A review of physical experimental research in jet electrochemical machining

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Abstract

Jet electrochemical machining (Jet-ECM) is a non-traditional machining process that has developed rapidly since its introduction in the 1980s with progress being made in micro-machining and surface finishing. This paper critically reviews the development of physical experimental work in Jet-ECM and corresponding hybrid technologies and their applications, e.g. laser- and air-assisted Jet-ECM. In addition to discussing the merits of the physical experimental research, the paper concludes with research challenges in the future of Jet-ECM development.

Keywords Air-assisted Jet-ECM · Electrochemical machining · Jet electrochemical machining · Laser-assisted Jet-ECM

1 Introduction

Jet-ECM, also known as electro jet drilling, electro jet machining, electrochemical jet machining is a non-traditional machining technique in which a free jet of electrolyte locally removes material from an electrically conductive workpiece via anodic dissolution. Although Jet-ECM is developed from and shares several similarities with traditional electrochemical machining (ECM), it has its own unique characteristics. Unlike ECM, jet-ECM does not use a tool to produce a negative imprint in the workpiece; instead, a pressurised jet of electrolyte is expelled through a nozzle to locally dissolve material at the contact area between the jet and the workpiece [1].

Although the concept of Jet-ECM first appeared in the 1980s [2], the rate of research and development has accelerated in the twenty-first century, both in physical experimentation and in modelling and simulation of the process, for example, simulation of material removal [3] and energy distribution modulation [4]. Jet-ECM has become an attractive area of research due to its benefits over both

traditional and alternative electrochemical processes due to its ability to machine micro-size features regardless of material hardness, without producing heat-affected zones, surface stresses, micro cracks and burrs at good energy efficiency [5]. These characteristics lend Jet-ECM to several manufacturing sectors, including but not exclusive to aerospace, micro-electronics, medical and biomedical applications.

This paper critically reviews the development of physical experimental work in Jet-ECM and corresponding hybrid technologies and their applications, that is experimental work exclusive of modelling and simulation studies.

2 Overview of the Jet-ECM process

Jet-ECM is built upon the application of the electrochemical process of anodic dissolution. Fundamentally, as in ECM, the system requires two electrodes (an anode and a cathode), a conductive electrolyte which contains ions that can freely move and a power supply or battery connecting the two electrodes (Fig. 1). In the case of Jet-ECM, the electronically conductive workpiece becomes the anode, and the nozzle the cathode.

The process of anodic dissolution can be complex depending on material constituents, current, passive oxide layers, oxygen evolution and electrolyte-surface films. Using iron (Fe) as an example, and in its simplest form, the dissolution reactions are:

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Fig. 1 Schematic of electrolyte jet machining [1]

At the anode (workpiece), the base metal dissolves in contact with water to produce ionic metal (1).

At the cathode (nozzle), the free electrons flow to the nozzle where hydrogen evolution occurs (2).

At the electrolyte-anode boundary, the base metal reacts with the hydroxide ions to produce a metal hydroxide (3) which can be carried away from the workpiece.

The dissolution process continues in this continuous cycle. However, as previously mentioned, there are several dissolution mechanisms and variables. For example, in oxygenated environments, the ionic metal can react with the oxygen to produce new oxide layers on the material surface which in turn have to be overcome. Due to this process occurring only at areas on the workpiece in contact with the electrolyte jet, the electrochemical reaction provides localised and controlled material removal. When material removal rates and profiles are known with controlled process parameters, Jet-ECM has the ability to machine micro features.

3 Unassisted Jet-ECM

The majority of research performed in the field of jet-ECM has been physical experimentation, and within that bracket most has been performed in unassisted Jet-ECM, that being using only an electrolyte jet with no laser [6] or ultrasonic assistance [7].

Ippolito et al. [2] looked into the use of electron-jet drilling to produce the holes in diesel motor injection valves in collaboration with the Fiat research centre. They looked to use a stationary nozzle, as a fixed electrode is

more reliable than that found in electro stream drilling for large machining cycles, and a fixed glass electrode would offer wear, corrosion and electrodeposition resistance over a platinum counterpart. Contrary to their study on literature, it was found that the relationship between current and voltage was not linear, and is adiabatic rather than isothermic [8]. The high voltages used (200, 300, 500 V) caused heating in the electrolyte, increasing conductivity but also gas bubbles from electrolyte boiling. A new relationship (4) for conductivity is proposed; however, this mode is both electrolyte and workpiece material specific, with the electrolyte used unknown.

$$k = k_0(1 + f(\Delta T)) \quad (4)$$

Where:

k = conductivity

k_0 = measured conductivity at 180°C

ΔT = difference in temperature from 18 °C

$f(\Delta T)$ = polynomial function of ΔT

The authors also focus on the relationship between the working parameters (nozzle diameter, electrolyte flow rate, voltage and gap) and the diameter of the hole produced at these parameters. It was found that the ratio of the diameter of the hole to the nozzle has a minimum value that decreases with voltage and at an optimum flow rate for each voltage. It was concluded that the ratio could never be nominal, that there is 'no simple relationship between the working parameters and the hole diameters' [2] and that working gap had no influence on the hole diameter.

Sen and Shan [9] analysed the effect of process parameters on roundness error, surface roughness and material removal rate (MRR) response parameters on SUPERNI 263A material using an acid electrolyte. As in Ippolito's study [2], a glass nozzle was used. Although using a glass nozzle offers higher corrosion resistance and reduced risk of sparking, the working gap between the current providing anode and cathode is significantly increased, requiring much higher levels of potential difference to apply the required threshold currents. Using central composite design (CCD), the major findings suggest the applied voltage and electrolyte concentration have the highest effect on all 3 response parameters, with MRR and roundness error increasing with voltage and electrolyte concentration and surface roughness improves with increased voltage and decreased electrolyte concentration. With a focus on applied voltage, the study does not present the current achieved in experimentation making comparison with later studies difficult. Parameters for best quality holes produced using $NaNO_3 + H_2SO_4$ electrolyte are presented in Table 1.

Natsu and Kunieda performed two investigations into producing complex surfaces [1] and three-dimensional surfaces using Jet-ECM [10]. The work built upon

Table 1 Parameters for best hole quality [9]

Applied voltage	340 V
Capillary outside diameter	0.4 mm
Feed rate	0.5 mm/min
Electrolyte concentration	17.5%
Inlet electrolyte pressure	0.3 MPa

investigations in the 1990s in which Yoneda and Kunieda studied the electric potential distribution and the current density distribution in the electrolyte flow and workpiece (Fig. 2) respectively while producing micro indents [11], and in the second investigation on rolling bearings [12]. From both experiments, it could be seen that using superimposed paths could produce complex shapes, with an 8% error on calculated expectations. However, optimising the parameters in each machining interval reduces this error [10]. Other findings include:

1. At constant current, pit depth vs. time is a positive linear relationship, but surface roughness does not vary with time.
2. Increase in current improves surface roughness values, up to a current density (J) of 110 A/cm^2 where the relationship plateaus.
3. When machining grooves, lower speeds produce higher removal, while surface finish is improved with more scanning runs due to reduced exposure to the peripheral low current density.

Unlike Ippolito et al. [2], Natsu et al. [10] found that altering the gap width did have an effect on the machined profile diameter. To predict the machined profile from superimposed paths, a function of machined depth was calculated from a sample experiment in which a pit was machined with known parameters. This function could then be used to predict material removal. Although for these experiments this gave good results, it is both material and

parameter specific and so would require a large range of sample experiments for a comprehensive database of material removal when compared with a prediction based on basic principles.

In 2011, Kunieda et al. proposed a novel technique for Jet-ECM. Whereas earlier Jet-ECM experimentation was developed around the use of a cylindrical nozzle, the use of an elongated or ‘letter box’-shaped nozzle was first used in order to increase the jet contact area [13]. An investigation into jet quality showed that the working gap plays a big role. The length of the machined profile, parallel to the slit nozzle decreased with increased gap, but the width increased. Increasing the pressure caused the jet to keep better shape, but the ends of the produced groove were rounded due to surface tension at the jet edges, an issue not found with traversing cylindrical nozzles. An expanding throat nozzle was introduced to combat the larger width at larger working gaps. Expanding the jet parallel to the slit direction allows the thickness to decrease. The machined groove length increased with increasing working gap up to 6.5 mm; where it began to decrease due to surface tension with increased working gap.

Although the concept of the slit nozzle increases the machined area in micro-milling and surface texturing applications, it also lends itself to turning applications. When machining cylindrical workpieces with a slit jet with a greater width than the cylinder diameter, initial positioning perpendicular to the cylinder length is unnecessary. It also ‘enables significantly quick machining compared with cylindrical jets since the flat jet can hit the circumference at the same time [13]’. Grooving, cutting off and face turning procedures all produced good results using a nozzle with dimensions of $2000 \times 40 \mu\text{m}$ (Fig. 3). When investigating longitudinal turning and profiling, a copper wire was successfully turned down from 300 to $60 \mu\text{m}$ as well as producing a sinusoidal profile by varying current along the feed length.

Fig. 2 **a** Electric potential distribution. **b** Current density distribution [1]

Fig. 3 Longitudinal turning [13]

In setting up a new generator to an existing Jet-ECM prototype, Schubert [14] studied the influence of electrical voltage and working gap on achieved current densities and widths, depths and surface qualities of the machined geometries. Although several of these relationships had been studied before, for example current and surface roughness relationships [10], this experiment includes preliminary studies to specify breakdown voltages at several working distances, allowing a safety against breakdown and derivation of maximum working voltages at each distance. At working distances below 20 μm , wide and imprecise cavities were generated, up to 2.5 times the nozzle diameter. This was due to the fact that in such a short gap, a free jet is unable to form and the nozzle is in fact enclosed by the electrolyte [14].

Over a range of 5–100 V and working gaps of 10–100 μm , higher voltages produced higher material removal rates, and larger working gaps reduced material removal; however as previously mentioned, at small working gaps, accuracy is reduced. Schubert [14] found that surface roughness values improve with increased current, the same trend found by Natsu et al. [1]. The surface roughness value of 0.1 μm Rz achieved by Schubert is an improvement on that achieved by Natsu et al. As expected, applied current decreases with distance at constant voltage due to increased resistance over the length of the jet, while at constant working distance, applied current increases with voltage.

Following the research performed by Natsu et al. [1] and Natsu et al. [10], two further studies were performed at the University of Tokyo by Kawanaka et al. [15] and Kawanaka, Kunieda [16] based around the surface qualities achieved through Jet-ECM. Originally, looking at the influence of current density on surface roughness of machined pits of equal depth (50 μm) using sodium nitrate (20% by wt.) electrolyte as current density increased, surface roughness improved, but only to a certain point. The finest surface roughness value of 14.1 nm Ra was achieved at a current density of 87 A/cm^2 , where after this point, surface roughness values increased (Fig. 4). However, the measurement method for the surface roughness values

Fig. 4 Surface roughness vs. current density [15]

and the parameters chosen are not outlined in the study. This upwards trend was different to that seen previously by Schubert [14]; however, a larger number of current values were studied by Kawanaka et al. It was found that any current density above 50 A/cm^2 produced a glossy, ‘mirror like’ surface (Fig. 5) [15]. When looking more closely at the surface morphologies, the surface at low current densities (<50 A/cm^2) was anisotropic and heavily influenced by the original surface quality, whereas at high current densities (137 A/cm^2), the surface morphology was isotropic [15].

Kawanaka et al. also compare the influence of electrolyte on surface textures. At low current densities, complicated porous structures were produced, but within that, sodium chloride produced larger pores than the sodium nitrate counterpart showing that the surface morphology is electrolyte dependant and surface textures can be varied by changing electrolyte and current densities [15].

Later, Kawanaka and Kunieda investigated the effect of translating speed on surface roughness, as well as producing a comparison between finishing with direct current, pulse current and bipolar pulse current [16]. To study the effect of translating speed on surface roughness, the number of reciprocating translations changed in proportion to translated speed and inversely proportional to current density to machine grooves of the same depth. It was found that increasing translational speeds produced better surface finishes at all current densities studied, with all current densities being above the threshold value for machining.

In an electrolyte jet, the current distribution causes the current density to be higher at the centre of the jet than on the outer edges. While the high current density smooths the surface quickly, the lower current densities roughen the surface in comparison [10, 15] and at lower translating speeds, the dwell time over a certain point causes a roughing effect. However at higher translational speeds, this roughing effect becomes insignificant as the dwelling time is short [16].

Fig. 5 Machined dimples (50 μm depth) with varying current densities [15]

Furthermore, when comparing the surface roughness without translation and with translation of 100 mm/s, only one current density investigated had a better surface roughness value without translation, leading to a belief that producing mirror surfaces requires translation as a prerequisite [16]. However, mirror surfaces ($<0.2 \mu\text{m Ra}$) were achieved when pitting in a previous paper [15], therefore, although translating speeds aid surface roughness, it is not a prerequisite, especially in machining situations where high-speed translation is difficult or not required. Although built upon the previous study by Kawanaka et al. [15], the surface roughness values of 14.1 nm Ra were not re-iterated in this study.

Using a pulsed current with pulse duration 100 μs and varying the duty factor (1, 10, 100%) allowed an examination of the effect of pulsed current on surface roughness [16]. Pulsing the current with sufficient pulse length prevents the formation of the electric double layer in the areas of low current density, therefore preventing machining in low current density areas. Both the 1% and 10% duty factors produced better surface roughness values than a 100% cycle for all translating speeds with mirror like surfaces produced at very low translating speeds (0.01 mm/s) at 1% duty factor. However, this came at a cost of significantly lower material removal. The use of a bipolar pulsed current allowed the discharging of the electric double layer when the workpiece became the cathode. Again, this improved the surface roughness values achieved at all translating speeds, with lower duty cycles producing better surface finishes. The bipolar current could produce surface roughness values equivalent to those of the pulsed current at duty factors 5 times higher (Fig. 6), allowing faster material removal. However, use of a bipolar current wears the metallic nozzle, removing one of the major benefits of Jet-ECM. Bisterov et al. [17] developed an electrochemical jet processing (EJP)-specific computer-aided manufacturing software with the aim of controlling the Jet-ECM process to produce specifically located micro-scale features. The software allows the definition of process parameters as well as tool path strategy as well as the ability to replicate images

in to machined profiles. Roughness variation tailors the roughness gradients across machined profiles. Ultimately, the study and development of CAM software shows the ability to move from machining relatively simple profiles (straight lines) to more complex patterns.

Chen et al. [18] proposed a method of machining micro dimples through the use of a conductive mask. The use of a conductive mask was thought to reduce the intensity of the electric field around the edge of the dimple. The mask used had through holes of 200 μm diameter on stainless-steel samples. The machining localisation was improved with the use of a conductive mask over an insulated mask, at the cost of a reduction in current efficiency [18]. Comparatively, this study produced dimples 240 μm wide by 85 μm deep, no better than those achieved by Hackert-Oschätzchen et al. [19] without the use of a mask. It is worth noting that the mask requires close contact with the surface, so limits the method to flat surfaces. Although the conductive mask presents benefits over traditional Jet-ECM, the inclusion removes a benefit of the process over traditional manufacturing and EDM in the need for no specific tooling.

Similarly to the studies on electrolyte jet turning performed by Kunieda et al. [13] and Mizugai et al. [20],

Fig. 6 Influence of bipolar current on surface roughness [16]

Martin et al. analysed the removal geometries in Jet-ECM profile turning [21]. Unlike the previous studies by Kunieda et al. [13] and Mizugai et al. [20] in which a ‘letter box’ nozzle was used, Martin et al. performed the turning operations with a cylindrical jet [21]. Voltages of 10 to 60 V were analysed with the number of rotations increased from a single rotation to 10 rotations at constant rotational speed for each voltage. It was found that removal depth increased with both increased voltage and increased rotations in a non-linear fashion, with a declining increase with increased rotations at all voltages, attributed to increased resistance with increased IEG. In a comparison with Jet-ECM on planar surfaces, the width of channels was lower in the turning application at similar removal depths to those on planar surfaces [21].

Whereas Jet-ECM is usually performed in an unsubmerged environment, Ming et al. studied the Jet-ECM process in a kerosene submerged environment [22]. They expected that submerging the process in an insulating liquid medium would enhance the localization of the current in the jet. It was found at all applied voltages; surface roughness was improved in the submerged experiments in comparison with an unsubmerged experiment. However, improvement of localisation, or aspect ratio of dimples, was only found at specific parameters, namely at lower applied voltages. For example, at a working gap of 0.2 mm, aspect ratio was only improved at applied voltages lower than 14 V [22]. Although at some parameters kerosene submerging provides a benefit over standard jet-ECM, in general, no improvement is seen or dimple diameters are larger with kerosene submersion. Kerosene submersion adds an extra complexity to the process, as well as safety concerns.

Up to this point, all mentioned experimental studies have been performed on stainless-steel workpieces of various kinds. The rest of this section addresses experimentation performed on other materials and the variations in processes and results that arise.

Lu and Leng performed a study into the use of Jet-ECM on titanium alloy (Ti6Al4V) surfaces for biomedical applications where surface features in the range of 100 μm are essential on load-bearing implants [23]. They used

a metal nozzle of diameter 300 μm coated in epoxy to reduce the electrical resistance and an electrolyte of 5 mol/L NaBr aqueous solution. In general, the current density used in this study was low compared with previous studies with values less than 50 A/cm²; however, the depths of machined holes in the study were greater than 1 mm after 3 min of machining, with a depth to width ratio of between 1.2 and 1.4 and the diameters of the holes produced being over two times the diameter of the nozzle. When compared with through mask ECM, although through mask ECM produces regular patterns in a batch process, the Jet-ECM process can be used on irregular curved surfaces, and produce holes with a higher aspect ratio with a more simple setup [23].

In 2013, Hackert-Oschatzchen et al. attempted to machine step holes and grooves in tungsten carbide alloys [24]. The structure of carbide alloys makes them highly challenging to machine, and especially machine micro-geometries with traditional mechanical methods and with machinability via ECM being separated from mechanical properties this provided a good opportunity. In preliminary studies, it was seen that when machining purely cobalt (the predominant binder in cemented carbides) that a sodium chloride electrolyte (20% by weight) produced smoother surfaces with less stray machining than sodium nitrate (30% by weight)[24]. This is the opposite to that seen by Kawanaka et al. [15] on stainless steel where larger pores were produced by sodium chloride. When the experimentation was expanded onto tungsten carbide, neither of the pH-neutral electrolytes produced any material removal (Fig. 7). Using an alkaline electrolyte previously investigated by Schubert [25] on cobalt consisting of a mix of 1.2 mol/l of NaNO₃ and 0.6 mol/l of NaOH in de-ionised water, the machining of tungsten carbide was successful. For the main study, samples of tungsten carbide with different average grain size (1, 2, 4 μm) in a cobalt binder with binder ratio 6% were investigated for point and linear erosions. On pre-ground samples, the surface roughness deteriorated with increased grain size. At a machining voltage of 20 V, the depth of machined pits increased with grain size; however when the voltage is increased to 30 V, with a

Fig. 7 SEM images of point and line erosions in pure tungsten carbide with 20% of NaCl (a) and 30% of NaNO₃ (b) [24]

corresponding current increase, the fine and course samples produce pits of reduced depth, where the medium particles removal is relatively unchanged. This lead to a belief that the particle sizes are affected by the applied voltage in a noticeable way [24]. The relationship of pit width and voltage for each sample was much more varied, but also voltage dependant.

Secondary findings show that increasing the salt factor of the electrolyte (increasing the conductivity by a factor of 1.5) increases the aspect ratio of machined pits, as seen previously, longer machining times increased both the width and depth of machined pits, and again, opposing Ippolito et al. [2] increasing the gap width results in wider profiles up to an optimal electric potential [24]. Overall, the surface roughness was not improved over the original ground surface, as the grain size is the predominant factor in the surface roughness of the material.

Hackert-Oschätzchen et al. [24] also investigated creating 3D geometries, similar to the experiments on superimposition previously performed by Natsu et al. [1]. Whereas Natsu used an algorithm to alter the machining feed rate at fixed intervals to produce superimposed shapes, Hackert-Oschätzchen et al. replicated this technique but also attempted to produce a sloped surface using fixed speed, with fixed distance between runs, but repeating certain runs to increase material removal along certain paths [24]. Using the variable speed technique, a smooth convex surface was achieved using a small distance between passes of 20 μm . Using the several pass method, a slope was achieved, however with the increased distance between passes of 175 μm , kinematic roughness or ridges could be seen (Fig. 8). Using smaller distances between passes would reduce this roughness.

An alternative study for Jet-ECM of cemented carbides was presented by Mizugai et al. in the same year [20]. Whereas Hackert-Oschätzchen et al. [24] were unable to machine tungsten carbide with a pH-neutral sodium nitrate solution, Mizugai et al. successfully performed this task using both D.C. and A.C. currents. Mizugai et al. found that NaOH was formed at the cathode during the Jet-ECM process, and is in turn transferred to the anodic workpiece

via the electrolyte jet flow, meaning no NaOH had to be added to the original electrolyte. However, the NaOH is produced on the inner wall of the nozzle, and is therefore transferred in the outer areas of the jet, causing wider machined geometries (4 times the nozzle diameter) as the NaOH required to breakdown the material is not mixed to the centre of the nozzle [20].

Replacing the metallic nozzle with one made of ceramic allows premixing of the NaOH into the electrolyte in a metallic nozzle holder, and then applied to the workpiece equally to the workpiece. As the current is highest in the centre of the jet contact area, the ceramic nozzle allowed deeper, more precise machining under a direct current. This result was up to a current limit of 30 mA, as further increased current resulted in shallower, wider pits as the current limit for breakdown was reached over a wider area.

Mizugai et al. offer another option of using an AC current to machine the tungsten carbide samples, similar to what would be later seen on stainless steel by Kawanaka and Kunieda [16]. The concept was that when the polarity was reversed, the now cathodic workpiece would produce NaOH on the surface as previously found on the metallic tool, a concept based upon the work of Masuzawa and Kimura [26]. The NaOH produced on the workpiece dissolves the tungsten oxide layer on the workpiece surface. Like Kawanaka and Kunieda [16], when using the metallic nozzle with an AC current, the inner portion of the nozzle was badly worn out after 15 min of machining time (Fig. 9). When swapping to the ceramic nozzle, the tool wear was prevented; however, the machined pit had a lesser aspect ratio, showing the ceramic nozzle lost some of the accuracy of its metallic counterpart. This was put down to inaccuracies in the nozzle itself, as the ceramic nozzle was not produced for purpose [20].

When using an A.C. current with ceramic nozzle, machined depth increased with current and time, up to a limit where the pit depth became saturated if the current was too high. The optimum current frequency was found to be 5 Hz, and duty factor of 70%. At a lower duty factor, surface roughness increased, above 70%, the pit shape became erratic [20].

Fig. 8 Three dimensional slopy surface (a) and convex surface (b) produced by Jet-ECM [24]

Fig. 9 Metallic nozzle wear from AC machining. Before machining (a) and post-machining (b) [20]

In 2016, Hackert-Oschätzchen et al. studied the machining of particle-reinforced aluminium matrix composites using both sodium nitrate and sodium chloride pH-neutral electrolytes [27]. The experiments were performed on an EN AW 2017 aluminium matrix containing silicon carbide particles of either 5 or 10% content. Both electrolytes were used in quantities that provided the same conductivity of 185 mS/cm. They found that in preliminary testing, sodium nitrate produced a passivating effect on the aluminium surface, whereas sodium chloride did not, and also provided more rounded edges to the pit machined. At a machining voltage of 20 V and for a time of 2 s, using sodium chloride produced pits nearly twice as deep as that using sodium nitrate, where both had pit widths twice the nozzle diameter. In conjunction with other experiments studied in this paper, depth and width of machined pits increased with voltage and machining time. Interestingly, changing the percentage of silicon carbide particles in the matrix did not change the machining results [27].

Building upon the work performed by Kunieda et al. on electrochemical turning using a flat jet [13] and by Mizugai et al. on machining cemented carbide [20], Miyoshi and Kunieda developed a jet turning system for the machining of cemented tungsten carbide rods [28]. As seen by Hackert-Oschätzchen et al. [24] and by Mizugai et al. [20], when machining with a DC current on tungsten carbide, a tungsten oxide layer was formed on the workpiece, preventing further machining. Using the bipolar current investigated by Masuzawa and Kimura [26] and using current parameters from the experiment by Mizugai et al. (5 Hz at a 50% duty factor), Miyoshi and Kunieda achieved an aspect ratio of 20 on a turned section of a tungsten carbide rod, with a finished diameter of 36 μm . However, contrary to the results of Hackert-Oschätzchen et al. [27], material removal increased with decreasing grain size, although the range of grain sizes was much larger in Miyoshi and Kunieda's investigation (2–10 μm) compared with 1–4 μm in the Hackert-Oschätzchen et al. [27] study. It is also worth noting that the duty factor selected in this experiment is different to the optimum found

by Mizugai et al. [20] of a 70% duty factor as although material removal is less at 50% duty factor, the width of the machined geometry is significantly reduced, allowing more accurate turning. Like Hackert-Oschätzchen et al. [27], Miyoshi and Kunieda did agree that the surface roughness values achieved are heavily influenced by the grain size [28].

Similarly to how Hackert-Oschätzchen et al. [27] studied the effect of electrolytes on an aluminium alloy, Speidel et al. [29] investigated the Jet-ECM of titanium alloys using novel electrolyte solutions, specifically how the use of bromides, chlorides and fluorides compare with nitrates on surface finish, material removal rate and pit formation. It was known that during the ECM process, a non-conductive passivating layer formed on the material surface and that neutral pH electrolyte had previously performed poorly on titanium alloys.

Due to the insolubility of sodium fluoride in water, it could not be directly compared with the other electrolytes at the studied concentrations and therefore a sodium chloride electrolyte doped with fluoride was used for comparison [29]. In agreement with Sen and Shan [9] when increasing the concentration of salt in the solution, the pit depth increased when using sodium nitrate. However, for the chloride- and bromide-based electrolytes, increasing the salt concentration had no effect on the machined depth achieved allowing similar machining performance to be achieved with lower electrolyte concentrations. The fluoride-doped electrolyte achieved lesser depths than the chloride-only electrolyte in the same concentration.

In terms of surface textures, Speidel et al. [29] found the surface produced by the formation of the 'short-lived titanium (IV) chloride (TiCl_4) species at the machining interface, which hydrolyses as it is washed away from the machining surface' leaving no oxide layer on the surface. Although bromides caused a similar reaction, the titanium bromide species decomposed too quickly to be washed away, leading to a scale being left on the surface of the titanium. Overall, the chloride-only electrolyte gave the best surface qualities. Chloride-based electrolytes led to the greatest pit depths,

material removal rates (Fig. 10) and surface finishes but in terms of machining accuracy, bromide-based electrolytes outperformed the chloride counterpart.

Liu et al. published a comprehensive study on machining TB6 titanium alloy with aiming for industrial applications [30]. They used a copper nozzle of 2 mm diameter, much larger than those seen in previous experiments, for example 50 μm [10] and 100 μm [14]; however, the focus is based more upon material removal than the machining of microgeometries. Investigations included a large range of voltages, working gap and flow rate parameters in depth, and for the first time the effect of electrolyte temperature on machining results, although it had been previously touched upon by Natsu et al. [1]. Liu et al. also give a more in-depth analysis on the effect of electrolytes and the associated mechanisms [30]. Whereas previous studies analyse the surfaces machined using various electrolytes [29], they suggest the reason for the chloride-based electrolytes are more effective at machining titanium due to the ions being much smaller and more efficient at penetrating the oxide passive layer.

Increasing the sodium chloride electrolyte temperature from 20 to 60 °C halved the energy required to activate the dissolution process as at higher temperatures, the attack and removal of the passive layer are accelerated [30]. However, Liu et al. found there to be a limiting factor to the temperatures used, as in the inter electrode gap (IEG), the electrolyte can increase in temperature by 60 °C and if evaporation occurs, performance is severely hindered. When using sodium nitrate, increased temperatures in the electrolyte increase the rate of oxidation making the surface more counterproductive for machining. When investigating parameters for material removal, in agreement with Speidel et al. [29], it was found that increasing the concentration of sodium chloride resulted in higher material removal on titanium due to higher conductivity and therefore higher current at constant voltage. In the research, it was found

Fig. 10 Material removal rates in various electrolyte solutions on titanium [29]

the same relationship as Schubert [14] in that increasing the inter electrode gap decreases the material removal rate as well as discovering an increased flow rate improves material removal rates [30].

When studying how the machining parameters affect the surface finish, Liu found that the surface machined using sodium nitrate, oxide layers and micro-pitting left undesirable surface qualities. However, when using sodium nitrate, an increased voltage, and therefore current improved the surface roughness values, as seen in previous studies [9, 10, 14, 15] albeit on a different material. Increasing the inter electrode gap had a negative effect on the surface roughness, but due to the increased resistance, as in decreased current rather than the quality of the jet over different lengths [30]. Liu also considered the effect of process parameters to realise the optimal parameters for machining performance, with the results seen in Table 2. Liu claims these are acceptable parameters from an industry viewpoint [30].

Mitchell-Smith et al. investigated the effect of nozzle geometry on the ability to machine complex surface structures [4]. They aimed to address the fundamental limitations of Jet-ECM through changing the nozzle geometry, and subsequently the current density distribution. In straying from the traditional cylindrical nozzle, a new parameter defining spacing between nozzle and workpiece was required rather than the standard IEG. They used several modified nozzles, produced by wire EDM of a standard nozzle, as seen in Fig. 11.

It was found the off-centre single point element nozzle produced the deepest machined profile, and the symmetrical twin element nozzle produced a wider cut than the standard nozzle, but with steeper side walls [4]. Overall, the study showed that altering the mechanical design of the nozzle can alter the profile of the machined areas in comparison with a standard nozzle, and that combinations of nozzles can machine complex geometries providing a larger degree of control and profile prediction.

Clare et al. purposely built an enhanced tool holding system to allow the nozzle angle to index relative to the workpiece [31]. In the study, nozzle orientations of 22.5° and 90° were compared on Inconel 718 workpieces, with two current densities (200 and 400 A/cm²) and two

Table 2 Optimum parameters and machining results on TB6 titanium alloy [30]

Optimum parameters	Machining results using optimum parameters
Voltage: 24 V	Material removal rate: 10.062 g/min
IEG: 0.6 mm	Surface roughness: 0.231 μm
Flow rate: 2.1 L/min	Taper: 2.5
Electrolyte: NaCl 15%	Average overcut: 1.01 mm

Fig. 11 SEM images of standard nozzle (a), centre point element nozzle (b), symmetrical twin element nozzle (c) and off-centre single point nozzle (d) [4]

nozzles, one standard and one chamfered similar to that in the study by Mitchell-Smith et al. [4]. They found the use of an iodide-doped electrolyte increases the precision with a 172% increase in slope and 99% reduction in overcut compared with standard sodium nitrate electrolyte. The chamfered nozzle at 22.5° orientation significantly enhances the precision of the cut. Overall comparisons between modes, or combinations of electrolyte, nozzle and orientation angle are also analysed.

In a similar study to that of Clare et al. [31], Mitchell-Smith et al. also studied the effect of nozzle orientations on an Inconel 718 workpiece [32]. Whereas Clare et al. [31] studied two nozzle orientations, Mitchell-Smith et al. [32] studied the effect of nozzle orientations of 22.5° , 67.5° and 90° to the material surface, as well as the effect of machining direction relative to the nozzle orientation angle, which they define as ‘pushing’ or ‘pulling’ while varying the jet flow rate. It was found the surface finish was better when the nozzle was ‘pushed’ or angled towards the direction of movement compared with when the nozzle is angled away or ‘pulled’. This is due to the current being higher on the trailing edge of the jet due to a lower IEG, and the surface roughness is dominated by the parameters of the trailing edge, as this machines the surface last. Orientating the nozzle at 22.5° or 157.5° increased the depth of the machined profile by 23% in comparison with a 90° orientation. The jet velocity had no noticeable effect on the results in this study [32].

A study into the finishing of silicon carbide re-enforced aluminium using various electrolytes was produced by Lehnert et al. [33]. The study looks into the use of sodium bromide, sodium chloride and sodium nitrate on finishing aluminium matrices of 0, 5 and 10% SiC particles under identical process parameters. It was found dissolution characteristics are electrolyte dependent, with sodium chloride electrolyte producing the deepest point erosions, and sodium nitrate electrolyte the shallowest, results in keeping with those produced by Hackert-Oschätzchen et al. [27]. Similarly to Hackert-Oschätzchen et al. [27], the percentage of silicon carbide particles in the matrix

did not affect machining using sodium nitrate electrolyte [33]. However, with the use of sodium chloride, a larger percentage of particles reduced the width and depth of erosions, while using sodium bromide, the presence of particles reduced the width and depth of erosions, but is less influenced by the percentage of particles themselves.

Mitchell-Smith et al. [34] built upon a previous study of nozzle geometry, introducing sodium iodide (NaI)-doped electrolytes and including the concept of current filtering and re-refresh rate at varying machining parameters. Material removal associated with NaCl-, NaNO_3 - and NaI-doped electrolytes are compared and analysed. As in the study previous of nozzle geometry, the ability to machine complex surface structures with varying nozzles was illustrated. However, with the inclusion of the doped electrolyte, precision with the use of the complex nozzles is improved but at the cost of lower current efficiencies with increasingly doped electrolytes. Overall, dimensional accuracy improvements and ‘superior surface intersection’ are achieved with iodide-enhanced electrolytes; however, there is a decrease in material removal rates with increased doping [34].

Mitchell-Smith et al. aimed to build upon the work produced by Speidel et al. [29] to utilise the effects of different electrolytes for the optimisation of feature generation on an Inconel 718 workpiece [35]. They produced a system capable of electrolyte multiplexing, with the ability to mix four separate electrolyte tanks. For this study, striations were produced with two passes over a coincident toolpath, using various combinations of the electrolytes. The electrolytes used were NaNO_3 , NaCl and NaI, or more specifically a mixed sodium nitrate and sodium iodide solution with 20% NaI referred to as NaI20 as previously used by Mitchell-Smith et al. [34], with all electrolytes kept at the same temperature and concentration. It was found the best combination took advantage of the high removal rate of NaCl followed by the better surface finish produced by NaI20. The study shows the ability to combine both precision and material removal performance, as well as the ability to produce continuous profiles of varying surface properties [35].

Speidel et al. [36] showed that material precondition effects the resultant surface produced by Jet-ECM when comparing an annealed and non-annealed copper sheet. They found for fine-grained materials, surfaces are more porous post-machining at lower current densities than those that have been annealed and are therefore large grained. Increasing the current density overcomes any pre-existing grain texture, as well as reducing pore size.

4 Assisted Jet-ECM

Assisted jet-ECM is the combination of jet-ECM with additional technologies to produce a hybrid system. The aim of these hybrid systems is to improve at least one area of the unwanted machining characteristics in Jet-ECM such as overcutting, stray machining, tapered holes and aiming to improve the performance and capability of the process [37, 38].

4.1 Laser-assisted Jet-ECM

Laser-assisted Jet-ECM (LAJECM) is the combination of a low power laser working co-axially with the electrolyte jet to improve the process localisation by heating both the electrolyte jet and the workpiece surface at the centre of the contact with the jet. The thermal energy of the laser transmitted to the workpiece enhances the kinetics of electrochemical reactions and hence enables the localisation of dissolution [39]. As the temperature increases, the conductivity of the electrolyte increases, allowing a higher current density while higher temperatures on the workpiece lower the activation energy for the chemical reaction [39].

The first paper published on the subject of LAJECM was published in 1989 by Datta et al. in which a 22-W CW argon ion laser (75-mm focal length) was used alongside a 0.5-mm diameter nozzle [40]. The experiment aimed to analyse the MRR and efficiency of machining nickel and steel samples of 750 μm thickness using sodium nitrate and sodium chloride electrolyte solutions. In their study, Datta et al. (1989) study results at 5 current densities from 8 to 75 A/cm^2 at constant flow velocity. It was found that when using sodium chloride as an electrolyte with steel and nickel, current efficiency of the process was near 100% independent of current density and the inclusion of a laser. However, with inclusion of a laser, it was found the holes produced at all current densities were deeper for the same amount of material removed. This leads to a belief that the laser concentrates the dissolution area through the heating of the metal, improving the localisation of the reaction and reducing stray machining, thus improving accuracy. When using a laser with sodium nitrate solution, at every current density the inclusion of a laser beam severely reduced the

current efficiency on both nickel and steel, with a maximum drop of 70 to 10% with and without laser respectively. It was found when using nitrate solution on steel, the current efficiency dropped at a current density of 75 A/cm^2 reversing an otherwise positive trend with increasing current density. At higher current densities, the heat in the reaction area is increased, causing an unwanted reaction between the iron II ions and nitrate ions, consuming a high amount of ions at the anode, and severely reducing current efficiency. Finally, Datta et al. raised the issue surrounding the measure of current density, when it was found the material removal rate continued to increase when the applied current density passed the limiting current of the material. This suggests that the area used to calculate current density relates more to the reaction area, which is larger than the nozzle area. However, in this experiment and the majority of following studies in Jet-ECM, the nozzle area is still used for this calculation. An illustration of LAJECM can be seen in Fig. 12.

DeSilva et al. released a paper around modelling and experimentation of LAJECM in 2004 [39]. The modelling aspect was centred around the energy balance equations of the process, assuming that the process is endothermic, isobaric and with negligible energy and heat loss [39]. The paper only outlines the modelling idea and requires further investigation. The experimental aspect of the investigation aims to compare JECM and LAJECM on the VRR and taper of machined profiles on aluminium and stainless steel. It was found that contrary to the findings of Datta et al. [40] that laser assistance yielded a higher VRR on both aluminium and stainless steel as with laser assistance, the process energy is higher; therefore, VRR increases up to 55% higher. In agreement with Datta et al. [40], the use of a laser improves the taper of a machined pit or hole, which is accelerated with a higher IEG, producing tapers 40% narrower with laser assistance. Also, at a higher IEG, the laser assistance has more effect on increasing the VRR as more laser energy is able to be transferred to the electrolyte,

Fig. 12 Illustration of the LAJECM process [41]

Fig. 13 VRR against electrolyte concentration for JECM and LAJECM [42]

increasing conductivity and the ability to apply current to the material. The same year, Pajak et al. [42] released a similar study outlining the same trends (Fig. 13) in the experimental results as that in the study by DeSilva et al. [39].

Pajak et al. [6] then built upon this previous study, expanding the previous range of materials to include Hastelloy, high carbon steel, and a titanium alloy. The materials provide different absorption factors for laser, as well as a range of thermal and electrical conductivities and materials prone to an oxide layer. In agreement with the previous studies performed by Pajak et al. [42] and DeSilva et al. [39], there is an increase of VRR with the use of laser, this time in titanium alloy and Hastelloy. Also in agreement, the inclusion of a laser has the highest effect on increasing VRR at slower process parameters, for example low voltage and high IEG (Table 3). However, in materials that form an oxide layer, in this case titanium, the laser causes a large spike in the material removal at the breakdown of the oxide layer, which occurs much sooner in the process than without laser assistance. In terms of shape precision, LAJECM provided a reduction in taper of 65% in titanium alloy and in general a larger reduction of taper at low voltages with laser assistance. The overcut however was larger with LAJECM. For the first time, a study looks in to the effect of laser

assistance on surface roughness. For titanium alloy, stainless steel and aluminium alloy, the surface roughness value was improved, and for Hastelloy the opposite trend was found. However, the results are only representative on one set of process parameters, and the range of the results suggests these trends may not always be the case.

Building upon this previous work, De Silva et al. performed further analysis of the thermal effects of JECM with both modelling and experimentation [41]. Comparatively, the same laser density was used as in the study by Pajak et al. [6], 47.5 W/mm^2 , but with a lower range of electrolyte concentration, 5–10% concentration against the previously used 10–20%. As found previously, stainless steel and titanium alloy saw improved surface finishes when using LAJECM but Hastelloy (nickel-based alloy) saw no change with the introduction of laser assistance, and contrary to previous findings, aluminium alloy saw a larger surface roughness value with the introduction of laser assistance. LAJECM facilitates the removal of brittle oxide layers improving machining on titanium, an oxide prone metal, while increasing VRR and precision [41]. However, De Silva et al. introduced a concern with LAJECM, where the increase in surface temperature and electrolyte temperature from laser absorption can cause electrolyte boiling. This electrolyte boiling can decrease electrolyte conductivity, because of machining stoppage and potential sparking.

Malik performed further experimental studies into LAJECM on Inconel 718 [38]. Again, it was found there was a 29.7% increase in MRR with the introduction of laser assistance, and a 33.2% decrease in taper at optimal parameters.

Zhang et al. [43] proposed a novel hybrid process of laser drilling assisted with jet electrochemical machining in an experimental study, which was followed by a modelling and experimental study into the same process [44]. Unlike the previous studies with the combined processes, these investigations aimed to maintain the laser drilling as the main material removal process with JECM as a secondary process. Recast and splatter are a major issue

Table 3 Relative increase in VRR for LAJECM vs. JECM [6]

Voltage (V)	IEG = 2 mm		IEG=5 mm	
	Cp = 10%	Cp = 20%	Cp = 10%	Cp = 20%
Titanium alloy				
80	20.27	19.79	24.53	9.52
140	14.43	8.77	19.74	8.79
180	12.5	14.43	14.44	2.86
Hastelloy				
80	10.06	39.06	13.27	33.33
140	5.71		13.14	9.79
180	1.82		9.73	9.46

when producing holes with laser drilling; however, the introduction of JECM as a secondary process effectively reduces the recast and splatter at the cost an annular overcut at the entrance of the hole and a reduction in efficiency of up to 50% compared with laser drilling in air in both the study by Zhang et al. [43] and Zhang and Xu [44].

4.2 Ultrasonic-, air- and abrasive-assisted Jet-ECM

Air-assisted Jet-ECM uses a jet of air expelled co-axially or at an angle to the electrolyte jet. The air jet gives momentum to the flow of electrolyte radially across the surface of the part, moving the hydraulic jump on the material surface beyond the machining zone [37], an issue arising with lower electrolyte flow rates [45]. In doing so, the current density is localised to the machining area, with the aim to reduce over cut and stray machining [46] while helping to remove debris from the machined area.

Ultrasonic-assisted Jet-ECM is a process in which ultrasonic vibrations are applied to the system via direct vibration of the tool or workbed [47], or via a separate ultrasonic emitter providing waves to the machining area [37, 46]. The aim of ultrasonic assistance is to enhance the reaction in the machining zone by aiding the removal of the reaction products [48]. The ultrasonic assistance can also aid the breakdown of the passive layer on a material surface which prevents machining [47].

Abrasive-assisted Jet-ECM is a hybrid process that takes inspiration from water jet cutting, by adding abrasive particles to the jet of electrolyte. The aim of the hybrid process is to combine mechanical abrasion of the workpiece surface and passive layers with the electrochemical process for combined material removal mechanisms [49, 50].

In 2008, Hackert et al. used an additional jet of compressed air to remove the electrolyte film enclosing the nozzle caused by surface tension, and thus reducing the possible working gap [51]. In the experiment, the air nozzle was not co-axial to the jet direction, but when machining pits, the stray machining was dramatically reduced. With this reduction, sharper edges were also produced in grooved channels, atypical for Jet-ECM processes [51]. Later, Kai et al. used a co-axial air jet to produce a thin film on the workpiece surface at low electrolyte flow rates, which when unassisted do not produce a film flow [45]. It was found the maximum depth of machined holes increased from 120 to 180 μm with the use of air-assistance. Goel and Pandey performed a study into the effect of air-assisted Jet-ECM on MRR and hole taper [46] followed by a more in-depth performance evaluation of the process [37]. It was found the taper of the hole increases with increased air pressure due to the reduction in stray machining [46] and localization of current density [37] while reducing the chance of sparking.

Goel and Pandey studied the effect of ultrasonic assistance alongside their experiments on air-assisted JECM [37] as well as in a following study [48]. Goel and Pandey fabricated an attachment of consisting of a piezoelectric transducer at 20 kHz frequency, ultrasonic processor and ultrasonic horn [37]. The aims of the ultrasonic assistance were to aid removal of the reaction products from the machining area and thus enhance the electrochemical reactions. It was found that the MRR increases up to 40% with the use of ultrasonic assistance and produce holes of less taper [48]. Mitchell-Smith and Clare [47] studied the effect of ultrasonic assistance on removing the passive layer on titanium alloys during Jet-ECM. Whereas Goel and Pandey used acid electrolyte in the 2016 and 2017 studies, proven to aid the removal of passive layers [24], Mitchell-Smith and Clare claim this should be avoided as it creates a health and safety risk [47]. Mitchell-Smith and Clare found the use of ultrasonic assistance enhanced the aspect ratio of the grooves due to passivation breakdown, increased depth and reduced passivation layer formation during machining by 23% [47]. However, this study only used a single excitation frequency, and further work into frequency response is required.

Finally, Liu et al. produced two studies presenting the use of electrochemical slurry jet micro-machining, or the use of abrasive particles in Jet-ECM, firstly on Stellite12 material [49] then on tungsten carbide with a sodium chloride solution [50]. The work looked to determine whether abrasive water jet machining and Jet-ECM could be combined to form a hybrid process (Fig. 14). The use of abrasive particles produced higher material removal rates over that of standard Jet-ECM under comparable machining conditions on Stellite 12, whereas the roughness values were better with the use of abrasive particles over standard Jet-ECM, particularly as particle concentration increased and abrasion became the more dominant process [49]. However, the roughness values were higher than those found in abrasive water jet machining.

Fig. 14 Schematic of electrochemical slurry jet micro-machining [50]

Liu et al. also aimed to machine tungsten carbide with sodium chloride abrasive slurry electrolyte [50], compared with the mixed sodium chloride/sodium nitrate electrolyte used previously [49]. Due to the material hardness, abrasive jet machining was unable to machine tungsten carbide with aluminium oxide particles, while Jet-ECM using non-abrasive sodium chloride electrolyte also proved to be ineffective due to the inability to breakdown the oxide layer [50], as previously found by Hackert-Oschätzchen et al. [24]. The combined process allowed the machining of tungsten carbide due to the removal of the oxide layer using the abrasive particles followed by the dissolution of the unoxidized tungsten.

5 Conclusions and research challenges

Over the last three decades, it can be seen that there has been large amounts of development in the field of Jet-ECM. The main areas of previous study revolve around Jet-ECM of various materials, investigations into process parameters on material removal, machining geometries and surface roughness values, as well investigations into current delivery and nozzle variations. The majority of research has been performed on stainless-steel samples [1, 9–11, 13–19, 21, 22] with a focus on surface texturing and material removal. The finest surface roughness value was achieved by Kawanaka et al. (2014) with a value of 14.1 nm Ra. Summarising the effects of machining parameters on machined results:

- Conductivity and material removal rate (MRR) increase with electrolyte temperature up to a point where electrolyte boiling is reached [2, 30].
- Working gap has an effect on resistance, and therefore machined geometries. Larger gaps decrease MRR and surface roughness [10]. A too small working gap does not allow the formation of a jet and hydraulic jump and hinders machining [14].
- Surface roughness increases with reduced electrolyte concentration [9] on stainless steel with sodium nitrate solution.
- Surface roughness improves with increased voltage and current [9, 10, 14] up to a current limit where surface roughness values increase [15, 16].
- MRR increases with increased voltage [9, 14].
- MRR increases with increased electrolyte concentration, on stainless-steel samples using sodium nitrate electrolyte [9].
- Lower scanning speeds increase MRR [10] but higher scanning speeds provide better surface roughness results [10] due to a lower dwelling time [16].

- Use of a pulsed DC current improves the surface finish on stainless-steel samples with sodium nitrate electrolyte, but reduces MRR. [16]
- Bipolar current increases the MRR rate with the same surface roughness value of a DC current, but erodes the tool [16].

All experiments studied used cylindrical nozzles varying from 0.05 mm diameter [10] to 2 mm diameter [30], aside from two studies where ‘letterbox’ nozzles were used for turning applications [13, 28]. In turning applications, the use of Jet-ECM was successful, producing high aspect ratios in turned rods, allowing larger areas to be machined than using a cylindrical nozzle. Jet-ECM has been proven to be able to produce complex 3D geometries in pitting, grooving and turning applications [1, 10, 13, 24] and the development is promising.

Changes to the nozzle geometries have been shown to alter the machined profiles, with the ability to produce more complex structures with nozzle combinations [31, 34]. Changing the angle of address of the nozzles can significantly enhance the precision of cuts [31] as well as increasing the depth of cuts [32].

When machining tungsten carbide alloys [20, 24, 28], the process raised more issues than when machining stainless-steel samples. When machining with pH-neutral electrolytes (NaNO_3 and NaCl), oxide layer growth prevented machining. This was overcome by adding sodium hydroxide to the electrolyte to breakdown the tungsten oxide layer [24], or by using the NaOH produced naturally on the cathode surface during the Jet-ECM process. When using a ceramic nozzle and a DC current, the NaOH was mixed into the electrolyte, but resulted in less accurate machining [20]. Alternatively, using an AC current produced NaOH on the workpiece when the current was reversed, allowing a breakdown of the tungsten oxide layer, but producing tool wear which could be reduced with the use of a ceramic nozzle [20].

When machining an aluminium matrix composite, Hackert-Oschätzchen (2016) found sodium nitrate electrolyte caused a passivating effect, while sodium chloride electrolyte, of equal conductivity produced pits with twice the depth with the same machining parameters. For titanium alloys [29, 30], sodium chloride produced a better pit depth, MRR and surface finish than bromide, nitrate and fluoride counterparts, partly due to the production of titanium chlorides that are hydrolysed and leaves no oxide layer when machining.

Iodide-doped electrolytes have been shown to increase precision [31] and dimensional accuracy [34] as well as improved surface finish in some cases over neutral electrolytes such as sodium chloride [35]. Combinations of

electrolytes can be used to further improve the Jet-ECM process [35].

More recent studies have developed hybrid processes involving Jet-ECM, namely laser-assisted, ultrasonic-assisted, air-assisted and abrasive-assisted hybrid processes. The use of laser assistance tends to improve the conductivity in electrolyte and material and localisation of the reaction at the risk of electrolyte boiling [41]. It was in agreement throughout the studies that laser assistance increases the material removal rate compared with standard Jet-ECM [38, 39, 41, 42], especially at lower currents and electrolyte concentrations [6] as well as improving hole taper [6, 38, 39, 42]. The effect on roughness was material dependant [6] and in some cases, the laser assistance caused a larger overcut [6].

Air-assisted Jet-ECM can produce a lower working gap [51], while producing the thin film required for Jet-ECM when used co-axially with the electrolyte jet [45]. The hybrid process was also shown to improve machining depth [45] while improving taper [37, 46, 51] through the reduction of stray machining, and producing sharper edges [51].

The introduction of ultrasonic assistance as a hybrid process again showed improvements over standard Jet-ECM. Material removal rate and taper were improved with the introduction of ultrasonic assistance on copper and stainless steel through as the ultrasonic vibrations aided the transport of reaction products from the reaction area [37, 48], with MRR improving by up to 40%. Mitchell-Smith and Clare also showed the useful nature of ultrasonic assistance in removing the passivation layer on titanium alloys [47] which was previously difficult with standard Jet-ECM.

The final hybrid process, combining abrasive particles within the electrolyte, also improved MRR over standard ECM [49] while improving surface roughness of machined areas, especially with a higher concentration of abrasive particles. Similarly to that found with ultrasonic assistance, slurry jet machining helps overcome passivation layers in tungsten carbide, allowing machining through the hybrid process that was not possible with either abrasive water jet machining or standard Jet-ECM [50].

This paper has described the experimental work performed in Jet-ECM and related hybrid technologies. Although research has accelerated from 2005 onwards, the picture of the process is not completely clear nor is it completely understood. More work still needs to be done in all aspects of the process, including a wider range of materials and electrolytes. The hybrid technologies outlined in this review also show good promise at early stages of research, but also require a larger amount of understanding to move the technology further towards being a fully understood and controlled technology. More recent studies have shown

major improvements to system control and machining precision [4, 17, 31, 32, 35] but further developments are still required.

From the review of literature, Jet-ECM is still limited as a manufacturing technology. In this paper, the benefits of Jet-ECM over competing technologies are presented. Although progress has been made, the application of the process is limited. These limitations include but are not limited to:

- Jet-ECM requires an electrically conductive workpiece, and therefore removes the vast majority of non-metallic materials, vastly limiting the range of possible applications for machining.
- The technology requires low transitional feed rates for material removal, in general less than 2 mm/s, which is more time consuming compared with laser technology or traditional manufacturing methods while producing lower material removal rates. Although nozzle design has aided the ability to machine a larger area [13, 28], applications for machining areas in the centimetre range have not been widely attempted.
- Although assistive technologies such as laser assistance have been shown to improve the material removal rate, accuracy and surface roughness, the setups are more complex than those of non-assisted counterparts and are thought to reduce the cost-effectiveness of the technology.
- The nature of the process produces naturally rounded edges as well as tapered holes and geometries, and is not suitable to produce geometries 90° to the top machined surface. In addition, the high aspect ratios achieved in EDM (ratios up to 15) are not achievable in Jet-ECM nor are the accuracies in the range of 1 μm achieved in EDM possible with Jet-ECM, with accuracies of around 5 μm [52] with overcuts commonly found.
- Only external component surfaces of metallic parts have been machined, and within that only top surfaces, limiting the features Jet-ECM can process; however with developments in the angle of address [32], a wider range of features should be accessible for machining with further work.
- Although the machining of through holes has been achieved in thin materials (250 μm thickness) [52], depth of cuts higher than 500 μm have been rarely achieved [23, 45].

Moving forward, a combination of experimental and modelling work must be performed to move away from a prediction of machined geometries based around machining trials and towards a predictable machining outcome based around parameters. The challenge is understanding the effect of each process variable, their relationships to other variables, and knowing these effects on a wider range of materials than is currently known. This challenge will

be increased with the introduction of hybrid technologies, adding further unknown variables to the process.

Applications mentioned in research have been minimal, with the use of the technology leaning towards biomedical applications [23] with several studies being performed on biomedical-type materials. Further applications for the technology need to be found and developed, with the Jet-ECM process being tested as a manufacturing technique and assessed for industrial use. In doing so, the range of geometries and materials currently capable of being processing need to be developed and increased.

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