Electrochemical Jet Machining of High Volume Fraction SiCp/Al Composite using Electrolyte of Sodium Chloride

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Abstract. This paper investigated electrochemical jet machining of high volume fraction SiCp/Al using NaCl electrolyte. The mechanism of material removal has been discussed according to electrochemical theory and properties of the material. Experimental results show that the entrance diameter of machined holes is almost 3-4 times larger than jet diameter at present conditions. Compared with 2mm gap distance, machining with 5mm gap didn’t show advantages on machining localization.

1. Introduction

Silicon carbide aluminum matrix composite materials (SiCp/Al) combine the advantages of metal and ceramic materials, and therefore exhibit excellent material properties and performance [1, 2]. In these combinations, the aluminum acts as a matrix and the silicon carbide acts as reinforcement. The matrix material distributes the stress applied over it to the reinforcement constituents which also protects and gives shape to the matrix material. The reinforcement provides the desired mechanical strength to the composite material in a preferential direction [3]. The size and volume fraction of SiC reinforcement significantly affect the thermal and mechanical properties of SiCp/Al. For instance, the small size of SiC particles provides better mechanical properties and thermal stability, while large size and high volume of that give better wear resistance. Generally, the higher volume fraction SiCp/Al composites are commonly used in fields of aerospace, electronic packaging, precision instrumentation and automotive industry.

Machining processes are methodologies that remove unwanted material from a bulk workpiece and form the shape as a final product. The SiCp/Al composites are hard-to-machine materials because of the marked difference of physical properties between the reinforcement and matrix material. The use of traditional machining processes, e.g. milling and turning, to remove high volume fraction SiCp/Al composites will cause serious tool wear due to the significant hardness of SiC particles [4, 5]. The non-conventional techniques, such as electro-discharge machining (EDM), laser-beam machining (LBM), electrochemical machining (ECM) and abrasive water jet machining (AWJ), have been increasingly applied to these materials due to non-contact between tool and workpiece. Different non-conventional machining methods of SiCp/Al have their specific material removal mechanisms, and consequently have their own advantages and drawbacks.

Electrochemical jet machining (ECJM) is a non-conventional process which employs an electrolyte jet to corrode metals with a potential applied between workpiece and orifice [6,7,8,9]. Many research have successively fabricated various micro and small structures, e.g. holes, grooves, channels and...
cavities, at surface of different metals using ECJM. For example, Bisterov et al. applied a specific computer-aided manufacturing software tool and an ECJM machine to make complex surface structures at metals [8]. Martin et al. investigated removal geometry in profile turning with continuous electrolytic free jet at stainless steel with a jet diameter of 100 μm, a constant working gap of 100 μm and aqueous solution of 30wt% sodium nitrate [9]. They achieved a series of grooves having depth of tens of microns to around 100 μm.

Recently, ECJM of SiCp/Al has been paid attention because that process is independent of material strength and hardness. According to the theory of electrochemical anodic dissolution, the aluminum matrix can be easily corroded at a corrosive environment. This results in reduction of the area of interface between SiC reinforcement and metal matrix. As the interface becomes small enough, the SiC particle can be removed by the impact of high speed jet fluid. Literature [10] investigated ECJM of low volume fraction SiCp/Al with different neutral electrolytes. They found that the aqueous electrolytes of NaNO3 and NaCl cause different electrochemical dissolution characteristics. While the diameters of the dimples created with both electrolytes are similar, the usage of NaCl electrolyte results in significantly deeper dimples. However, the ECJM of high volume fraction SiCp/Al has never been explored yet. Therefore, this paper aims to experimentally study some characteristics of electrochemical jet machining of high volume fraction SiCp/Al.

2. Experimental configuration

The experimental apparatus is composed of a horizontal X-Y stage, a nozzle head, a diaphragm metering pump, a working liquid tank, a pulsation damper and a DC power supply, as illustrated in Figure 1(a). The nozzle head was made by stainless steel and assembled with a 300 μm diameter sapphire orifice in it. The metering pump was used to propel the electrolyte through the nozzle head to form an approximately 300 μm diameter jet. The DC power supply, which has a maximum output voltage of 200V, was used to provide a working voltage between metal nozzle and target for the experiments. The gap distance between nozzle and specimen can be regulated between 0 to 20 mm to meet experimental requirement. The presented apparatus is able to perform ECJM experiment as exhibited as Figure 1(b).

![Experimental apparatus](image1.png)

![Electrochemical jet machining](image2.png)

**Figure 1.** Schematic of electrochemical jet machining and experimental apparatus

The specimens used in the experiments are 65%-SiCp/Al plates with 5mm thickness provided by Hunan Harvest Technology Development Company (China). The SiC reinforcements have irregular shapes and its dimension of length is between 100-120 μm. A series of dimples were machined at a stationary jet impingement and constant conditions of jet pressure, gap distance, electrolyte concentration and applied voltage. Table 1 summarized the process parameters used in this work.
Table 1. Process conditions

| Jet diameter (mm) | Jet pressure (MPa) | Gap distance (mm) | Electrolyte concentration (wt%) | Applied voltage (V) | Process time (min) |
|------------------|-------------------|-------------------|---------------------------------|--------------------|-------------------|
| Ø0.3             | 4                 | 2.5               | 15%-NaCl                        | 150                | 1, 2, 3           |

3. Results and discussion

Figures 2, 3 and 4 illustrate typical machining results due to different gap distance and processing time. The surface topography of machined area can be clearly seen by cross-sectional views of Figures 2(a), 3(a) and 4(a). In the meantime, geometric shapes of the machining area can be identified by side views of Figures 2(b), 3(b) and 4(b). As can be seen from cross-sectional views, many micro pits distributed at the surface of the machining area. These micro pits are formed due to extraction of SiC particles during the ECJM process. As previously discussed, SiC is a non-conductive material and cannot be corroded in the ECJM, while the aluminum matrix can be quickly dissolved at a corrosive environment with NaCl solution. Thus, the electrolytic jet removes Al matrix continuously and it results in reduction of the interface of SiC-Al, and the SiC particles will be extracted from machining surface at the impact of high speed jet finally. Obviously, these micro pits significantly influence the roughness of the machining surface. Larger size of SiC reinforcement will definitely result in rougher machining surface.

Figure 2. Typical machining results due to 2mm gap and 2 min processing time.

Figure 3. Typical machining results due to 2mm gap and 3 min processing time.
Figure 4. Typical machining results due to 5mm gap and 3 min processing time.

Figure 5 exhibits inspected cross-sectional profiles due to varied gap distance and processing time. As illustrated by the figures, the machining depth and volume loss increase with processing time, and decrease with machining gap. This is coincident with the theory of electrochemical dissolution. Generally, the anodic dissolution rate \( v \) is determined by current efficiency \( \eta \), electrochemical equivalent \( \omega \), electrolyte conductivity \( \kappa \), applied voltage between two electrodes \( U \), applied potential of cathode and anode \( \delta E \) and gap distance between electrodes \( G \), e.g. \( v = \eta \omega \kappa (U - \delta E)/G \). Obviously, the material removal rate markedly affect machining depth and mass loss which will decrease with machining gap.

The Figure 5(a) also shows that diameter of entrance due to 2 min processing time varies between 1200 to 1600 \( \mu m \) in ECJM of the present material with NaCl electrolyte. These diameters are approximate 400-500% larger than diameter of the impinging jet. This is because that the sodium chloride is a type of electrolyte having stronger corrosively than sodium nitrate (NaNO\(_3\)). In other words, the machining localization of using NaCl is worse than using NaNO\(_3\). However, the machining depth significantly increases from 900 to 1500 \( \mu m \) (increase of 67%) while the entrance diameter almost has no change when processing time increases from 1 to 3 min. The geometry of the blind holes due to the present process also changes from a bell-shape to a straight-hole during that processing time. For the machining gap of 5 mm, the geometric features of machining area due to processing time 1, 2 and 3 minutes are similar. They are all bell-shaped and their volumes are significant smaller than using machining gap of 2mm at comparative conditions.

Figure 6(a) demonstrates the inspected material removal rate due to varied gap distance and processing time. In general, machining with gap distance of 2mm achieved material removal rate almost 3-4 times higher than that of 5mm. However, the machining of 5mm gap achieved smaller diameter of entrance than that of 2mm gap. Figure 6(b) compares typical cross-sectional profiles of machining with 2mm gap and 1 min processing time, and 5mm gap and 3 min processing time. As can be seen, these
two set of conditions performed similar geometric features, such as diameter of entrance and depth. This reveals that machining with 5mm gap cannot improve machining localization than using 2mm gap. Besides, machining of 5mm gap shows uncompetitive material removal rate compared with that of 2mm gap.

**Figure 6.** Comparison of material removal rates and cross-sectional profiles

### 4. Conclusion

This paper investigated machining of high volume fraction SiCp/Al using electrochemical jet with NaCl electrolyte. A set of blind holes have been experimentally drilled to evaluate the geometric features and material removal rate for the present process. In the process, the aluminum matrix was dissolved firstly and the interface between SiC particles and matrix was reduced consequently. Finally, SiC particles could be extracted from surface under continuous impact of high speed jet, which results in many micro pits at the machining surface. The entrance diameter of machined holes is almost 3-4 times larger than jet dimension at present conditions. Compared with 2mm gap distance, machining with 5mm gap didn’t show advantages on machining localization. In conclusion, electrochemical jet machining can be used as a costly and efficient process to machine high volume fraction SiCp/Al.

### Acknowledgments

This work was financially supported by National Science and Technology Major Project (2017-VII-0015-0111).

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