong adhesive copper coating on aluminium alloy substrate. Ammonium bi-fluoride ($NH_4F{\cdot}HF$), a fluorine-containing inorganic substance was added to the anodizing solution to increase the porosity of aluminium alloy surface. The copper-coated surface was characterized with SEM/EDS and XRD. Lower electrode wear, surface roughness and higher MRR were found for copper-coated 6061 Aluminium alloy EDM electrode compare to uncoated 6061 Aluminium alloy electrode.

30.1 Introduction

Electrical discharge machining (EDM) is one of the most widely used nontraditional material removal process. In this process, thermal energy is uniquely utilized for material removal from electrical conductive workpiece material despite its hardness. Due to its extraordinary capability of machining, it is used for manufacturing of different components of aerospace and automobile, mold, die and the instrument used in surgical operation and the component of highly intricate shape [1–3]. In EDM operation, a series of electrical spark is generated in between EDM

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tool and workpiece [4]. These sparks are melted and vaporized the workpiece materials and produced the mirror image of EDM tool [5]. The sparks are not only removed the material from workpiece but also erode material from the electrode. This is known as electrode wear (EW) [2]. Higher electrode wear is undesirable because it degrades the shape of electrode. Several researchers were tried to develop high wear resistance, easy formability, highly available and low-cost electrode material for EDM [6]. A number of different materials such that Al, Cr, Cu–Co, Cu–Sn, Cu–W, Cu–TiC, Ni, Cr–Ni, Ni–Fe, Ni–Co, Ni–Si, Ni–TiC, Ti, Ti–Al, etc. were used electrode in order to achieve higher material removal rate (MRR) with lower tool wear and better surface finish [7].

Aluminium, most abundant of all metal, is found to be superior material in compare to copper when cost and lightweight is the primary concern. It is quite inferior to copper if the comparison is made on the basis of electrical, thermal and mechanical properties. The improvement of these properties of aluminium has enlarged the applicability in various industrial fields. It may also be used as a correct alternative of copper. The mechanical strength is improved by adding alloying element to the aluminium. Though the mechanical strength is increased for 6061 aluminium alloy but the electrical and thermal conductivity is reduced by 41 and 22%, respectively compared to pure aluminium [8]. The enhancement of electrical and thermal conductivities of 6061 aluminium alloy have improved the performance where electrical and thermal conductivity play a crucial role. The electrical [2] and thermal [9] conductivities of the electrode materials play crucial role for the performances of EDM operation.

The copper can be deposited on the various substrate materials using a simple and easy electrodeposition technique. This process has an ability to deposit uniform thick, strong adhesive and dense structured coatings on geometrically complex surfaces [10]. The metal deposition on aluminium and its alloy using electrodeposition process are faced number of specific difficulties. The natural oxide layer of aluminium surface is the main obstacle for achieving a strong adhesive coating. This oxide layer is needed to remove from the surface of aluminium alloy prior to electroplating [11]. The anodizing process can be used to resolve this issue by utilizing the oxide layer rather than removing it from the aluminium surface. The anodizing process is generated highly porous structure on the aluminium surface. These porous structures on the surface of aluminium are enabled to enhance the bonding strength between substrate and deposited metal [12]. Devyatkina et al. [13] formulated an effective combined electrolytic bath for both anodizing and copper plating for aluminium and its alloy. A fine crystalline structure of deposited copper was achieved by introducing fluorine in electrolytic bath. The electrodeposited copper coating developed from combined electrolytic bath exhibits high adhesion to aluminium. Mandal and Mondal [14] were observed better electrical and thermal property of copper coated stainless steel specimen compare to uncoated stainless steel specimen. The electrical and thermal conductivity of 6061 aluminium alloy was greatly improved with deposition of copper using electrodeposition process [15].

The high thermal and electrical conductivities of electrode material are the key parameters for enhancing the performance of electrode in EDM operation.

Aluminium is an easy formable material. Any shape of electrode can be easily prepared with aluminium. Electrical and thermal properties can be enhanced by deposition of copper on aluminium electrode. It is aiming that this process can be improved the operational performance and sustainability of electrode. In this paper, copper-coated 6061 aluminium alloy specimen is prepared using electrodeposition process. The anodizing process is applied for the surface preparation prior to copper plating. Newly developed copper-coated specimen is used as electrode for EDM operation to machining of AISI 304 stainless steel. The performance of EDM operation is evaluated on basis of material removal rate (MRR), electrode wear (ER) and surface roughness (SR).

30.2 Experimentation

Commercially available 6061 aluminium alloy extruded rods (diameter of 16 mm and length of 20 mm) were used for preparation of copper-coated electrode. Prior to anodization, the aluminium alloy specimen was degreased in 100 g L^{-1} NaOH solution for 5 min, then it is rinsed in distilled water and it clarified in a solution of nitric and hydrofluoric acids (3:1). Properly cleaned aluminium alloy specimen was anodized in anodizing solution at anodic current density of 20 mA/cm^2 in the room temperature. The anodizing solution was composed of sulfuric acid (150 ml L^{-1}), phosphoric (150 ml L^{-1}) and ammonium bi-fluoride (2 g L^{-1}). The copper was deposited on anodized specimen from copper sulphate electrolytic bath. The electrolytic bath was composed of copper sulphate (200 g L^{-1}) and sulfuric acid (20 ml L^{-1}). The copper was used as an anode and anodized 6061 aluminium specimen was used as a cathode. The electrodeposition was carried out with cathodic current density of 20 mA/cm^2 for 2 h. Uncoated, copper-coated aluminium alloy and copper electrode shows in Fig. 30.1.

The experiments were conducted in Electric Discharge Machine (Rantanparkhi, Model-400×250) with three different electrodes. The EDM experimental setup is

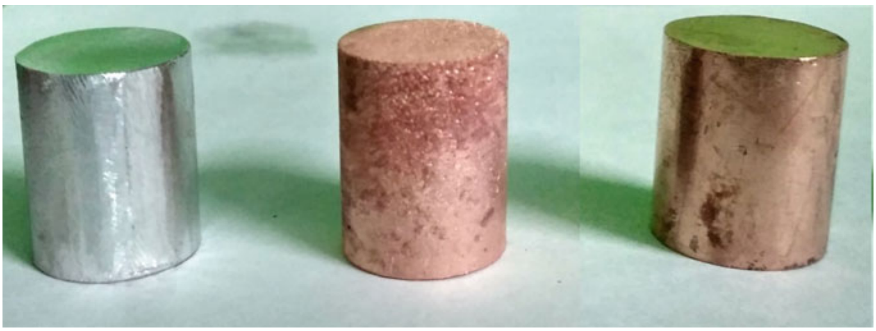


Fig. 30.1 Three different electrodes

Fig. 30.2 EDM setup

shown in Fig. 30.2. The machining parameters used for the experiment are shown in Table 30.1. The AISI 304 stainless steel upon which electric discharge machining was carried out for investigation of the performance of three electrodes.

30.3 Results and Discussion

The microstructural study and compositional analysis of coated surface were investigated using scanning electron microscope (Hitachi, S-3400N, Japan) equipped with energy dispersive x-ray spectroscopy (EDX). Figure 30.3 shows the microstructural view of anodized aluminium alloy specimen. A square cross-sectional porous structures were uniformly created all over the anodized surface. In electrodeposition process, the copper first penetrated into pores of

Table 30.1 EDM operating parameters

Polarity of electrode	Positive
Pulse on time (μs)	45
Duty cycle	9
IP (Sparking current) (A)	2
IB (Bi pulse current) (A)	3
SPK (Spark time) (μs)	3
Gap voltage (V)	50
Dielectric fluid	Clean EDM oil

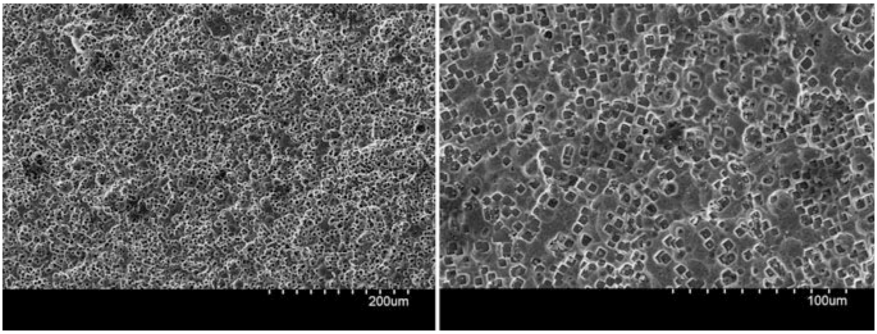


Fig. 30.3 The microstructure of anodized surface

anodized surface which is ensuring a strong adhesive bonding between coating and aluminium alloy substrate.

The microstructure of copper-coated aluminium alloy surface is shown in Fig. 30.4. The homogenous surface with tiny wrinkles morphology is observed. A smooth and dense structure of copper is formed on anodized porous structure of aluminium. The dense copper (less porosity) helped for reducing electrode wear rate of copper-coated 6061 aluminium alloy electrode.

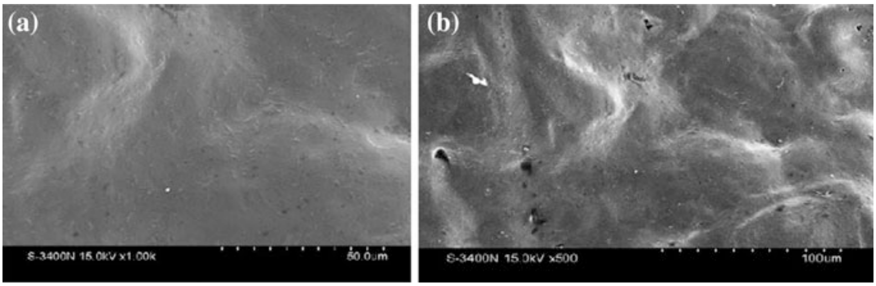
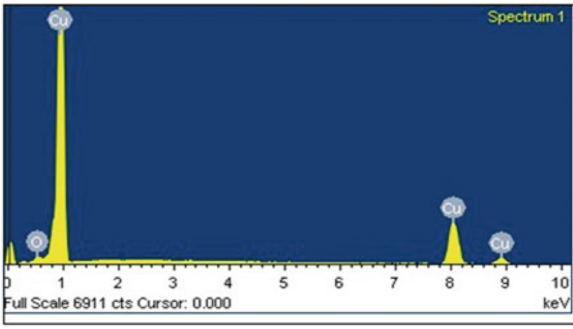


Fig. 30.4 SEM image of copper-coated surface

The EDX analysis and chemical composition of copper-coated aluminium alloy specimen are shown in Fig. 30.5. The chemical compositional analysis shows that 98.59% of copper and negligible amount of oxygen is present in coated surface. The presence of pure copper on coated surface is surely enhanced the electrical and thermal conductivity of 6061 aluminium alloy specimen. That will be influenced by the performance of EDM operation.

X-ray diffraction (D8, Bruker USA) with Cu-K_{α} radiation at $\lambda = 1.5418$ Å was employed for analysing of coated surface. PAN analytical X' Pert High Score Plus with JCPDS database (version 2) software was used to analyse the different peaks. The X-ray diffraction (XRD) pattern shows that only pure copper is present in coated surface (Fig. 30.6).



Element	Weight%
O K	1.41
Cu L	98.59
Totals	100.00

Fig. 30.5 EDX spectra of pure Cu coating

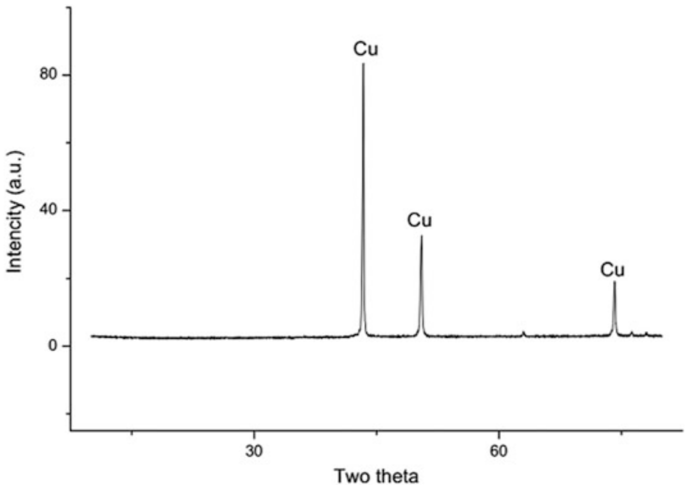


Fig. 30.6 XRD patterns of pure copper-coated surface

The EDM operation was carried out to cut the depth of 0.5 mm on AISI 304 stainless steel with each electrode for a set of particular operating condition (Table 30.1). Material removal rate (MRR) is the volume of material removed from workpiece in unit machining time. It calculated with the following formula:

$$\mathrm{MRR} = \frac{\left(w_i - w_f\right)}{t * \rho} \tag{1}$$

where w_i and w_f are weights of the workpiece before and after machining, t is the machining time and ρ is density of workpiece. Electrode wear rate (EWR) is the volume of material erode from electrode in unite machining time.

$$\mathrm{EWR} = \frac{\left(w_{ei} - w_{ef}\right)}{t * \rho} \tag{2}$$

where w_{ei} and w_{ef} are weights of the tool electrode before and after machining, and t is the machining time and ρ is density of electrode. The surface roughness of work surface was measured with non-contacting surface roughness measuring instrument (Rtec, 1401, USA).

The experiments were carried out using three different electrode materials for the same set of operating parameter. The calculated MRR for three electrodes is shown in bar chart (Fig. 30.7). About 6% higher MRR is achieved for copper-coated 6061 aluminium electrode than uncoated 6061 aluminium electrode. Compared to copper electrode, 24% lower MRR is observed for copper-coated 6061 aluminium electrode. The higher value of electrical conductivity is the main reason for the increasing of material removal rate [16]. The higher value of electrical conductivity can increase more energy transfer into workpiece and it causes more material

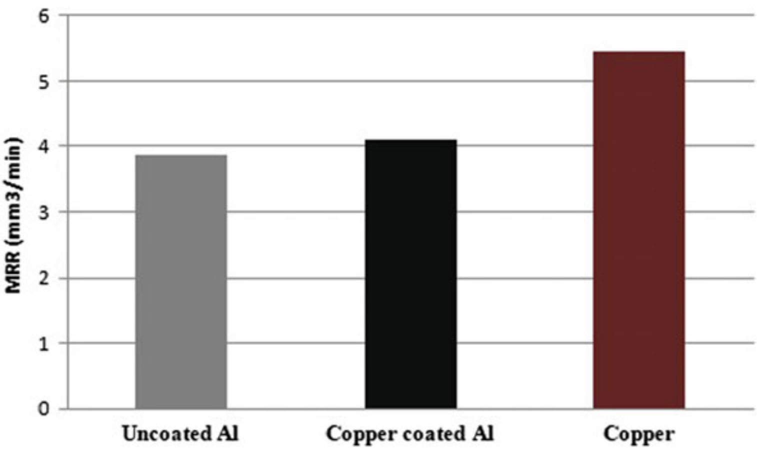


Fig. 30.7 Influence of different type of electrode material on MRR

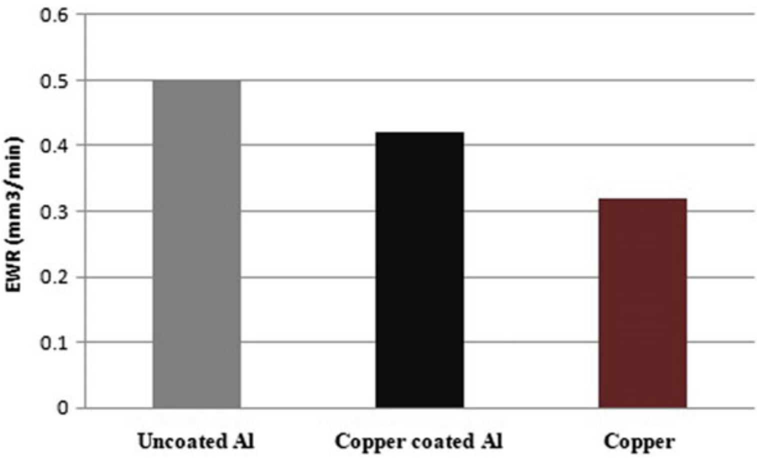


Fig. 30.8 Influence of different type of electrode material on EWR

removal from the workpiece. Though the electrical conductivity of 6061 aluminium is improved by copper coating on it, it does not reach the electrical conductivity as much as copper. This is the reason for observing this type of result for MRR.

Figure 30.8 shows the calculated electrode wear rate (EWR) for three different electrodes. The EWR is decreased by 16% after applying copper coating on 6061 aluminium electrode. About 23% lower EWR is found for extruded copper electrode. The thermal conductivity is mainly responsible for electrode wear rate [17]. The higher thermal conductivity of electrode material can be driven out more heat from sparking zone more quickly. This is reduced the electrode erosion. Thermal

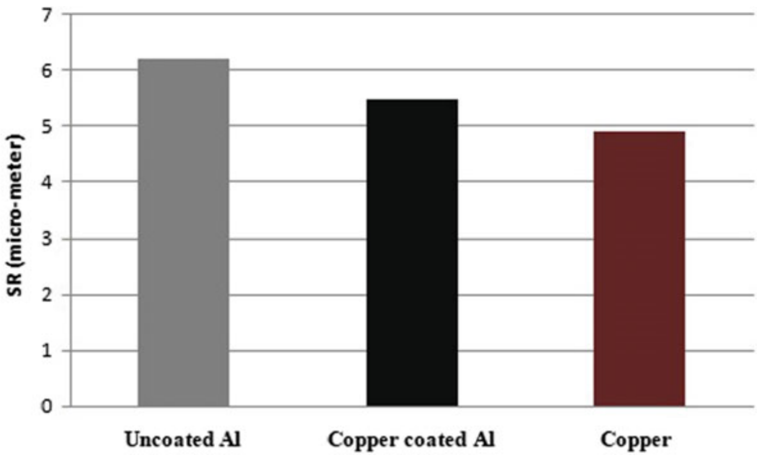


Fig. 30.9 Influence of different type of electrode material on SR

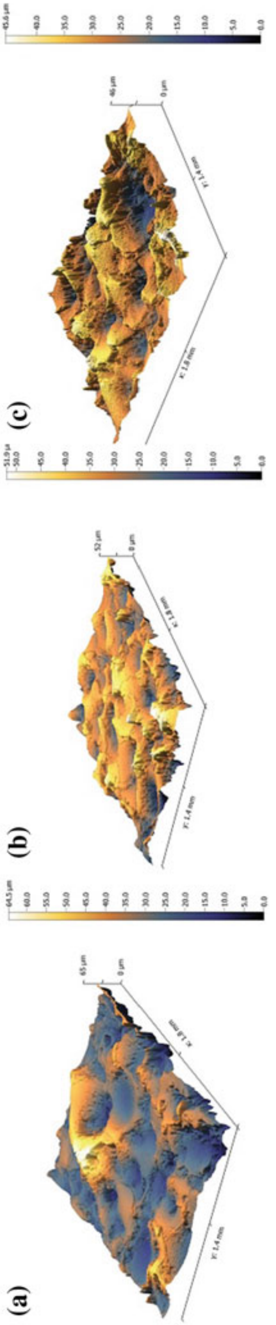


Fig. 30.10 Surface profile of machined surface, **a** uncoated 6061Al, **b** copper-coated 6061Al, **c** copper electrode

conductivity of copper-coated 6061 aluminium is higher compared to uncoated 6061 aluminium alloy. The higher thermal conductivity of copper-coated 6061Al electrode can reduce the electrode wear compared to the uncoated 6061Al electrode.

Bar chart (Fig. 30.9) shows the influence of three different electrodes on the surface roughness of workpiece. The results show that better surface is achieved using copper-coated 6061 aluminium electrode compared to uncoated 6061 aluminium electrode. The higher wear rate caused the degradation of surface of electrode. The degraded surface of electrode has generated more rough surface.

Figure 30.10 shows the surface profile of workpiece after machining with uncoated 6061 aluminium, copper-coated 6061 aluminium, and extrude copper EDM tool. It shows that quite better surface profile is observed while EDM operation is done with copper-coated electrode.

30.4 Conclusion

Copper-coated 6061 aluminium electrode was developed using electrodeposition process. Prior to electrodeposition, the surface of 6061 aluminium was prepared by anodizing process. The EDM operations were performed with newly developed electrodes. The performance of three electrodes was compared on the basis of MRR, EWR and SR. The results show that copper coating on 6061 aluminium has enhanced the performance compared to uncoated 6061 aluminium. The performance of copper-coated aluminium is not as much good as copper electrode but it is comparable to copper electrode. The result shows that copper coating on aluminium alloy has significantly improved the applicability and sustainability of 6061Al as an EDM electrode. The copper-coated 6061 aluminium can be used as EDM tool in a large scale in industry.

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