



Electrochemical slurry jet micro-machining of tungsten carbide with a sodium chloride solution



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ABSTRACT

Electrochemical slurry jet micro-machining (ESJM) is a new non-conventional process that couples abrasive slurry jet machining (ASJM) and electrochemical jet machining (ECJM) concurrently. A micro-jet of abrasive particles and electrolytic solution is made to impinge on the target while applying a DC potential between the jet nozzle and the workpiece. ESJM can be used to remove material that is difficult to machine through a combination of erosion, corrosion and synergistic effects. This study focuses on ESJM of tungsten carbide (WC) using a pH-neutral NaCl electrolyte rather than an alkaline solution which is more commonly used in the electrochemical processing of WC. For the studied process parameters, it was shown that the erosion due to ASJM alone was not able to erode the WC, and that the corrosion under ECJM was slow and produced unacceptably wide channels. The combined ESJM process however, was found to involve erosion of the developed oxide layer and subsequent exposure of un-corroded WC, leading to a much higher machining current density, corrosion rate, and machining localization than using ECJM alone. It was also found that the total abrasive kinetic energy, working voltage and solution concentration strongly affected the machining current density, material removal rate and aspect ratio (depth to width ratio). The results indicate that ESJM has a high potential to machine difficult-to-cut metals efficiently and economically.

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1. Introduction

Tungsten carbide (WC) alloys are fabricated by sintering extremely hard particles in a softer metallic matrix such as cobalt, resulting in a very high hardness and wear resistance [1,2]. WC alloys are thus commonly used in cutting tools, mining bits, sand-blasting nozzles and other wear resistant applications. However, their superior wear properties make them extremely difficult to machine using conventional processes [3,4].

In order to overcome the difficulties of using traditional approaches to process hard-to-cut materials such as WC and its composites, non-conventional machining processes are

increasingly being investigated, particularly for applications where micro-sized geometrical features are required [3]. For example, abrasive particles driven by a stream of fluid, usually air or water, have been used in an attempt to erode these materials. The erosion rate of several cermets (WC-Co and TiC metals) was investigated using SiC and Si₂O₃ particles, and a relationship between the target mass loss rate and the hardness of the erodent was hypothesized [5]. Rateick et al. (2006) [6] compared the solid particle erosion of WC-Co cermet to that of hardened AISI 440C stainless steel using aluminum oxide (Al₂O₃) abrasives with impingement angles of 20°, 50° and 90°, and at velocities of 60 and 120 m/s. It was found that the WC-Co cermet proved to be generally more erosion resistant than the AISI 440C. Akbarzadeh et al. (2012) [7] utilized magnetite particles driven by an air jet to investigate the erosion behavior of 12 materials, and found that there was no measureable erosion of WC even after 400 s dwell times.

The electrochemical machining (ECM) process removes metals using anodic dissolution in electrolytes under an electric field. Since its efficacy does not depend on the mechanical properties of the target material, it has received attention as a potential alternative process for machining hard metal alloys [2]. During the

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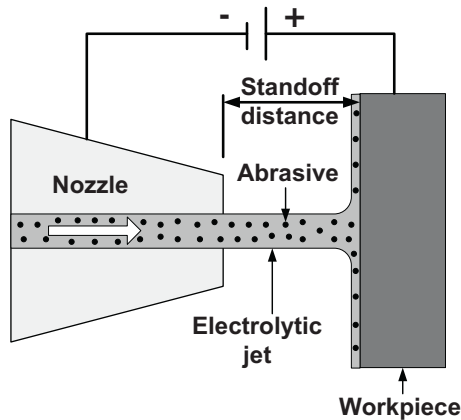


Fig. 1. Schematic of electrochemical slurry jet micro-machining (ESJM).

electrochemical machining of WC with a pH-neutral electrolyte, an oxidation film of tungsten (WO_3) with a thickness between two or three monolayers develops, and dissolves very slowly [8]. However, since this oxidation layer is known to be rapidly dissolved as WO_4^{2-} in an alkaline solution, a mixture of neutral and alkaline solutions (e.g. NaCl plus NaOH or NaNO_3 plus NaOH) is often used in the ECM of WC alloys [9,10].

Electrochemical jet machining (ECJM) uses a charged electrolyte jet impinging on a target to achieve anodic dissolution and is commonly used to process hard-to-cut metals [2,11,12]. However, the ECJM of WC alloys with a pH-neutral solution has similar problem to those described above for ECM. For example, Hackert-Oschätzchen et al. (2013) [2] studied the anodic dissolution behavior of WC applying ECJM with a neutral solution (NaCl and NaNO_3) and observed the formation of an oxidation layer on the specimen surface, which prevented the anodic target from continuously corroding. However, they were able to corrode micro-dimples and grooves on WC by using a mixed solution of NaNO_3 (1.2 M or 2.4 M) with NaOH (0.6 M or 1.2 M). Nevertheless, the use of alkaline solutions such as NaOH or KOH have not gained widespread acceptance in industry because they are hazardous and thus expensive to dispose of [9,13].

Electrochemical slurry jet micro-machining (ESJM), as shown in Fig. 1, is a new non-conventional machining process which employs a pre-mixed slurry jet (electrolyte mixed with abrasives) and a DC potential applied between the jet nozzle and target to remove material through anodic dissolution, erosion and synergistic effects [14]. It is a hybrid process that combines electrochemical jet machining (ECJM) with abrasive slurry jet machining (ASJM), in which a pre-mixed abrasive slurry is pumped at relatively low pressure (2–8 MPa) through an orifice to erode the target [15,16]. The combined process of ESJM results insignificantly higher metal removal rates than either ASJM or ECJM alone, and produces smoother surfaces than ECJM alone [14]. The major synergistic effects in ECJM are expected to depend on the target material and utilized process parameters. For example, in the case of the ESJM of ferrous metals using a NaCl solution, no oxide film will be developed on the target, and the corrosion simply enhances the rate of metal removal due to erosion [14]. However, in the case of the ESJM of WC using an NaCl solution, an oxide film is expected to rapidly develop and be removed by impacting particles, thus exposing new material to the electrolyte, leading to a continuous anodic dissolution; i.e. an erosion enhanced corrosion.

The objective of the present work was to investigate the interaction between solid-particle impact and anodic dissolution during the ESJM of WC with a pH-neutral electrolyte. Sodium chloride (NaCl) solution was selected as the jet electrolyte because it is safe

to handle, inexpensive and commonly used in industry [17]. Other advantages include its ability to corrode material rapidly, and for ferrous materials, the fact that it does not produce a passivation film on the machining surface [18]. As mentioned previously, the use of a NaCl solution in the electrochemical processing of WC alloys results in the generation of a surface oxide layer, because tungsten is oxidized readily by a pH-neutral aqueous solution [8]. During ESJM, this oxide layer is expected to be damaged by the impingement of the high kinetic energy particles, thereby achieving continuous anode dissolution by exposing the target surface to the corrosive environment. In the present work, the influences of working voltage, abrasive concentration, slurry jet velocity and solution concentration on the ESJM of WC specimens were investigated, and compared to ASJM (erosion alone) and ECJM (corrosion alone). In addition, the ESJM material removal mechanisms and machining localization were determined and discussed.

2. Experimental setup

2.1. Experimental apparatus

The ESJM apparatus, described in detail in Ref. [16], was based on a pre-existing low-pressure (1–8 MPa) ASJM setup consisting of a stirred slurry tank, a slurry pump (LCA/M9/11-DC, LEWA Inc., Leonberg, Germany) with pulsation damper (FG44969/01-9, Flow-guard Ltd., Houston, TX, USA) and a linear stage (KTLSM100A, Zaber Technologies Inc., Vancouver, BC, Canada). A regulated DC power supply was used to provide a working voltage between metal nozzle and target material. A current data logger (Hantek365A, Qingdao Hantek Electronics Co., Shandong, China), with an accuracy of $\pm 1\%$ and resolution of $10 \mu\text{A}$ over a range of 60 mA, was used to record the machining current for a better understanding of the anode dissolution behavior.

The slurry pump was used to propel the pre-mixed electrolyte slurry through a stationary $300 \mu\text{m}$ thick, $180 \mu\text{m}$ diameter sapphire orifice (KMT Waterjet, KS, USA), thus forming an approximately $180 \mu\text{m}$ diameter jet. The specimens were mounted on a linear stage that could move horizontally below the nozzle at velocities of up to 7 mm/s. The used electrolyte was collected and filtered for recycling.

2.2. Process conditions

WC grade K3109 plates with 2 mm thickness having the material properties listed in Table 1 (Kennametal, Latrobe, PA, USA) were used as the target material. For the ASJM and ESJM experiments, angular alumina (Al_2O_3) particles with a nominal diameter of $10 \mu\text{m}$ (Comco Inc., Burbank, CA, USA) were mixed at room temperature (25°C) with the NaCl solution (1 M, 2 M and 4 M concentration) to form slurries at various particle concentrations (0.125, 0.25 and 0.5 wt%).

Micro-channels were machined using ASJM, ECJM and ESJM by scanning the samples below the stationary slurry jet at a speed of 0.05 mm/s over a 10 mm length for two consecutive passes. Table 2 summarizes the process conditions for these experiments. For the ESJM experiments, the slurry jet pressure, abrasive concentration, solution concentration and working voltage were regulated from 2 to 4 MPa, 0.125 to 0.5 wt%, 1 to 4 M, and 60 to 120 V, respectively. For the ASJM experiment, the WC was very difficult to erode, and thus only the highest abrasive concentration (0.5 wt%) and jet pressure (4 MPa) were used for comparison purposes. Similarly, since material removal was low using ECJM, the working voltage was restricted to 120 V, the highest available voltage.

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