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Analysis and performance of slotted tools in electrical discharge drilling

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ABSTRACT

Accumulation of machining debris due to inadequate gap flushing severely limits the material removal rate and impairs the quality of the machined surface in electrical discharge machining. This is particularly pronounced in electrical discharge drilling of holes with a high aspect-ratio, wherein conventional flushing techniques essentially cease to be effective. To this end, this paper proposes the application of novel tool electrodes comprising geometric features specifically designed to promote tool rotation-induced debris egress. The corresponding flow fields are modelled numerically to optimize said designs. Relative to conventional rotating cylindrical tools, removal rate enhancements on the order of 300% are demonstrated.

1. Introduction

Sufficient gap flushing is of decisive importance in electrical discharge machining (EDM) with respect to the rate of material removal, geometric accuracy and surface quality. Since no level of sophisticated process control can compensate for issues arising from adverse gap contamination, several flushing techniques have been devised in the past to maintain optimal debris concentration [1]. These primarily entail forced flow of the dielectric fluid from outside the machining zone in the form of a jet, or through channels provided within either the tool or the workpiece; alternatively, flushing could be induced by incorporating a secondary relative motion between the electrodes, as in planetary, vibration-assisted and jump EDM processes.

There have also been several attempts at modelling the flow field in the inter-electrode space with a view to augmenting gap flushing. The first of these appears to be due to Koenig et al. [2] who correlated the pressure and velocity distributions to the machining responses, for through-tool flushing applications. Masuzawa et al. [3] simulated the flow fields in sink-EDM to model the efficacy of motion-coordinated multiple sweeping jets in enhancing form accuracy. Kunieda and Masuzawa [4] proposed the application of sink EDM in a horizontal configuration with synchronous rotation of the tool and the work, so as to tap into the buoyancy of bubbles for the evacuation of debris off the working gap. In their work, a simple model was developed to map the debris distribution and clarify the physics behind the optimal rotational speed that maximizes machining stability and accuracy.

The availability of software suites for computational fluid dynamic (CFD) analysis has of late led to significant advances in the modelling of fluid flow in EDM processes. Wang and Han [5] have recently developed a three-dimensional, three-phase numerical model of the machining gap to simulate debris and bubble movements during consecutive pulse discharges. Cetin et al. [6] modelled the flow field and debris distribution in the frontal and lateral machining gaps to examine the effect of electrode lift height on the geometric form of holes machined in jump EDM. Flow simulations indicated the manifestation of vortices under certain combinations of electrode lift parameters, which tend to redistribute debris within the gap, rather than evacuate them off it. This in turn triggers secondary discharges that compromise process stability and performance. Similarly, Pontelandolfo et al. [7] report numerical investigations into the influence of electrode geometry and kinematics, as well as the relevant dielectric fluid properties, on the trajectories of individual debris particles, with a view to identifying stagnation zones in jump EDM. Such a modelling capability is indeed invaluable in facilitating effective, physics-based design of the tooling as well as the process.

Okada et al. [8] utilized CFD analysis to chart flow fields and debris motion in wire EDM, which were found to be in good quantitative agreement with flow visualizations realized using high-speed particle image velocimetry. Model simulations in their research enabled comprehending the role of such parameters as the flow rate and the nozzle stand-off distance in the formation of stagnation zones, which can be acutely detrimental in inducing catastrophic wire failure. Gu et al. [9] proposed the application of an assembly of tubular electrodes that have been appropriately bundled to correspond to the geometry of three-dimensional tooling, for rough sinking of features with large frontal areas. Relative to conventional solid electrodes, the high material removal rates obtained using this novel tooling concept has been attributed to the favourable distribution of dielectric flow velocity across the machining gap, as revealed by a numerical model.

In the context of flushing in EDM, this paper focuses on electrical discharge drilling (EDD) of blind macro-holes, and comprises aspects of tool development and numerical flow modelling. Machining of such features using jump EDM relates

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to a low efficiency on account of the reciprocating tool motion representing lost machining time. In the event of using a through-tool flushing technique in such applications, an orbital motion is required to remove the footprints left on the machined surface that pertain to the flushing holes. In this light, the present work examined the efficacy of introducing geometric features into the cylindrical tools that simply rotate in place, with the intent of promoting debris egress. CFD is employed as a tool to gain insights into the flow fields associated with the proposed innovative tooling geometries, and further to assess and optimize the geometric features towards maximizing the material removal rate.

2. Experimental

The objectives of the experimental work were to: (i) benchmark the performance of rotating solid cylindrical electrodes in an EDD process as a function of rotational speed and machining depth in terms of material removal rate, and (ii) to characterize the relative enhancement in the performance of these tools with such geometric features as helices and longitudinal slots.

Experiments involved copper tooling, and considering that the intention was to rapidly assess the effectiveness of flushing in terms of comparative performance, involved 6061 aluminium alloy as the workpiece material. The tools were of a nominal diameter of 15.8 mm, and were trued in-place by fine cutting to minimize the axial and radial tool run-outs, so as to ensure stable machining. Based on technology recommendations from the machine tool manufacturer, experiments involved a hydrocarbon-based dielectric fluid, a tool-positive polarity, a gap voltage of 100 V, a discharge current of 21 A, and a pulse on-time and off-time of 100 μs and 42 μs, respectively.

3. Modelling

On the assumption that fluid flow essentially governs the transport and egress of debris particles, the flow fields in the frontal and lateral gaps were simulated using ANSYS CFX software. The meshing of the fluid domain referring to EDD proved to be indeed intricate, on account of the machining gap being quite small, relative to the tool diameter and the machining depth. Ironically, this is much the same issue that renders gap flushing to be a challenge in EDD. The frontal and lateral gap lengths were hence considered to be 200 μm as a reasonable compromise.

The efficacy of flushing was investigated in the numerical simulations by uniformly dispersing spherical aluminium particles of 20 μm diameter [1] in the frontal machining gap, and by tracking their movement through and out of the fluid domain. The total volume of particles introduced into the gap per unit time was consistent with the nominal material removal rate. To simulate the profound influence exerted by the bubbles generated in EDM on the physical transport of the debris elements [5], the specific gravity of the particle artefacts was assumed to be 0.3; this refers to a vapour to particle mass fraction of 0.125, which was determined to aptly capture the buoyant effect of bubbles. This model is experimentally validated later.

For a tool rotational speed of 1000 rpm, a tool diameter of 15.8 mm, and a dielectric fluid kinematic viscosity of 3×10^{-6} m^2/s that are pertinent to this work, the rotational Reynolds number Re_Ω computes to ~2200; this is well below the threshold of 2×10^5 that signifies the onset of a transition to turbulence [10]. The flow was hence considered to be laminar. The flow field was generally modelled as two separate domains: a rotating tool domain with a specified angular velocity and a stationary fluid domain, except for cylindrical tools wherein a rotating wall boundary condition was found adequate. The use of an immersed solid domain referred to less computational effort by restricting the tool domain to just the region of tool-fluid interaction. Tool and workpiece walls were set as no-slip boundaries, and the fluid regime was considered to constitute a single continuous 3D domain.

The simulation of fluid flow and particle motion entailed an Eulerian–Lagrangian approach. One-way coupling of the fluid flow influencing particle motion was deemed an expedient trade-off between model accuracy and computational cost. Momentum transfer between the fluid and the particles was modelled using the Schiller–Naumann drag model, given that the flow was laminar and involved sparsely-distributed spherical particles.

4. Results and discussion

The experimental and numerical components of this research did truly complement each other in the design of EDD tools. Flow modelling facilitated comprehensive insights into phenomena associated with experimental observations, and served as the basis to build up on, towards conceiving novel tool geometries. Typical computational cycle times being less than 20 min on a desktop computer enabled the rapid virtual testing, selection and optimization of tool geometric features. The performance of tools thus optimized was thereafter verified experimentally. These aspects are detailed in the following.

Fig. 1 compares the material removal rate corresponding to three tool geometries as a function of tool rotational speed when the machining depth is less than 1 mm. The slotted tool comprised 4 radial slots equispaced around the tool circumference, each of which were of width 2 mm and height 1.5 mm. This represents a tool frontal area that is 94% of that of a cylindrical electrode. The helical tool corresponded to a single start of the same slot section above, and a helix angle of 22°. Electrode rotation can be seen to have brought about a substantial enhancement in the removal rate relative to a stationary electrode in all cases, especially at the lower end of speed; a further speed increase thereafter refers to diminishing returns. Over the entire range of rotational speeds tested, the slotted tool outperformed the helical and cylindrical tools, the performance of which was largely similar.

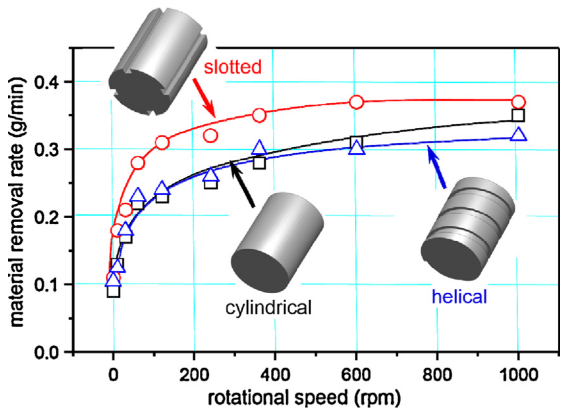

Fig. 1. Effect of rotational speed and tool geometry on removal rate.

Fig. 2 depicts tool performance at a rotational speed of 60 rpm in terms of the machined depth. At a depth of 5 cm, which is roughly 3 times the hole diameter, the removal rate for the cylindrical electrode is just 30% of that near the surface. This highlights the debilitating consequence of a progressive lack of effective gap flushing with increasing machining depth. Experiments further indicated the application of external jet flushing to be of little recourse in such instances. Notwithstanding the common trend of declining removal rate with machined depth, incorporation of helical and slot geometric features can be seen to have translated the characteristics upwards towards higher removal rates, in that order. The improved performance of the helical tool is intuitive in light of the inherent pumping action that can be expected to enhance gap flushing. The slotted tool yet again significantly outperforming the helical counterpart is but counterintuitive. Relative to the cylindrical electrode, the slotted tool refers to more than a 200% enhancement in the removal rate, at a machining depth of 5 cm.