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Electrolyte multiplexing in electrochemical jet processing

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Abstract

Electrolyte design for electrochemical jet processing (EJP) techniques can directly affect form and finish of machined structures.

A newly developed, industrially focused, EJP machining centre was designed to incorporate complete control of all relevant machining parameters. A computer numerically controlled, electrolyte multiplexing system, was developed to allow rapid changes in electrolyte type and the ability to mix and fade between electrolytes to create roughing and finishing strategies, and functionally graded surfaces as part of the toolpath program. In this study, the use of three electrolytes (NaNO₃, NaCl and a hybrid electrolyte NaI20) are used. Through dynamic electrolyte selection, applied in a sequential manner, it was demonstrated that a combination of NaCl / NaI20 achieved the best compromise of precision and performance, with an increase in depth of 10% over NaI and a 9% kerf reduction over NaCl. Surface finishes were demonstrated to be varied by 40% dependant on the sequence of electrolytes applied without effecting the form. It was shown that graduated surfaces can be created from a high lustre finish to matte by fading electrolyte types. For the first time, an automated method of electrolyte multiplexing is described and the flexibility and process enhancements that can be imparted by this methodology are demonstrated.

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1. Introduction

It is well understood that differing electrolytes used in ECM can produce significantly different form and finish with the same applied energy [1, 2]. The purpose of this work is to exploit these differences through a newly developed machining tool to enhance the process capability of electrochemical jet techniques.

Electrochemical jet processing (EJP) is the combination of electrochemical jet machining (EJM) [3, 4] where material is removed, and electrochemical jet deposition (EJD) [5, 6] where material is deposited, within the same machine tool. Reversal of polarity between the nozzle supplying the electrolyte jet, and the workpiece surface, being the defining factor if material is deposited or removed (Figure 1). A high degree of variation of surface features along different length scales has been demonstrated to be possible using EJP. In subtractive mode, variation in the form of meso-scale

features has been observed through variation of toolpath and parameters [7-10],

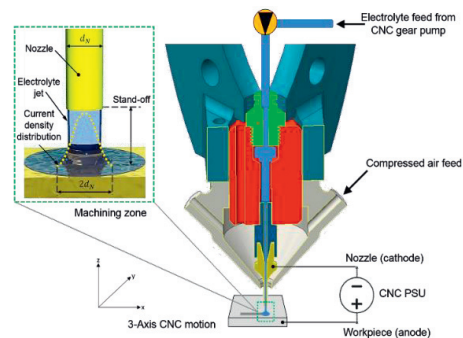


Figure 1: Schematic of electrochemical jet processing configured in subtractive mode

and by mechanical design to modulate the applied current distribution within the inter electrode gap [11].

The form of meso-scale features can also be varied through utilising differing electrolytes and the addition of dopants in order to increase the precision of machined features [12]. In addition, the non-deterministic microscale surface finish can be affected through manipulation of the electrolyte in response to the chosen workpiece material [13]. From this research it can be observed that different electrolytes exhibit different traits in material removal rate (MRR), precision and surface finish. Often a single electrolyte is incapable of satisfying all process design criterion and instead is selected as a compromise. This study is intended to build upon this prior knowledge to develop machining strategies that utilise the different advantages found with differing electrolytes. This allows for the optimisation of feature generation and demonstrate further process control of surface dissolution, through multiplexing electrolytes in a single machined feature. Thus, adoption of this methodology allows for greater flexibility in surface creation and efficient machining strategies.

2. Methodology

A new machine tool was designed and built to expand on prior knowledge gained in electrochemical jet techniques (Figure 2).

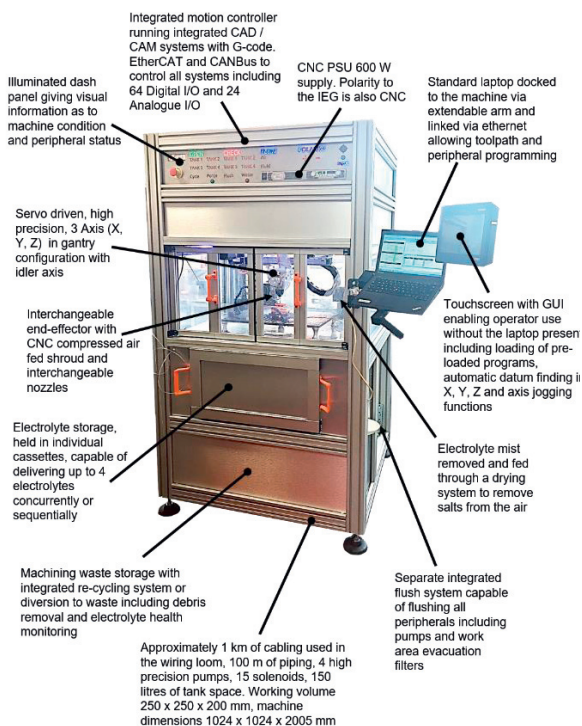


Figure 2: Overview of newly developed Electrochemical Jet Processing machine tool.

This new machine tool was intended to build upon contributions made by several researchers and be more industrially focussed than previous research platforms developed by the present research team. In doing so it is intended to increase precision, reliability and repeatability of the process. To achieve this, each influencing factor of the process is monitored and controlled, including electrolyte supply and health, energy supply, jet characteristics and machine kinematics.

This system includes the development of an electrolyte multiplexing system (Figure 3). Four separate 12 litre electrolyte supply tanks (ST) are used each with an NC solenoid. Two tanks share a single precision gear pump. These lines are fed into a 3/2-way valve which can either feed the nozzle or be diverted to a large bore pipe connected to waste. The effect of this means the electrolyte lines can be easily purged allowing for quick change over of electrolyte type. This can be achieved in less than 3 seconds including nozzle clearance.

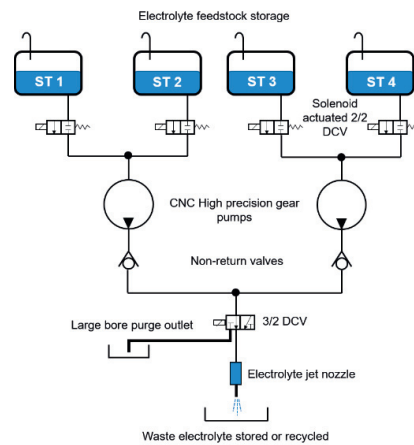


Figure 3: Schematic of the multiplexing system used in this study which allows rapid electrolyte exchange.

Utilising this configuration means it is possible to mix and vary electrolyte composition as part of the machining program. Each pump is controllable and operable independently over the full range of the possible flow rates. Therefore, each pump allows the electrolyte to be proportionally supplied creating dynamic mixing of electrolyte composition ‘on the fly’.

All other parameters are set by the main control program remaining constant during the form and finish experiments reported here. Current density was set at 250 A/cm^2 , when used with a stainless-steel nozzle of $500 \text{ }\mu\text{m}$ internal diameter. Nozzle tip stand-off was set initially at 0.5 mm using the in-built automatic datum finding system which works by using an electrical continuity approach. Nozzle traverse speed was 0.5 mm/s and for these experiments pump flow rate was set to achieve a jet speed of 29 m/s .

The workpiece material used in this study was a nickel superalloy, Inconel 718. Chosen for its low machinability rating by traditional means and prior knowledge gained in processing this material. This material is also sensitive to thermal process in applications where surface integrity is key.

For the assessment of form and finish, multiple striations were created with two passes in opposite directions over a coincident toolpath. Table 1 shows the sample designation with the definition of the electrolytes used in each case and the sequential order in which they are used. The electrolytes were maintained at 21°C and a 2.3 M concentration throughout. Both NaCl and NaNO₃ are common electrolytes in EJP due to the relatively low toxicity and ease of availability. NaCl is understood to be a more aggressive electrolyte demonstrating greater throwing power due to increased electrolyte conductivity [14]. Therefore, it generates higher material removal than comparative electrolytes and leaves a bright, clean finish when used with nickel based alloys as is the case here. However, this aggressive nature can lead to undesirable inter-granular attack at the interface surface and poor dimensional control due to the relatively flat current efficiency profile from low current densities. Due to its passivating nature NaNO₃ does not exhibit these tendencies. Current efficiency at lower current densities is suppressed because of the generated passivation film inhibiting machining until a threshold current level is reached. Thus, the dissolution area is restricted improving precision. The NaI20 hybrid electrolyte has been previously reported by the authors for its ability to increase precision specific to EJP [12] by creating a transitory electrochemical mask that filters low level current through the generation of a sacrificial anodic film.

Table 1: Sample designation with defined electrolytes and sequential processing order

Sample designation	Electrolytes	Forward pass	Reverse pass
NaCl	2.3 M Sodium Chloride (NaCl)	NaCl	NaCl
NaCl/NaI20	2.3 M Sodium Chloride (NaCl), 2.3 M 80% Sodium Nitrate + 20% Sodium Iodide (NaI20)	NaCl	NaI20
NaI20	2.3 M 80% Sodium Nitrate + 20% Sodium Iodide (NaI20)	NaI20	NaI20
NaI20/NaCl	2.3 M Sodium Chloride (NaCl), 2.3 M 80% Sodium Nitrate (NaNO ₃) + 20% Sodium Iodide (NaI20)	NaI20	NaCl
NaCl/NaNO ₃	2.3 M Sodium Chloride (NaCl), 2.3 M Sodium Nitrate (NaNO ₃)	NaCl	NaNO ₃
NaNO ₃ /NaCl	2.3 M Sodium Chloride (NaCl), 2.3 M Sodium Nitrate (NaNO ₃)	NaNO ₃	NaCl
NaNO ₃	2.3 M Sodium Nitrate (NaNO ₃)	NaNO ₃	NaNO ₃

The drawback of NaI20 is the lower material removal than that found in NaNO₃ and NaCl.

For the functionally graded surface demonstration NaCl and NaNO₃ were used. Fed to the nozzle at the same flow rate, through the same pump, but dispensed at different times along the toolpath. Each line of the surface was created in the same direction following the same programmed tool path and solenoid control for each line.

All parameters were maintained as previously described except current density which was reduced to 100 A/cm² to limit material removal as this is intended to demonstrate changing surface texture effects rather than form. The solenoids were then set to open and close as a function of time with respect to the known traverse speed giving a repeatable pattern. As the nozzle traversed back to the beginning of the next line with a 0.5mm step over, the electrolyte lines are purged in time for the succeeding electrolyte.

Analysis of the surface was carried out through areal imaging of the surfaces using focus-variation microscope (Alicona G5), and processed using Mountains Map software. Roughness was extracted and filtered in accordance with ISO 25178 for S_a and ISO 16610-21 for R_a .

3. Results and Discussion

3.1. Form

Considering Figure 4, the difference in resultant profile shape due to the electrolyte type can be observed. Using a NaCl electrolyte gains the greatest performance removing a mean area of 50090 μm² (SD <1%) and mean depth of 87.2 μm (SD <1%) across all samples tested. In comparison, the resultant profile of the NaI20 electrolyte achieves 18% less maximum depth (71.4 μm SD <1%) and 22% less area (39305 μm² SD <1%) across the range of samples analysed.

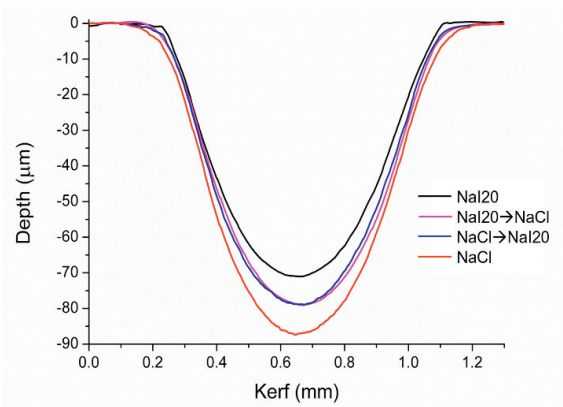


Figure 4: Exemplar resultant profiles from striations machined with two passes of the same electrolyte and two passes with differing electrolytes applied sequentially in this case NaI20 and NaCl

Prior work [12] has demonstrated that this type of electrolyte achieves a narrower dissolution kerf due to a current filtering effect, in this case achieving a 14% reduced width in comparison to NaCl and achieves a sharper interface between the cut area and the workpiece surface. When the differing electrolytes are applied sequentially it can be observed that the resultant profile is a compromise between the precision of NaI20 and material removal performance of NaCl. The width of the striation being 6% more than NaI20 but 9% less than NaCL.

The depth is also 10% deeper (mean $78.7 \mu\text{m}$ SD $<1\%$) than NaI20, but, 11% shallower than NaCl. It is worth noting that the sharp intersection between striation wall and workpiece surface is somewhat lost due to the flatter current efficiency profile found with NaCl. This enables material dissolution even at low current densities found at the peripherals of the jet. This in turn overwrites the enhanced precision obtained using NaI20. This compromise is achieved without creating a specific electrolyte type simply through sequential application. However, there is very little difference in form between which order the electrolytes are applied which is also seen in Figure 5. Here NaNO_3 is applied sequentially with NaCl and compared to the previous results.

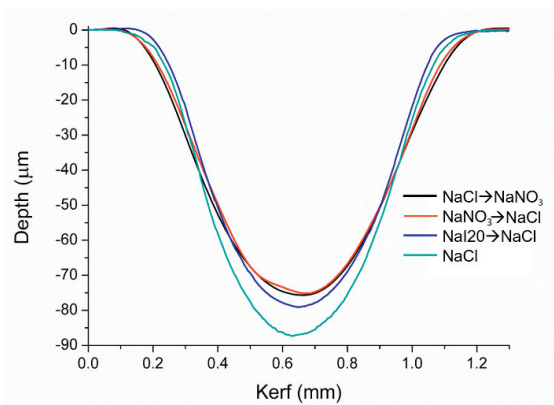


Figure 5: Exemplar resultant profiles from striations machined with two passes of NaCl and two passes with differing electrolytes applied sequentially in this case NaI20, NaCl and NaNO_3

Again, the differing current efficiency profiles [2] of the individual electrolytes denote the shape of the resultant profile when combined. The NaNO_3 sequentially applied with NaCl gives a much steeper side wall and lower radius intersection with the un-machined surface albeit with a mean striation cut width of $1.14 \mu\text{m}$ (SD 2%), 8% wider than NaCl and 19% wider than the NaI20/NaCl combination. The NaNO_3 /NaCl combination produces a similar depth to NaI20/NaCl with 2% less depth at $77 \mu\text{m}$ (SD $<1\%$) and 13% less than the twin pass of NaCl.

3.2. Surface Finish

Although a good compromise is found between performance and precision when using electrolytes sequentially there is little dependence on the order in which the electrolytes are

applied to affect changes to the resultant profile. This is not the case with the resultant finish.

In Figure 6 the difference in surface finish is visually obvious. The optical images demonstrate the NaI20/NaCl striation (Figure 6a) to have a much higher lustre finish than the NaCl/NaI20 striation associated with NaCl electrolytes (Figure 6b). The exposure of the grain boundaries can also be seen as inter-granular corrosion has occurred again a trait of NaCl electrolytes when used with Ni-based alloys. In comparison the NaCl/NaI20 demonstrates the surface finish associated with NaNO_3 producing a dark tainted surface proposed to be a result of the formation of passivating oxide films, albeit with a high integrity surface as little inter-granular corrosion is observed.

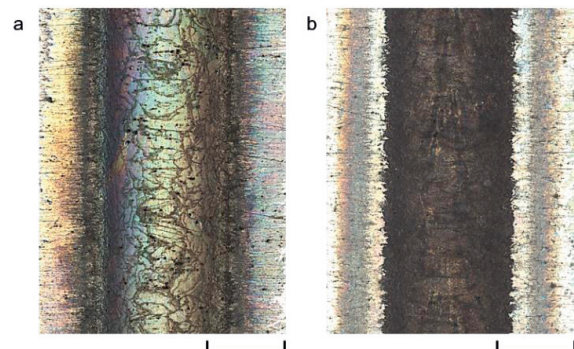


Figure 6: Optical images of the sequentially machined striations (a) NaI20/NaCl and (b) NaCl/NaI20. All scale bars are $500 \mu\text{m}$

This is supported by the profile roughness (R_a) figures extracted from the samples in Figure 6. The NaCl/NaI20 striations having a mean surface roughness of $0.11 \mu\text{m}$ (SD 11%) which reduces by 40% when the electrolyte order is reversed to $0.07 \mu\text{m}$ (SD 10%). This is comparable to the profile roughness (R_a) from the twin pass of NaCl achieving $0.07 \mu\text{m}$ (SD 6%) and NaI20 $0.1 \mu\text{m}$ (SD 17%) which demonstrates the resultant finish is not a compound effect.

3.3. Graduated surfaces

Manipulating the multiplex electrolyte system and the correspondent resultant surface finish of differing electrolytes, a graduated surface finish can be simply created (Figure 7). As part of the toolpath program, it is possible to run the feed pumps, separately and concurrently, and open and close valves supplying the feedstocks as a function of the toolpath. This allows for discrete surface finishes to be applied as per the component design intent.

In the case of Figure 7, a repeating single direction linear toolpath was used. Figure 7a being the optical image of the surface created showing the regularity and therefore predictability of the fade between electrolytes as the solenoids open and close. Alongside the change in surface roughness from NaCl, producing a surface roughness (S_a) of $0.13 \mu\text{m}$ (SD 22%) to $0.23 \mu\text{m}$ for NaNO_3 (SD 15%), there is

an optical difference. The surface transforming from a high lustre finish commonly associated with using NaCl (figure 7b) with Ni alloys [1], to a matte finish due to the adherent oxide formation associated with Ni alloys machined with NaNO_3 (Figure 7d) at this current density level. The transition being seen in Figure 7c. The latency in the system, when the purge function is not used, can be seen when noting the point at which the solenoid controlling the NaNO_3 is opened when compared to the point which it becomes the dominant texture. This occurs at approximately 6 mm after the solenoid is opened (equating to approximately 12 s), although a slight darkening of the surface appears much quicker. Even with both solenoids open the texture from the NaNO_3 supply remains dominant once established.

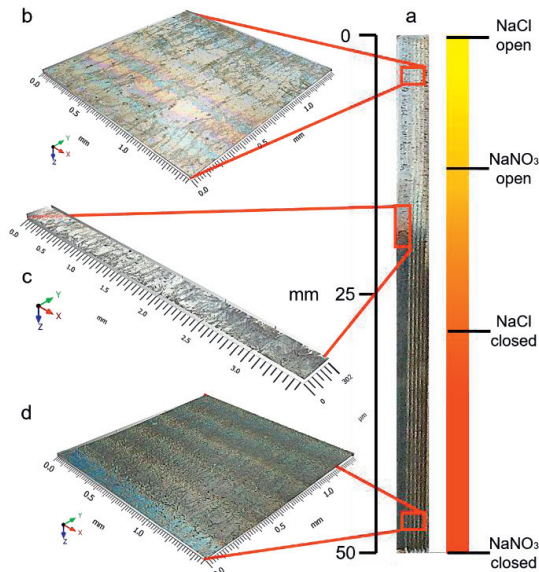


Figure 7: Graduated surface textures as a function of faded electrolytes (a) optical image of overall surface demonstrating the contrasting texture as the applied electrolytes open and close (b) extracted 3D reconstruction of the surface texture created with NaCl (c) extracted 3D reconstruction of the point of fade where NaNO_3 becomes the dominant texture (d) extracted 3D reconstruction of the surface created with NaNO_3

4. Conclusions

Electrolyte multiplexing is demonstrated to add an extra level of flexibility to electrochemical jet processes. Through the ability to quickly change between different electrolytes and apply sequentially, allows a cost-effective compromise between precision and performance to be achieved. The best combination of this being NaCl/ $\text{NaI}20$ electrolytes. This is difficult to achieve by simply parameter manipulation as increased energy density, seen at the surface, to achieve a higher performance will result in worsening precision.

The differing finishing characteristics of each electrolyte can also be exploited to create not only discrete areas of

surface roughness but graduated surfaces that repeatedly produce differing optical properties.

This type of expansion in the capabilities and flexibility of EJP demonstrates further competence of the process for efficient surface structuring in traditionally difficult to machine materials.

Acknowledgements

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