International Journal of Machine Tools and Manufacture 122 (2017) 32–46

Contents lists available at ScienceDirect

International Journal of Machine Tools and Manufacture

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

Energy distribution modulation by mechanical design for electrochemical jet processing techniques

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ABSTRACT

The increasing demand for optimised component surfaces with enhanced chemical and geometric complexity is a key driver in the manufacturing technology required for advanced surface production. Current methodologies cannot create complex surfaces in an efficient and scalable manner in robust engineering materials. Hence, there is a need for advanced manufacturing technologies which overcome this. Current technologies are limited by resolution, geometric flexibility and mode of energy delivery. By addressing the fundamental limitations of electrochemical jetting techniques through modulation of the current density distribution by mechanical design, significant improvements to the electrochemical jet process methods are presented. A simplified 2D stochastic model was developed with the ability to vary current density distribution to assess the effects of nozzle-tip shape changes. The simulation demonstrated that the resultant profile was found to be variable from that of a standard nozzle. These nozzle-tip modifications were then experimentally tested finding a high degree of variance was possible in the machined profile. Improvements such as an increase in side-wall steepness of 162% are achieved over a standard profile, flat bases to the cut profile and a reduction of profile to surface inter-section radius enable the process to be analogous to traditional milling profiles. Since electrode design can be rapidly modified EJP is shown to be a flexible process capable of varied and complex meso-scale profile creation. Innovations presented here in the modulation of resistance in-jet have enabled electrochemical jet processes to become a viable, top-down, single-step method for applying complex surfaces geometries unachievable by other means.

1. Introduction

The creation of next-generation, high-integrity surfaces [1–3] presents a significant manufacturing challenge. Advantage can be gained for anti-fouling, drag-reduction, enhanced adhesion [4,5] and enhanced osseointegration [6,7] in applications where complex surface structuring has been employed.

Contrived process chains involving polymer deposition [8,9], laser ablation [10,11] and by mechanical means [12], have been adopted, but results fall short when practitioners seek to process large areas to a level of complexity. Furthermore, when processing metallic surfaces, integrity is of paramount importance such that the metallurgy of the near-surface is assured and not adversely affected by thermal loading.

Electrolyte jet processing (EJP) is the amalgamation of electrochemical jet machining (EJM) [13–15] and electrochemical jet deposition (EJD) [16,17], within a unified machine tool. This technique can achieve jetted deposition of material with a cathodic workpiece, and jetted material removal with an anodic workpiece (Fig. 1a). Manipulation of process parameters, polarity and electrolyte chemistry enables application-specific, bespoke surface-structuring to be generated in a single process step.

To date, capability of the EJP process is fundamentally limited as a result of the characteristic energy density profile, which results from the use of 'standard' nozzles. Through modelling and experimentation of adaptations to the process, new capabilities are demonstrated here and qualified from first principles.

1.1. In-jet modulation of current distribution

Consistent with other energy beam processes such as laser [18], electron [19] or water jet [20] the energy density is typically seen to be of a Gaussian spatial distribution (Fig. 1b). This extends radially outward from a peak intensity at the centre of the beam. The resulting profiles exhibit tapered sides, a rounded apex and diffused edge definition (Fig. 1c). Significant work has been undertaken in the field of laser processing to modify energy distributions. Through beam profile shaping, more favourable and uniform thermal distributions [21–23] have been produced. In this case, holographs generated by custom optics are used to define the incident energy distribution. This can be considered as optically analogous to the work presented here.

Although EJM has been demonstrated to be capable of biomimetic type structures in the form of super-hydrophobic surfaces [24], EJP is

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http://dx.doi.org/10.1016/j.ijmachtools.2017.05.005
Received 14 December 2016; Received in revised form 5 May 2017; Accepted 8 May 2017
Available online 31 May 2017

Nomenclature

d_s	minimum distance of the nozzle tip from the surface (μm)
d_n	specific distance of the individual modified nozzle feature from the surface (μm)
A_A	annulus area of nozzle tip surface facing the incident surface (mm^2)
A_F	area of current focussing feature facing the incident surface (mm^2)
A_{exp}	area of profile expected from calculation (mm^2)
V	voltage (V)
I	current (A)
R	resistance (Ω)
p_r	probability of removal
S	Single point or element on the substrate facing the nozzle tip element (N)
N	Single point or element on the surface of the nozzle tip facing the substrate surface (S)
$I.D.$	inner diameter of the nozzle (mm)
STE	symmetrical twin element nozzle design
$OSPE$	Off-centre single point element nozzle design
STD	standard nozzle type
CPE	centre point element nozzle design
WC	wide castellated nozzle design
NC	narrow castellated nozzle design
E_{eff}	electrolyte current efficiency (%)
ECE	electrochemical equivalent
J	current density (A/cm^2)
m	mass (g)
L	length (m)
DIF	design impact factor
r_{noz}	radius of the nozzle (mm)
$O.D.$	outer diameter of the nozzle (mm)
t_m	total machining time

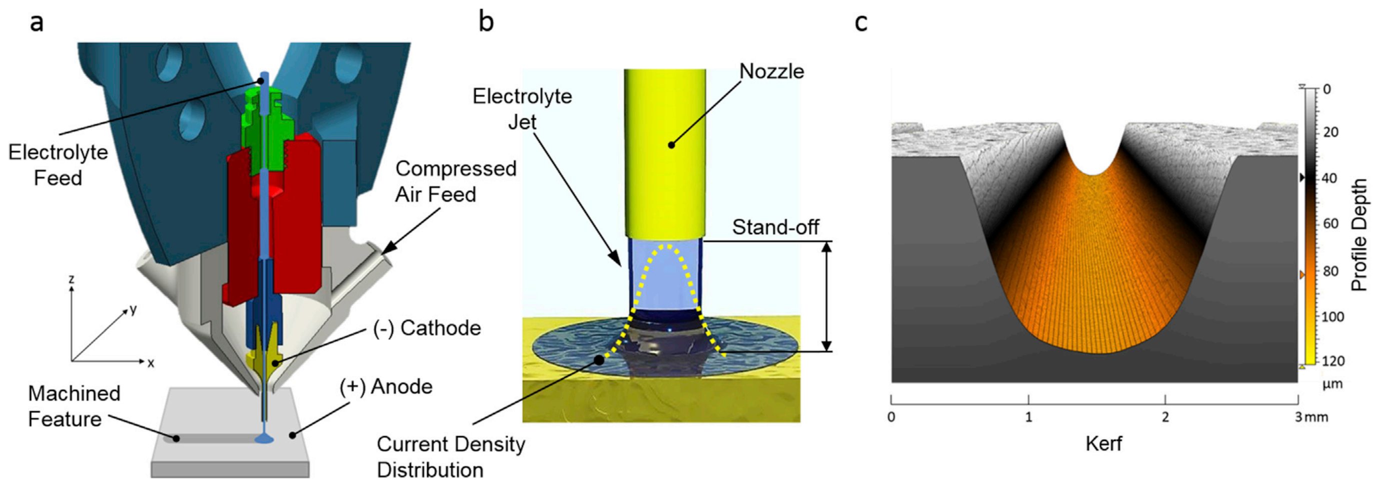

Fig. 1. (a) EJP end-effector in subtractive polarity configuration (material removal) as used in this demonstration. (b) Standard nozzle showing the standard Gaussian type current density profile within the incident jet. (c) 3D surface map from experimental results showing the profile currently achieved from a standard cylindrical nozzle reflecting the Gaussian profile of energy distribution. Demonstrating the tapered feature sides, a rounded apex and diffused edge definition.

currently limited by a characteristic energy profile (Fig. 1b). This is the principle factor in determining the dissolution profile [15]. By adapting this energy distribution, it is proposed that distinct meso- and micro-surface geometries can be created.

Typically, a uniform, straight-cut nozzle is addressed normally to the workpiece (Fig. 1b). In EJP, the peak current density is observed at the centre of the nozzle. Modifications to the nozzle tip can adjust the perpendicular distance between the nozzle element and workpiece therefore altering jet electrical resistance. It is proposed that the accepted definition of 'stand-off' (inter-electrode gap) is no longer sufficient. Instead, a new parameter is required which defines the spacing between nozzle rim contour and the work. This must accommodate spatial- and temporal-variation as the work piece shape evolves during machining. The result being the creation of preferential current pathways and therefore material removal can be modulated across the area of jet impingement. This has yet to be demonstrated and exploited.

Found experimentally, Fig. 2a shows that when using a standard profile nozzle, resistance increases from 15 Ω at a nozzle stand-off of 200 μm through to 200 Ω at 2.75 mm stand-off when used with a 2.3 M $NaNO_3$ electrolyte. This can then be related to localised resistance at nozzle tip features. Adjacent to this (Fig. 2b) is the expected 2D distribution as a percentage of the total charge created by proposed new nozzle geometries. Utilising the measured resistance data from Fig. 2a it is possible to calculate the percentage of total charge available (Equation (1)). Using the minimum and maximum points of current created by the nozzle features, a Gaussian distribution is then assigned around these giving an approximation of the current distribution. The area under the curve being equal to the total current density. This is, in turn, is proportional to the total material removed across the 2D section.

$$V = IR = \pi r_{noz}^{2} JR \tag{1}$$

Significant prior work has been carried out in the development and deployment of simulations of energy beam processes. A wide range of mathematical models to explain material removal and induce optimisation in comparative processes such as abrasive water-jet (ABWJ) [25–28], sandblasting [29], pulsed electron beam ablation (PEBA) [30], laser ablation [31,32] and fluid jet polishing [33,34] have been presented, each with specifics relative to the process in question. Previous work, in both removal and deposition electrochemical jet methods, has provided insight into the basic current distribution found with a standard cylindrical nozzle [35,36] and expanded to three dimensions [37]. Increasing temperature from joule heating and changing electrolyte