Die-sink EDM in meso-micro machining

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Abstract

Micro EDM has been identified since more than a decade as suitable process for machining complex shaped structures with high aspect ratio, though only through variations of EDM such as micro EDM milling, micro EDM drilling, coated electrodes etc. In the current paper, we present the research focused on analysing the capability for implementation of die-sink EDM in meso - micro scale machining (structures with surface area smaller than $10\text{mm}^2$ down to $0.05\text{mm}^2$) by concentrating on primary process parameters to obtain high material removal rate, low tool electrode wear with high form accuracy and precision. Graphite electrodes were mill machined in meso-micro scale with high precision and accuracy. Low tool wear technology was developed for using graphite electrodes in meso-micro EDM offering economical and energy efficient solution in meso-micro scale machining.

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1. Introduction

Ever increasing space, energy and efficiency requirements are pushing products towards miniaturisation in several areas such as biomedicine, electronics, dies-moulds, optics, energy, micro mechanics, micro fluidics, aerospace and aeronautics to name a few [1]. The parts for such devices are manufactured directly or using replication techniques for large throughput, where manufacturing restrictions considerably influence the design process and sometimes overall performance of the product [2]. In the manufacturing process chains for such products, various machining techniques such as micro-milling, micro-EDM, micro-ECM, IBM, Laser ablation, etc. are required either to machine final parts or for the die and mould machining for the replication techniques such as micro-injection moulding, micro-casting, micro-stamping [2][3]. Micro-milling is a promising technique with advancements in tool coatings, tool geometry, high precision machine structures and spindles, though high aspect ratio ($L/D>$10) structures and small feature dimensions (below 100µm) remain a challenge. Laser ablation with advancements in optics and with ultra-short pico- and femto- second pulses is finding increasing applications especially in bio-medicine sector, but higher costs limits its wide spread application. On the other hand, Micro EDM has been identified as one of the potential micro-machinghnique with obvious advantages of machining complex structures with high aspect ratios, high precision and accuracy irrespective of work-piece material hardness and toughness.

2. Meso - Micro EDM

The main difference between conventional EDM and micro-EDM can be drawn by smallest feature dimensions to be machined by the process which must also consider the contemporary levels of conventional technologies. In this regard, paradigm shift in process behaviour and thus need for process control allows definition of meso- and micro- EDM, where machining of features with projection area above $10\text{mm}^2$ is considered conventional EDM, between $10\text{mm}^2-1\text{mm}^2$ is considered meso EDM and surface area $1\text{mm}^2$ and below or smallest dimension below $1\text{mm}$ is considered micro-
EDM. In this regime of EDM, variants such as micro EDM drilling, micro EDM milling have been developed [4] [5]. In spite of its ability to machine complex cavities with high accuracy, micro EDM milling is employed mainly in niche applications whereas micro EDM drilling is limited by shape of the tool electrode.

Even though large amount of research is dedicated in the field, there is currently no existing alternative of EDM which offers manufacturing industry with an option to machine features in meso- and micro scale with the same ease as conventional EDM due to involved high tool wear, low material removal rate, surface – subsurface damages and thus poor process efficiency in this regime. The aim of current research is to facilitate an industrial, economical and energy efficient solution for meso-micro scale machining using die-sink EDM through qualitative and quantitative analysis of the process. The current paper introduces challenges for die-sink EDM implementation in meso-micro scale followed by the experimental setup for machining graphite electrodes in meso-micro scale and details of equipment used for the current research. Initial results are then presented along with discussion followed by conclusions and outlook.

2.1. Process outputs and challenges

Material removal rate, tool wear and surface quality are the main process outputs of EDM. The challenge for direct implementation of EDM in meso- micro scale machining is not only overall lower process efficiency but also high tool electrode wear. Various methods have been suggested such as coating of tool electrode [6], novel materials for tool material [7] or tool wear compensation [8] in addition to conventional method of using multiple electrodes. However, these methods cannot be widely implemented in machining industry due to involved costs of materials, equipment and process sensitivity. Also, electrode materials such as tungsten carbide are very difficult to machine and thus are limited by its machinability in meso-micro scale. On other hand, conventional electrode materials such as copper and graphite are easy to machine by milling or WEDM in meso-micro scale but incur extremely high electrode wear in meso-micro scale EDM, which requires multiple electrodes strategy. Especially for high aspect ratio structures and precision manufacturing, the number of required electrodes is quite high for meso-micro EDM since it follows a vicious cycle of corner wear as shown in fig. 1, which ultimately restricts the form accuracy of the machined part. As shown in fig. 1, first tool electrode being subjected to corner wear with increasing machining depth ultimately wear out frontally causing frontal and lateral wear (see, fig. 2).

The subsequent electrodes 2, 3, 4, 5 then start machining the contour produced on workpiece where electrode corners are initially engaged causing again high wear of corners leading to shape deformation. Thus, for example one achieves desired form precision, accuracy and smallest corner radius on workpiece by using 5 electrodes. Multi-electrode strategy thus results in higher costs, higher energy - resource requirements and lower productivity for meso-micro scale machining. Also for precision machining, lower accuracy of machined parts is expected due to positioning errors involved while machining and changing tool electrodes.

Fig. 2. Characterization of tool electrode wear: frontal wear, lateral wear and form distortion. Original electrode diameter in background is 0.8mm, length 5mm; machined from Graphite with average grain size 7µm. Applied maximum current per pulse is 20A, positive polarity.
3. Experimental setup and methods

3.1. Milling of graphite electrodes in meso-micro scale

With developments in EDM grade graphite with fine grain sizes (<5µm), machining of extremely small structures with high aspect ratios and complex structures has become possible. It must be noted only few publications [9][10][11] are available dedicated to graphite electrode machining and no publications were found studying the graphite machining in meso- micro scale.

High precision 5-axes machining centre Willemin W518MT was used to machine the electrodes where a hand-written cam strategy was used and optimised to achieve precise form of the electrode with high accuracy. To prevent damage of machine elements and maintain stable process, a graphite dust suction system was devised (see, fig. 3) using industrial vacuum suction pump and a regulated air flow was provided to keep the machining region of electrode free from dust-clogging which may distort the machined electrode geometry. Diamond coated special end-mill for graphite machining from Fraisa SA was used. For roughing, 2mm diameter and 10mm long end-mill whereas 1mm diameter and 10mm long end-mill with 200µm corner radius was used for finishing operations.

Machined graphite for tool electrode was POCO EDM-3 grade with average particle size smaller than 5µm and Ringsdorf R8650 with average particle size 7µm according to data specification from the manufacturer. The spindle speed above 85’000RPM specified by end-mill manufacturer was not attainable with specified machine and thus maximum spindle speed used was limited to 20’000RPM. Depth of cut was kept at 0.1mm whereas cutting velocity was set at 300mm/min. Additionally, turning operation was used to machine cylindrical electrodes and Wire-EDM was used to machine copper electrodes in meso-micro scale.

3.2. Equipment for EDM

High precision die-sink EDM apparatus Form 1000 from Agie Charmilles SA was used during current research. The machine structure is capable of positioning accuracy of less than 1µm and designed with optimal strategy for cooling, keeping workspace at constant temperature to achieve high precision and accuracy. No additional changes were made in the equipment since main focus of research lies in facilitating every manufacturing company with meso-micro scale machining at no added costs or skills. Special adaptive process control algorithms were generated during the work to achieve desired process outputs.

3.3. Experimental conditions

As mentioned earlier, electrode materials were selected as graphite and copper since they are most often used electrode materials in conventional EDM. Maximum pulse current in range of 2-20A with positive tool polarity and pulse duration in range of 5-180µs were used. Oelheld IME110 hydrocarbon based dielectric was used for all EDM experiments and hot work steel 1.2343 was mainly used as work-piece material.

4. Results and discussion

4.1. Meso-micro scale graphite electrodes

As can be seen in fig. 4, high precision micro structures can be machined with relative ease in a conventional workshop environment. Since the CAM software strategies could not bring desired form accuracy in micro scale dimensions (see, fig. 4c), a manual tool path was generated using loop around strategy as shown in fig. 5.

![Fig. 3. Experimental setup for machining of graphite electrodes using milling in meso- micro scale.](image)

![Fig. 4. Examples of machined graphite electrodes in meso-micro scale: Left: Features with different surface areas and ribs in micro scale and 6mm depth. Centre: Lookup table (LUT) processed image by contrasting different machined features to attest their form accuracy. Right: 15x15 mm² graphite electrode with machined features of different sizes from surface area 1mm² down to 0.075mm².](image)
Current limits were found by machining a (0.15x.015) mm\(^2\) cross-section electrode with length of 7.5mm thus L/D aspect ratio of 50 as shown in fig. 6. It is clear from the results that graphite electrodes are easily machined in meso- micro scale and thus graphite can be esteemed as ideal electrode material for meso-micro EDM. Removal of the dust from the machined region is crucial to keep machining stable. Also, better contour strategies are required in existing CAM software for meso-micro scale milling of graphite electrodes.

4.2. Meso-micro EDM

Recently several EDM equipment manufacturers have offered zero wear technology which considerably reduces tool wear in conventional die-sink EDM. In current research, this technology has been implemented successfully even in meso-micro EDM, solving one of the biggest challenges for implementation of die-sink EDM in this regime even with conventional machines and electrode materials.

As shown in fig. 7, a turned graphite electrode having diameter 0.62mm and length 20mm was used to machine hot work steel 1.2343 in a hydrocarbon based dielectric oil using maximum 5A pulse current and positive tool polarity. The process technology was optimized such as to have near zero frontal and lateral tool wear and thus achieve better form accuracy at end of roughing step with just one tool electrode. As shown in fig. 8, this technology avoids vicious cycle of tool corner wear for semi-finishing and finishing operations and thus considerably reduces number of required tool electrodes.

Underlying mechanism of this low or zero wear technology is carbon layer build-up mainly on the frontal face of the electrode where most of the discharges take place.
As shown in fig. 9, this discharge plasma formed layer consists of carbon embedded with sub-micron sized metal particles ejected during the process from workpiece material [12] and was confirmed using Energy-dispersive X-ray spectroscopy (EDX). The carbon layer formation as mentioned by Mohri et al. [13] mainly contains turbostratic structure where Iron, Nickel, Chromium, etc. act as a catalyst for carbon precipitation [14]. The carbon layer is a decomposition product from hydrocarbon based dielectric through pyrolysis occurring during the discharge plasma. It has been observed that lateral wear resulting in conical shape of electrode after certain depth of erosion is mainly caused by the flushing cycles used to remove debris from discharge region at every 0.2-1 second interval and rapid movement of the electrode (about 10m/s) in the eroded cavity building high pressure gradients. The eroded particles gaining this momentum would cause abrasion of the faces of the electrode as shown in fig. 10.

Also, hi-speed imaging (20-50,000 fps) was employed to observe the process in-mist (fig. 10 right) and in-liquid dielectric which revealed cloud build-up and gas bubble - shock waves respectively suggesting strong hydrodynamic forces in discharge region which may also be contributing to tool wear.

The process originated pyrolytic graphite layer on the electrode is mostly harder than the original graphite electrode material [15] whereas embedded metal particles are measured to be 10 to 30 times harder which sustains the difficult erosion conditions and prevents wearing away of the base electrode material. The type and structure of carbon depends mainly on involved temperature and pressure [16], which can be controlled by EDM process parameters [17]. In terms of modelling this effect, pyrolysis of hydrocarbon is complex and still not fully understood [18] since it involves a very large number of possible reactions and chains of reactions occurring in their breakdown such as ionization, dissociation, dissociative ionization, dissociative recombination, charge exchange reactions with hydrogen [19]. Carbon deposits during EDM are observed to be of a hemispherical nature, suggesting cathodic deposits mentioned by Koprinarov et al. [20].

![Fig. 10. Left: Rapid electrode movement in the eroded cavity and eroded particles causing abrasion of electrode faces. Right: Hydrodynamic effect during spark as a possible cause for wear.](image)

Since the power supplied in the discharge gap is dependent on current, discharge voltage and pulse duration; the supplied constant energy is mainly divided into three main components of energy dissipation into: electrode (\(E_E\)), workpiece (\(E_W\)) and dielectric (\(E_D\)) as shown in fig. 11. The energy dissipating into dielectric is mainly used for plasma channel expansion through hydrocarbon decomposition at boundary layer. The energy balance information and involved mechanisms can then be used to shape pulses to achieve optimum results e.g. low initial current can be applied to reduce \(E_E\) and sudden increase in applied current a few microseconds after dielectric breakdown to benefit from high \(E_W\), resulting in low tool wear and high material removal rate (MRR). This energy balance is also affected by material properties of anode-cathode and dielectric. Melting temperature of workpiece material seems to have high influence on material removal rates whereas specific heat of workpiece material has been currently identified as having high impact on carbon build-up process. Difficult to machine materials such as Titanium alloys (TiAl6V4), Nickel alloys (Inconel 718, Inconel 738LC), powder metallurgy stainless steel (X170CrVMo18-3-1), hot work steel (1.2343, 1.4435), etc. have been machined successfully with zero or low wear technology using graphite electrodes in meso-micro scale EDM.

5. Conclusion and Outlook

Considering significance of machining requirements for miniaturized products, die-sink EDM technology was successfully implemented in meso-micro machining offering high productivity, form accuracy-precision, lower energy-resource requirements and lower overall
costs; that too without any additional need of apparatus, materials, processes or skills. Using conventional electrode materials such as graphite and copper having good machinability, various difficult to machine materials such as titanium alloys, nickel alloys, hot work steels, stainless steels and powder metallurgy steels can be ED-Machined with high accuracy and precision in meso-micro scale (meso: 10mm²-1mm², micro: <1mm² / <1mm) having high aspect ratios (L/D>10) and complex shapes (circular, polygonal, etc.). Clearly, outstanding performance of meso-micro EDM is incomparable to currently available alternative micro-machining techniques.

As further steps, the lower limit of micro EDM will be pushed further from current limit of surface area 0.1mm² down to 0.05mm² or smaller. Here, due to its advantages to machine multiple features on single graphite electrode, surface adaptive technology will be generated [21] in order to offer ability to machine macro-meso-micro scale structures on single electrode with high material removal rate while incurring lower tool electrode wear. Also, another open aspect is Nanometrology of precision meso-micro machined parts, dies and moulds; which is extremely difficult with currently available instruments due to involved smaller dimensions and high aspect ratios.

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