Direct-writing by active tooling in electrochemical jet processing

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Abstract

Recent innovations in electrochemical jet processing have caused step changes in process flexibility and precision. However, utilisation of these innovations requires the development of new machine tool technology. Presented here is a new methodology enabling the exploitation of highly customisable energy density profiles regardless of toolpath vector whilst minimising any error from the intent profile. A further approach is defined whereby active tooling allows the energy density profile to be modulated as a function of position within the toolpath, giving rise to dynamic feature creation. Adoption of this methodology allows a new design freedom within electrochemical jet processes.

1. Introduction

A number of different advanced manufacturing technologies [1], such as electrochemical jet processing (EJP) [2], micro electrochemical machining (micro-ECM) [3] and micro electrical discharge machining (micro-EDM) [4] can be used to generate micro 3D geometry in low machinability materials. Applications include replication of micro surface geometries and bespoke micro-channels for microelectromechanical systems (MEMS), microoptoelectromechanical systems and microfluidic systems [5]. However, current technology is only able to create a desired profile in a single direction due to the contouring of the tool being unidirectional. Consequently, tooling that is able to vector independently of translation is required. Considering Figure 1, when a profiling tool is used in EJP, the initial profile matches the tool geometry, in this case a symmetrical twin element (STE) nozzle [2, 6] (Figure 1 starting profile). When applied in a constant vector toolpath, aligned with the intended orientation of the tool (Figure 1a), a constant profile is generated. In the case of Figure 1b, when the vector changes whilst the tool remains in the same orientation, the profile becomes discontinuous. This distorts the energy distribution and results in an incorrect profile geometry in the new vector direction. However, if the tool is re-orientated to follow the appropriate vector, the profile remains consistent with the intended energy distribution (Figure 1c).

Previous research has demonstrated that in-jet energy distribution in EJP can be manipulated through electromechanical and electrochemical innovations [2, 7-9] such as modification to the nozzle contour thus generating alternate profile geometries. However, to maximise the potential of these innovations, hardware augmentation is required to allow the profile to remain constant along a complex toolpath.

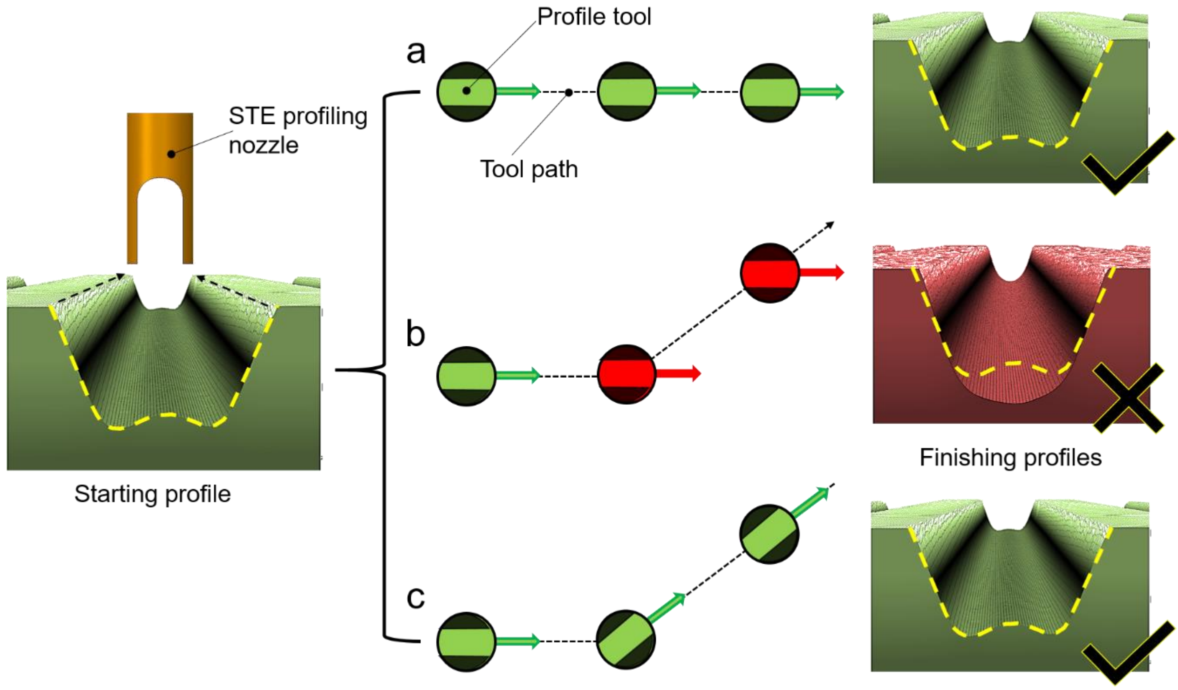


Figure 1: Simulation of machined resultant profile with changing nozzle orientation when using a STE nozzle[2] (a) Standard EJP end-effector and configuration maintaining a fixed nozzle orientation is consistent in a single direction giving a constant profile in a single direction, (b) when direction changes, response profile no longer tracks the toolpath and response profile changes from design intent, (c) profile would remain constant if head can rotate to allow the nozzle to track the vector toolpath in x and y demonstrating the ideal scenario.

It is also advantageous to enable the profile geometry to be dynamically varied along a channel or through a feature. This allows a single nozzle to produce an increased number of profiles dependent upon the orientation of the nozzle with respect to the toolpath vector. These changes can be enacted dynamically as a function of the toolpath program allowing a constantly evolving profile design intent to be realised. In this paper a new apparatus which delivers this capability is described and characterised.

2. Materials and Methods

Experimentation was carried out using a previously developed EJP platform [10]. To create constant and dynamic profiles, a rotary head end-effector was designed, allowing rotation of the tool (Figure 2a). For constant feature profiling, a tangential control routine was implemented in the control software to continuously monitor the direction of the toolpath in the x-y plane and assign a constant nozzle orientation angle in relation to the vector direction of the interpolated x-y axis, as defined by Equations 1, 2 and 3 dependant on the quadrant of the intended nozzle rotation:

$$\Delta y \geq 0 \rightarrow \alpha = -\tan^{-1}\frac{\Delta x}{\Delta y} + \beta$$ *Equation 1*

$$\Delta y < 0 \; and \; \Delta x < 0 \rightarrow \alpha = \pi - \tan^{-1}\frac{\Delta x}{\Delta y} + \beta$$ *Equation 2*

$$\Delta y < 0 \; and \; \Delta x \geq 0 \rightarrow \alpha = -\pi - \tan^{-1}\frac{\Delta x}{\Delta y} + \beta$$ *Equation 3*

Where α is the absolute angular position of the head with respect to the y axis, Δx and Δy are the incremental translations in x and y, β is nozzle orientation offset angle which can be specified and dynamically modified during machining (Figure 2b).

Three toolpaths were designed to test the head articulation and the resultant profile: a circle (Ø 10 mm), a square (side 10 mm) and an isosceles triangle (base 10 mm and corresponding height 10 mm). The nozzle orientation was initially aligned with the y axis allowing evaluation of resultant geometric response by travelling in an arc and at trajectories within the x-y plane. The features were machined over three passes using a doped electrolyte solution NaI20 [7], a traverse speed of 0.5 mm/s, supplied mean current density of 100 A/cm^2 and initial inter electrode gap (IEG) of 0.3 mm. The patterns were repeated with and without rotary head capability.

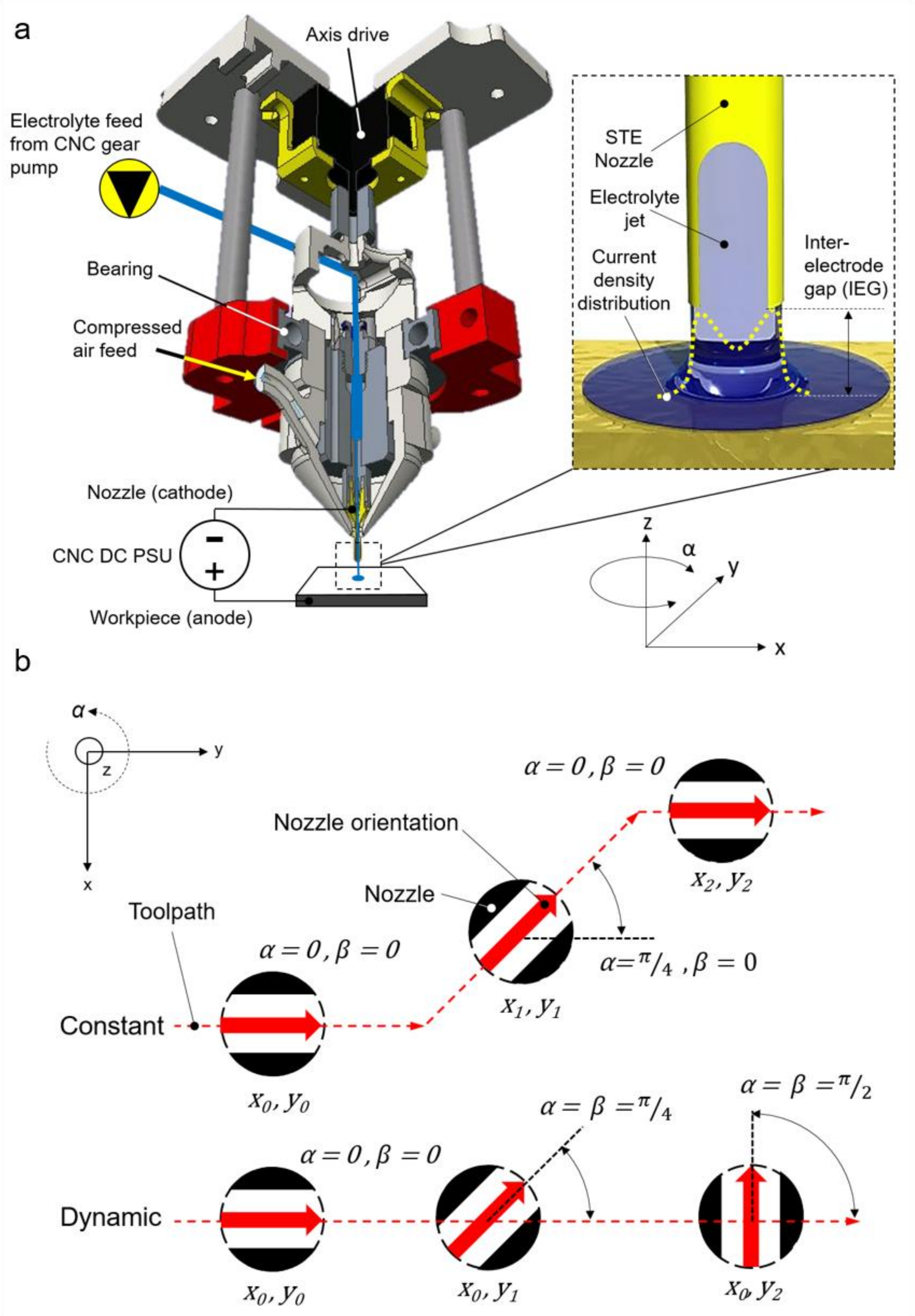
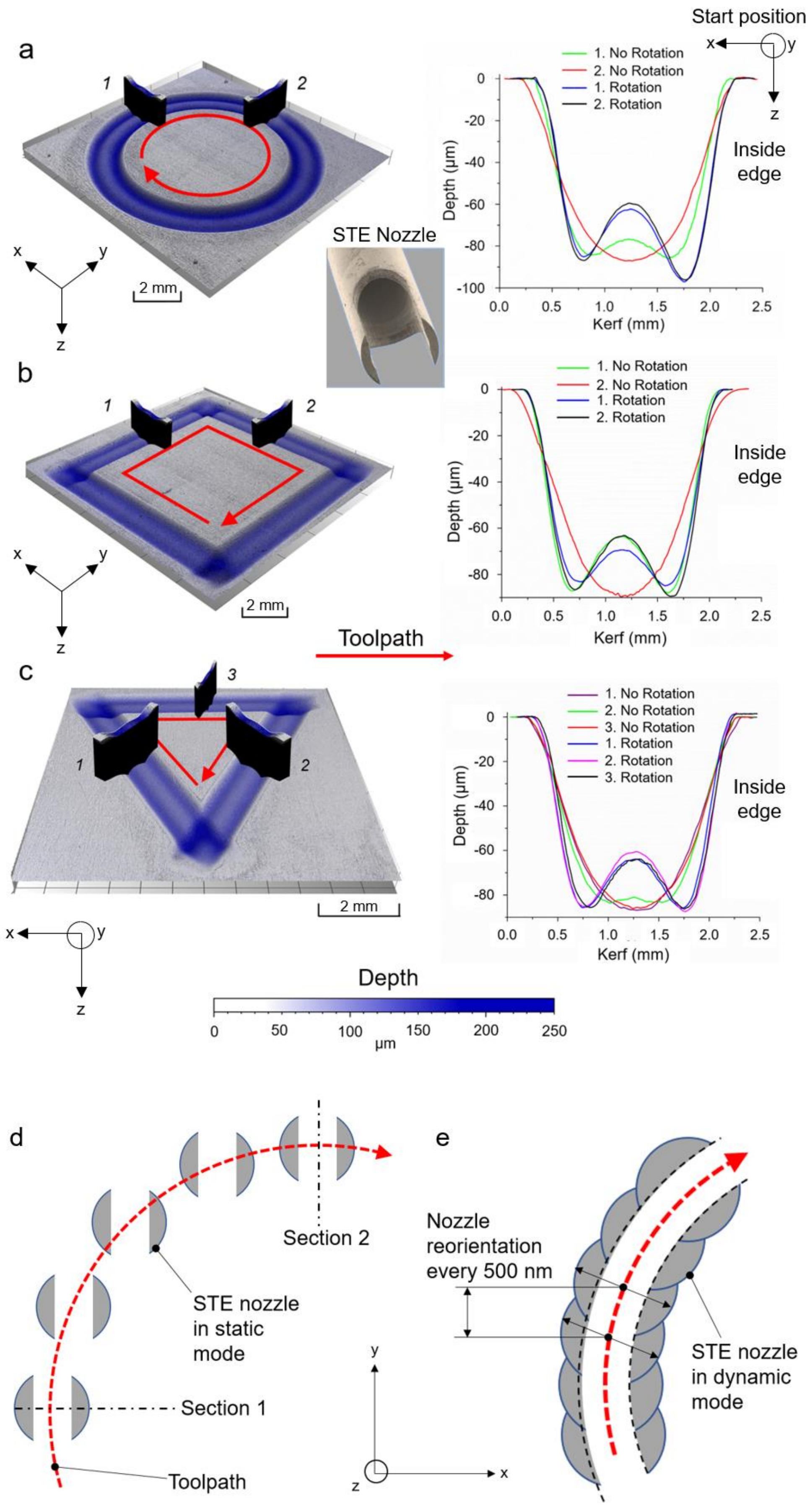


Figure 2: Rotary head design (a) creating rotation about the nozzle axis, allowing modified nozzles generating modulated energy density curves to remain perpendicular to the vector toolpath and so generate a constant resultant profile regardless of translation direction as per the nozzle design intent. (b) Schematic relating to equation used to determine nozzle orientation in constant profiling mode and dynamic profiling mode

Exploring further functionality, the nozzle was dynamically re-oriented whilst traversing the defined toolpath. This was created by positional control of the rotary head in the software creating a virtual gearbox, thus applying a fixed ratio with respect to reference from the positional increments of the x and y axis. Therefore, the nozzle changes orientation from 0° through to 90° over the predefined length of the striation, in this case 15 mm.

3. Results

Figure 3 compares the profiles when machining with a STE nozzle (Figure 2) with and without the rotary head engaged. Profiles of the features were extracted along the toolpaths at points 1-3 identified on the maps for comparison. With the rotary system engaged, the feature profiles generate the desired profiles in every toolpath vector, whereas profiles are predictably variable with the rotary head disengaged. For example the profile extracted from the circle (Figure 3a) at section 1 shows reduced impact of the STE nozzle geometry on the profile geometry, compared to the profile with the rotating head engaged. The two valleys created by the nozzle being closer than expected [7]. This is because the fixed orientation of the nozzle causes the geometry to be deformed by the leading and trailing edges of the nozzle as they pass over the toolpath. Therefore, the energy distribution over the surface is not solely representative of the nozzle but a hybrid of nozzle and direction as illustrated in Figure 3d. In comparison, at profile section two, travelling in the x direction, the nozzle produces the bell type profile synonymous with EJP, the nozzle now un-modified in its influence on the resultant profile. Similar features can be seen with the square (Figure 3b) and triangle (Figure 3c) toolpaths. In the case of the triangle toolpath when translating between the x-y planes it produces a convolution of the profiles created when traversing in the x and y directions with the non-rotary nozzle.



a
b
c
d
e
Start position
1. No Rotation
2. No Rotation
1. Rotation
2. Rotation
3. No Rotation
3. Rotation
Depth (µm)
Kerf (mm)
Inside edge
STE Nozzle
2 mm
Toolpath
Depth
µm
Section 1
Section 2
STE nozzle in static mode
Nozzle reorientation every 500 nm
STE nozzle in dynamic mode

Figure 3: STE nozzle (insert) used to create constant profiling experiments. 3D surface reconstructions of circle (a), square (b) and triangle (c) with accompanied profiles at sections denoted on the 3D surface. Shown with and without rotary the rotary head for comparison of the constant profile with the rotary head engaged and changing profile with it disengaged. Comparison of toolpath vector and nozzle orientation (d) without rotary head and (e) with rotary head engaged with constant nozzle orientation adjustment

In comparison rotational profiles achieve the desired profile in all cases, regardless of toolpath direction, as the nozzle orientation is constantly adjusted (a 1 ms processor loop correlating to a rotary response every 500 nm at the traverse speeds used here), to align with the vector tangent to the curve (Figure 3e) thus maintaining a constant profile.

There is a noticeable effect when the curve feature is generated which is not seen across the other rotary profiles in that the circle generated using head rotation is asymmetric (Figure 3a). The valley closest to the centre of the curve is deeper and wider than the valley to the outside of the circle, ≈10 μm deeper and ≈ 80 μm wider. Although total charge transferred remains constant, the localised energy is re-distributed to favour the inside valley. This is attributed to the linear velocity differential between the inside and outside of the edges of the curve [11]. This is likely to occur in any curved toolpath, although channel kerf and arc radius will have an impact and requires further investigation into methods to mitigate this. However, where the toolpaths intersect at corners in Figure 3b and c, to keep a sharp intersection on the inside edge, a radius was not created, rather the toolpath exceeded the feature distance and was then adjusted to start the next toolpath line prior to the start of the feature. This means these intersecting regions interact with the jet in opposing directions, eradicating the central feature to create a square and triangular pocket respectively.

Figure 4 illustrates the effect of operating the rotary head in dynamic mode. The profile constantly evolves across the feature (Figure 4a, b, c), utilising the OSPE nozzle (insert), set initially as shown. As the nozzle traverses in the x direction the deepest part of the profile, corresponding with the point of the nozzle tip, curves from the left of the profile to the centre. As the point approaches the centre, the profile becomes deeper by ≈20 μm and material removal is more localised at the centre (Figure 4c). This is due to the changing current density distribution as a response to the changing nozzle profile with respect to the direction of travel

[2]. The energy maxima will shift according to the apparent in-jet resistance found within the electrolyte jet at any discrete point. However, Figure 4b demonstrates that although the profile of the channel itself is changing, the dissolution kerf remains constant and in-line with the toolpath vector.

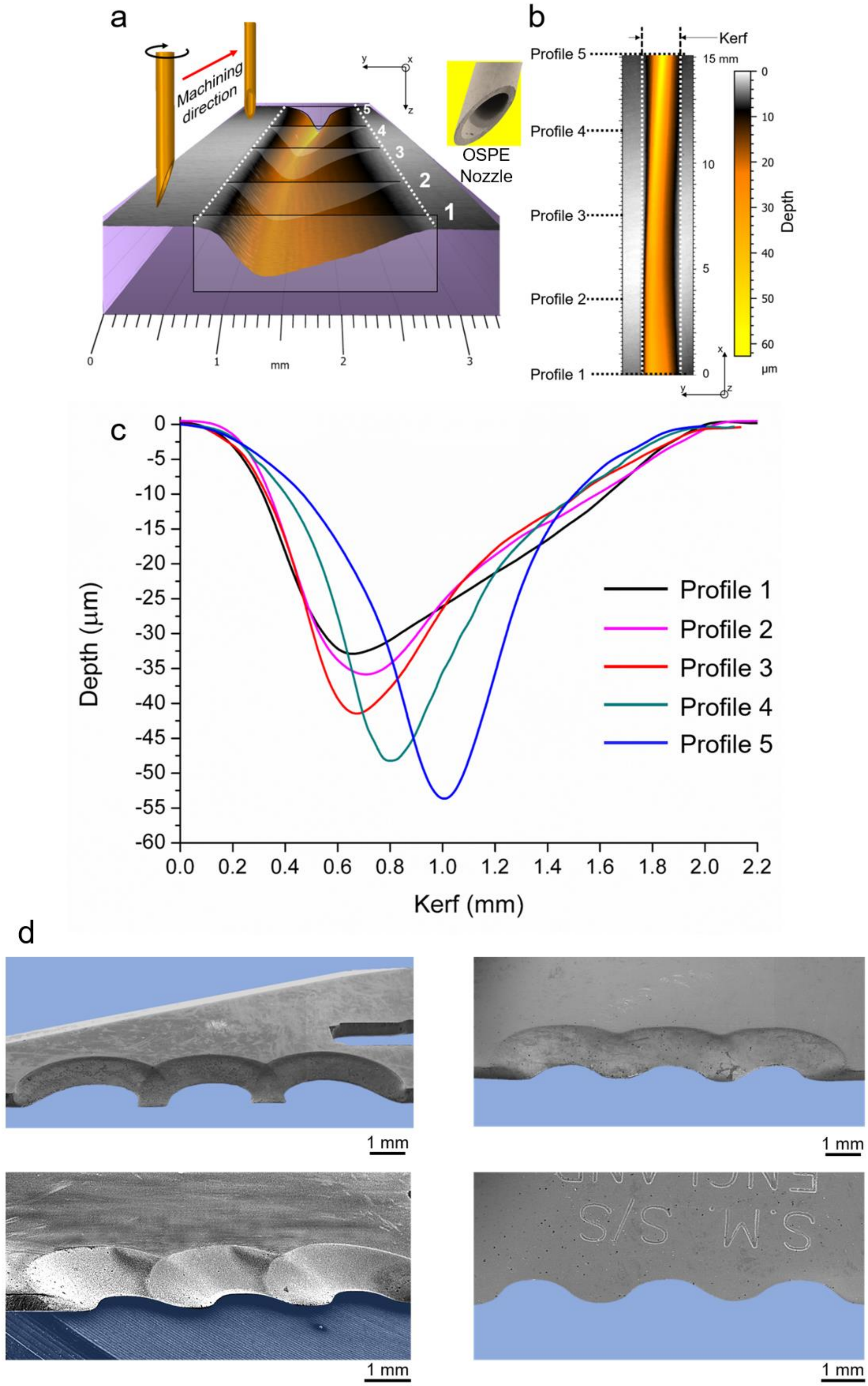

a
Machining direction
OSPE Nozzle
1
2
3
4
5
0
1
2
3
mm
b
Kerf
Profile 5
Profile 4
Profile 3
Profile 2
Profile 1
15 mm
10
5
0
Depth
0
10
20
30
40
50
60
μm
c
Depth (μm)
Kerf (mm)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Profile 1
Profile 2
Profile 3
Profile 4
Profile 5
d
1 mm
1 mm
1 mm
1 mm

Figure 4: Demonstration of rotary head in dynamic mode carrying out 90° clock-wise rotation over a 15 mm channel with OSPE nozzle. 3D surface reconstruction (a) and plan view (b) showing the extracted profile points which are shown in (c) where the change from an off-centre profile in section 1 can be seen to merge to a central deep profile in section 5. Utilising the OSPE nozzle with the rotary head to apply edge shaping to medical grade stainless steel. SEM images of (d) of varying bespoke serrated edge designs.

Utilising the OSPE nozzle and rotational head, features were machined into 0.8 mm thick medical grade stainless steel scalpel blades. Various serrated knife edge designs were developed in CAD and translated via CAM, developed by the authors [12], into toolpaths creating bespoke cutting type features (Figure 4d). All part features were created with 8 successive passes taking a total of ≈ 5 minutes to create each sample. The nozzle off-set being reduced by 30 μm after each pass. This presents a simple demonstration of the possibilities of the application of this hardware in a relevant material for the generation for features and serrations without thermal or mechanical impact. This could provide a distinct advantage in the rapid manufacture of bespoke medical tooling.

4. Conclusions

From this initial study the following can be concluded:

- A new approach enabling continuous complex profile micro-features and channels, regardless of toolpath vector, was established for non-uniform nozzle types.
- A methodology was developed to allow for dynamic tooling mode whereby the profile can be modulated as a function of position within the toolpath giving rise to a dynamic profile feature
- Sensitivity to radial translation is also shown to be an additional nuance which EJM researchers must apply.
- Bespoke, complex, features were rapidly created to demonstrate the applicability of these methodologies that would be inefficient by any other means.

In summary, a new design freedom is now available utilising active tooling in EJP to create one-step complex features in such applications as the tooling industry, microfluidics and general low production and prototype applications where micro channels are required and the added flexibility offered here in consistent and constantly evolving geometries is required.

Acknowledgements

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