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# Degradation of wire electrode during electrical discharge machining of metal matrix composites

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ABSTRACT

This paper investigated the degradation of wire electrode during electrical discharge machining of SiC reinforced Al-based metal matrix composites (MMCs). MMCs with different size of reinforcements (0.7, 3 and 13 μm) as well as corresponding matrix material were machined under similar machining conditions to understand the effect of reinforcement size on the degradation of wire. In addition, pulse-on-time and wire tension were varied to understand the effect of machining parameters and interaction between machining parameters and size of the reinforcements. It was found that initial circular shaped wire deformed during the machining process as curved front and rear edges and two straight side edges irrespective of cutting conditions and workpiece materials. The curved edge at the front and straight side edges take part in material removal and experience sever degradations. The final cross-sectional area of the wire after the machining process is decided by balancing two mechanisms: (i) downward flow of highly malleable soft wire material due to high temperature which increases the diameter of wire electrode and (ii) vaporisation of the wire material at higher temperature which reduces the diameter of wire electrode. These complex processes are affected by machining conditions as well as workpiece materials.

## 1. Introduction

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes where electrical discharge is used to machine electrically conductive materials regardless of hardness. Electric discharge generates high thermal energy which removes material by erosion during this process [1]. EDM process takes place in a dielectric fluid where the tool is one of the electrodes in the shape of the cavity to be produced and the workpiece to be machined is the other one. The tool is then feed towards the workpiece in a controlled path to produce the shape of the electrode or its movement. The electrode and workpiece do not make direct contact during the EDM process [1,2]. Wire electrical discharge machining (WEDM) is a spark erosion process used to produce complex two and three dimensional shapes. WEDM differs from conventional electrical discharge machining (EDM), as the electrodes are in the form of thin wire with diameter of 0.05–0.3 mm. The wire, which unwinds from a spool, feeds through the workpiece. A power supply delivers high frequency pulses of electricity to the wire and the workpiece. The gap between the wire and workpiece is flooded with a dielectric fluid. Workpiece material is eroded ahead of travelling wire by spark discharges, which are identical with those in conventional EDM [3]. Particle reinforced metal matrix composites (MMCs) which are hard to machine by traditional methods has the potential to be machined by EDM [4–7]. MMCs are different from monolithic materials because of the reinforced ceramic particles which bring better mechanical properties, however also cause higher tool wear and worse surface finish after machining process. Therefore, the complications related to the accurate and optimum machining of MMCs are significant [8–10]. Literature review [1–10] indicates that the EDM process is capable of machining MMCs, though lower electrical and thermal conductivities of the reinforced particles affect the material removal rate. EDM produces microscopic craters on the machined surface due to release of random sparks [4,11,12]. Hung et al. [13] noted that only the electrical current controls the surface roughness and the re-cast layer thickness rises with the rise of pulse-on-times as well as discharge current [11]. Agrawal et al. [14] investigated electrical discharge machining on 10 wt% of SiC and 10 wt% of $Al_2O_3$ containing Al-MMCs and modelled the process by artificial neural network. According to their model, material removal rate (MRR) rises with the rise of pulse current, wheel and workpiece speeds and depth of cut. However, the rise of duty factor reduces

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the MRR. In contrary, roughness ($R_a$) rises as the depth-of-cut, current, workpiece speed and duty factor rise. The rise of the wheel speed reduces surface roughness ($R_a$). Rozenek et al. [15] studied the influence of pulse-on-time, voltage, pulse-off-time and electric current on the speed and roughness after WEDM of $Al_2O_3$ and SiC particles reinforced Al-MMCs. The surface roughness rises with the rise of voltage, released energy and pulse-on-time. It was also noted that the type of reinforcement affects the machining speed. The highest speeds of machining of $Al_2O_3$ and SiC reinforced MMCs are around 6.5 and 3 times smaller than that of corresponding matrix material alone. Guo et al. [16] investigated 20 vol% $Al_2O_3$ particle reinforcement Al6061-MMCs by EDM at higher wire speed. Minor influence of the electrical parameters on surface roughness was noted in this investigation. Machining efficiency is improved by higher voltage, pulse-on-time and current. Yan et al. [17] performed WEDM on 6061Al-MMCs reinforced with 10 and 20 vol% $Al_2O_3$ particle as well as on matrix 6061Al alloy. The machining speed during machining of matrix materials was highest among all workpieces. The increase of the reinforcement volume fraction causes breakage of wire, narrower slit, rougher surface finish and wider/deeper craters on the wire surface. In the case of 20 vol% $Al_2O_3$ reinforced MMCs, the wire shifted due to impedance by protruding of reinforcement particles in the slit which causes bandings on the machined surface under low wire tension. Thus, frequency of wire breakage limits the machining speed of composites. However, Seo–Kim et al. [12] noted higher wear when volume percentage is lower which is contradictory to the results obtain by other researcher [18].

Too high electrical resistivity of engineering ceramics, such as $ZrO_2$, $Al_2O_3$ or $Si_3N_4$ hinders the EDM process of these materials. In order to use the advantages of the EDM process, a secondary electrically conductive phase, such as WC, TiCN, $TiB_2$, ZrC, or TiN can be added to obtain a composite that is electrically conductive enough to allow EDM machining [19–23]. Many studies on the EDM for conductive ceramic composites have been carried out [24]. The surface integrity of the EDMed specimens decreased with increasing current [25]. The mean surface texture improved as the discharge energy was reduced [26]. Martin et al. [20] have reported that $TiN/Si_3N_4$ composites are more easily machined than tungsten carbide and the tool consumption is lower. $ZrO_2$-based composites with 40 vol% WC, $TiC_{0.5}N_{0.5}$ or TiN phase addition have proven to be appropriate for wire EDM in demineralised water. The material removal mechanism was due to melting and evaporation. The machined surface consists of recast layer, resolidified droplets and voids as well as a micro-crack network. The surface roughness could be reduced by one third after consecutive EDM finish cutting. Amongst the $ZrO_2$-based composites, $ZrO_2$-WC exhibited better performance in EDM machinability (MRR and surface quality) and higher mechanical properties (strength, hardness and toughness), compared to $ZrO_2$–TiN and $ZrO_2$–TiCN composites with equal volumetric secondary phase content [23]. Pitman and Huddleston [21] applied a conductive silver coating over TiN reinforced $Si_3N_4$ composite workpiece surface. This coating reduced the drop voltage in workpiece material; thereby decreased energy loss. The conductive silver coating not only minimises the variation in resistance but also it increases the productivity of the process. The clamp position changes the cutting velocity significantly. As the cut approaches the clamp, there was an increase in MRR. A reduction in MRR occurs when the wire moves away from the clamp. Hence, it was found that actual MRR depends on the individual machining geometry and relative position of wire electrode with respect to clamping. Liu [24] investigated microstructure and conductivity of $TiN/Si_3N_4$ ceramic composites after electrical discharge machining (EDM). The wear rate of the electrode increases with increasing current in EDM process. The electrode wear rate of brass is higher than that of copper electrode. The wire surface was covered with resolidified-layer formation films. The wear surfaces of copper and brass electrodes are similar to those found after EDM process. These indicate that the erosion of tool electrode surface is smooth at EDM cutting. The sinker-EDM at higher pulse energy causes severe micro-damage in the surface. The micro-cracks are formed on the TiN grain boundaries of $TiN/Si_3N_4$ composites, which may play a role in toughening ceramics. The surface roughness was found to have greater dependence on pulse energy and, it also increases with the increase of pulse energy [24].

The literature review discussed above indicates that the available research works on WEDM are concentrated on the effect of machining parameters, spark energy and wire tension on the wire rupture, surface finish of the machined parts, MRR as well as the theory and experimental verification of crater formation on workpieces. So far, there is no published work on degradation of wire electrode during machining of MMCs though it is imperatively needed to have proper understanding on the dimensional accuracy of the machined parts as well as mechanism of WEDM. Therefore the present work investigates the role of different machining parameters on the degradation of wire electrodes during machining of Al-MMCs reinforced with different sizes of SiC particles.

## 2. Experimental

A series of WEDM of particle reinforced MMCs (with varying particle size) were carried out by FANUC ROBOCUT α-0iD machine. The metal matrix composites were made of 6061 aluminium alloy reinforced with 10 vol% SiC particles. Typical properties of 10 vol% SiC particles reinforced 6061 aluminium alloy MMC is given in Table 1 [27]. Three different reinforcement sizes were used: 13 μm, 3 μm and 0.7 μm. In addition, unreinforced 6061 aluminium matrix material was also machined under similar condition to understand the effect of reinforcement as well as size of reinforcement. During WEDM process, the following fixed parameters were employed: wire speed of 10 m/min, wire tension of 1200 gf, flushing rate of 10 l/min, open circuit voltage 85 V, servo voltage 44 V and hole-diameter of 12 mm. A brass wire with 0.25 mm of diameter and coated with zinc was used as wire electrode. Additional experiments were also carried out by varying pulse-on-time and wire tension to investigate the effect of pulse-on-time and wire tension on degradation of wire for MMCs reinforced with bigger (13 μm) and smaller (0.7 μm) particles. Details of the experimental conditions are given in Table 2. The machining conditions were selected based on the data presented in literature [15–18] and the existing facilities in the laboratory. A slot of 9 mm long and 12 mm width was produced on a plate of $137 \times 42 \times 9\ mm^3$ in each experiment. Several slots were produced in each workpiece under similar machining condition.

After WEDM, wire surfaces as well as wire cross-sections were investigated by Quanta 450 (FEI) SEM equipped with energy dispersive x-ray analysis (EDX). Cross-section samples were prepared by mounting the wires in resin followed by standard metallographic sample preparation procedure with final polishing in

**Table 1**
Mechanical properties of 6061 Al/SiC composite at room temperature (27 °C).

| Reinforcement (%) | Young's modulus (GPa) | Yield strength (Mpa) | Ultimate tensile strength (MPa) | Fracture stress (MPa) | Elongation to fracture (%) |
|---|---|---|---|---|---|
| 0 | 66 | 287 | 316 | 145 | 26 |
| 10 | 81 | 278 | 332 | 313 | 16.3 |
| 15 | 89 | 343 | 372 | 353 | 7 |