Journal of Manufacturing Processes 31 (2018) 273–285

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Transitory electrochemical masking for precision jet processing techniques

J. Mitchell-Smith, A. Speidel, A.T. Clare*

Advanced Component Engineering Laboratory (ACEL), Advanced Manufacturing Technology Group, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

ARTICLE INFO

Article history:
Received 1 October 2017
Received in revised form 23 November 2017
Accepted 26 November 2017

Keywords:
Electrolyte doping
Electrochemical machining
Electrolyte jet machining
Ecm
Electrochemical jet processing
Nickel superalloy

ABSTRACT

Electrochemical jet processing techniques provide an efficient method for large area surface structuring and micro-milling, where the metallurgy of the near-surface is assured and not adversely affected by thermal loading. Here, doped electrolytes are specifically developed for jet techniques to exploit the Gaussian energy distribution as found in energy beam processes. This allows up to 26% reduction in dissolution kerf and enhancements of the defined precision metric of up to 284% when compared to standard electrolytes. This is achieved through the filtering of low energy at discrete points within the energy distribution curve. Two fundamental mechanisms of current filtering and refresh rate are proposed and investigated in order to underpin the performance enhancements found using this methodology. This study aims to demonstrate that a step change in process fidelity and flexibility can be achieved through optimisation of the electrochemistry specific to jet processes.

1. Introduction

It is widely recognised that component surface enhancement through the application of multiple scale surface structures is paramount to the optimisation of a component's performance [1–5]. Realisation of these complex, often biologically inspired surfaces presents a significant manufacturing challenge. Electrochemical methods present distinct advantages over more commonly used technologies [6–9]. Creation of highly complex surfaces over a large area, while preserving the metallurgy of the near-surface is not easily achieved. Conventional processes which rely on thermal or shear-based interaction with a tool or energy beam can impart detrimental surface effects, such as residual stress and thermally affected zones.

Electrolyte jet processing (EJP) is a high-precision variant of electrochemical machining (ECM). EJP is the amalgamation of electrochemical jet machining (EJM) [10] and electrochemical jet deposition (EJD) [11,12] within a unified machine tool [13]. An electrolytic cell is formed between the nozzle, and the workpiece confined within the electrolyte jet (see Fig. 1). At sufficient velocity, a thin film area develops radially about the nozzle as the jet impinges. This creates a high resistance area on the target surface, which restricts current allowing for mask-less deposition or removal of material. In most experimental apparatus, this is further aided by an air shroud, co-axial to the nozzle (Fig. 1a) helping to constrict the jet further and also serving to assist in debris and gas bubble removal which form during machining [14].

EJP in subtractive mode has been successfully applied in creating *meso*- and micro-scale surface structures across a wide range of materials [15–21] and applications [22–26]. Prior research work has been carried out to enhance EJP through modification to the nozzle tip [13], enabling modulation of the machined profile, which is distinct from that resulting due to the Gaussian energy distribution (Fig. 1b and c). This modulation of the resistance in-jet allows the response geometry to achieve not only application specific features but, enhanced dimensional accuracy. This is manifested by reduced side wall taper and flatter cut floors analogous to more conventional machining methods.

Electrolyte feedstocks have been investigated in order to enhance resultant finish in EJP [27]. However, electrochemistry within the inter-electrode gap (IEG) has not been a design criterion in previous studies.

1.1. Profile fidelity enhancements

The electrolyte itself has a significant effect on the precision of feature creation due to characteristic conductivity profile specific to each electrolyte [28]. The concentration and composition of elec-

* Corresponding author.
E-mail address: adam.clare@nottingham.ac.uk (A.T. Clare).

https://doi.org/10.1016/j.jmapro.2017.11.028
1526-6125/

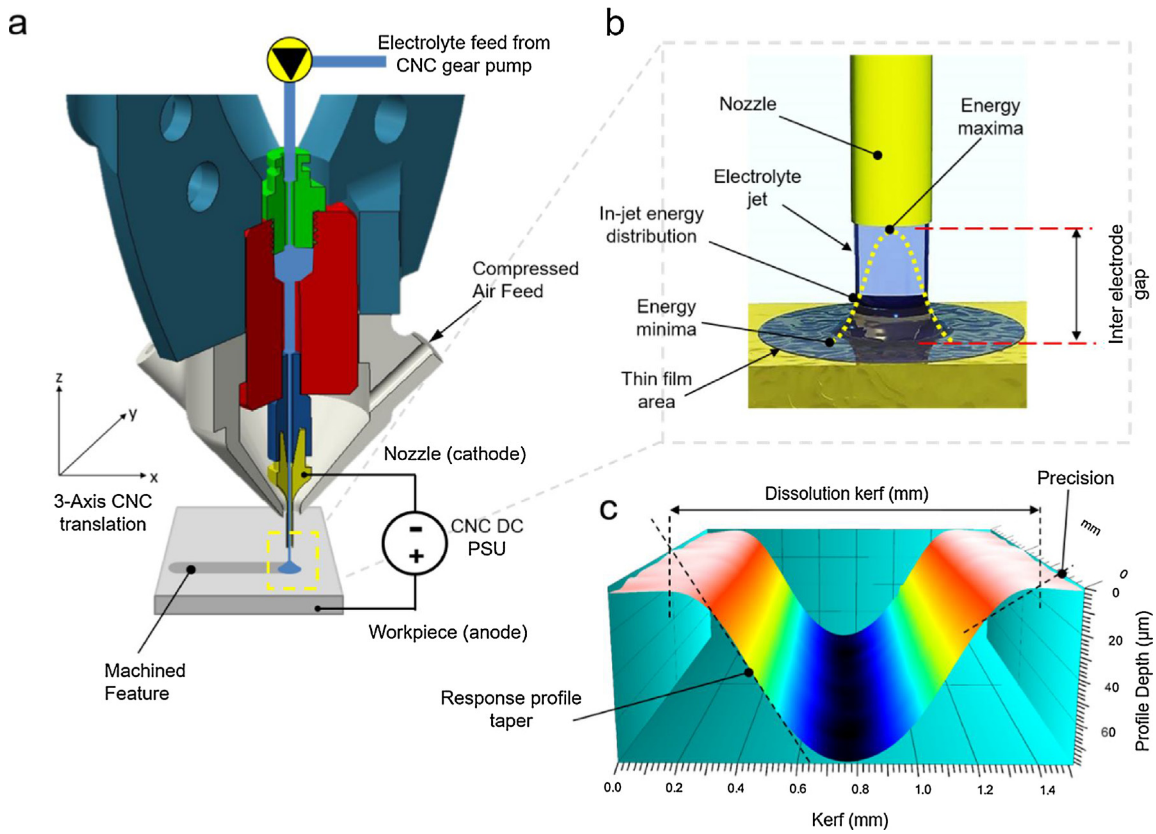

Fig. 1. (a) Schematic showing the rudimentary configuration of EJP apparatus in the subtractive mode (b) detailed schematic of jet interaction zone demonstrating Gaussian energy distribution in-jet (c) extracted resultant machined profile with geometrical definitions.

trolytes used in ECM and EJP specifically have been demonstrated [27,29] to influence the stochastic morphology of the machined surfaces. Electrolyte current efficiency dominates the fidelity of electrochemical machining processes [30,31]. This can be modulated for a given solution by controlling current density. Previous contributions in this field [17] have highlighted the role played by the electrolyte in defining process precision.

The relationship between current density and current efficiency is exaggerated for EJP techniques due to large spatial current density differentials [32]. This causes localised regions where current density exceeds the well-understood activation threshold and thus the onset of machining. Rounded profile features and significant side wall taper (Fig. 1c) are observed [33,34] due to the extremes in current density found across the jet when using conventional ($NaNO_3$ and NaCl) electrolytes. This is problematic since material removal/deposition rate is proportional to current density.

The effect of electrolyte composition has been reported to affect dimensional accuracy in the more established practice of electrochemical machining (ECM). The type of electrolyte to be used has been investigated [35,36] alongside concentration [31,37], which have been shown to improve precision. However, these innovations, although effective in general ECM, are not so applicable to EJP. This being due to the aforementioned large spatial current density differentials across the jet diameter.

Previous attempts to negate this deleterious effect and therefore improve the dimensional accuracy and aspect ratio of the deterministic feature have included the innovation of the hybrid EJM processes. Laser-assisted EJM [38–41] has been employed as a 'focussing' tool to enhance the conductivity at the centre of the electrolyte jet, through a localised temperature increase. This serves to normalise the effective current density outside of the central machining region to reduce overcut. Electrochemical slurry-jet machining [42,43] was developed, whereby the anodic dissolution mechanism is complemented by the application of abrasive jet, again increasing the material removal rate leading to higher aspect ratio holes, although at the loss of surface quality. A further adaptation is the introduction of a pulsed current power supply. First exploited in general electrochemical machining [37,44,45] inhomogeneity in the flow field is reduced due to the rapid updating of the electrolyte. This ensures that machining is restricted to beneath the jet as the electric double layer takes longer to form in the lower current density areas at the periphery of the jet [46,47].

It is hypothesised that significant process enhancements can be achieved by exploiting in-jet electrochemical reactions through doping of conventional electrolytes. It is proposed that when coupled with modified nozzles, predefined and high-fidelity profile geometries can be created. This study aims to demonstrate that a step change in process fidelity and flexibility can be achieved through optimisation of the electrochemistry specific to jet processes.

1.2. Current efficiency

Electrolytes such as $NaNO_3$ and NaCl are commonly employed in electrochemical jet techniques due to their low cost, availability and comparatively low toxicity. Despite response being dependent upon work piece material, these can lead to significantly different resultant profiles. Aggressive electrolytes such as chloride are understood to maintain high current efficiency over a wide range of current densities [28]. In comparison, the current efficiency when machining with sodium nitrate increases with current density, within current density ranges used in EJP. Noting the typical Gaussian distribution of current density found when a standard cylindrical nozzle is used (Fig. 1b). This can lead to significant mate-