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Super-finished surfaces using meso-micro EDM

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Abstract

A novel stochastic orbiting strategy combined with extremely low stray capacitance sinking EDM machine offers the capability to achieve super-finished surfaces (R\textsubscript{s} <0.1µm) without pre-polishing of the copper tool electrodes. Surface defects such as inhomogeneity, cracks, arc spots and black spots have been analysed and reduced, while improving material removal rate with lower tool wear. Super-finished surfaces thus generated have uniform white layer (re-solidified layer) with an average thickness below 1µm. Unlike mirror finishing using EDM with powder mixed dielectric, absence of the additives in dielectric results in smaller gap width during finishing, delivering sub-micron accuracy of the machined features. With the tool electrodes machined using conventional machining techniques such as milling, turning or wire-EDM having surfaces with R\textsubscript{s} ≤ 0.2µm, advancements of the work offers manufacturing industry an economic and energy efficient super-finishing process, especially in meso-micro scale.

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1. Introduction

Super-finished surfaces (R\textsubscript{s} <0.1µm) find an increasing application especially in electronic components, casing for consumer electronics, optics, tribology, micro mechanics and micro fluidics [1]. EDM is a widely used die and mould machining process, for example LED moulds or camera lens moulds. With the disadvantages such as high labour costs and achieved poor form accuracy in addition to the feasibility for machining complex shaped features, especially in meso-micro scale (meso: surface area <10mm\textsuperscript{2}; micro: surface area<1mm\textsuperscript{2}), conventional manual polishing trend is declining. The alternative finishing processes such as electron-beam machining, grinding or other abrasive processes and ECM fail to meet specifications such as accuracy and radii of smallest inner contour, for example in case of micro-connector moulds. Since EDM is a well-established machining process to achieve high precision and accuracy, it is desirable to achieve the final surfaces with the same process and on the same machine; thus reducing manufacturing costs, time and errors. Also, super-finishing using EDM may be desirable for rough machining of the moulds for optics in order to increase flexibility and productivity, which are then finished using diamond turning or cutting to achieve desired optical functionality.

While mirror-finish surfaces are achieved in EDM using the powder mixed dielectric [2][3], it increases the overcut during machining and thus reduces achieved accuracy of the machined features. Additionally, EDM has also been used for surface alloying, coating and texturing [4]. Luo and Chen achieved surface roughness of R\textsubscript{s}~0.04µm by analysing the effect of pulsed electromagnetic field during super-finishing EDM [5]. Objective of the current research is to achieve the super-finished surfaces using sinking EDM without additional equipment or additives, and to reduce or in some cases eliminate the requirement for pre-polishing of the tool electrodes and post-finishing processes for the machined workpiece, such as polishing. Thus, an economic and energy efficient super finishing process is aimed.
2. Experimental setup and methods

2.1. Stochastic orbiting strategy

It is a usual practice to use the electrode orbiting during finishing operation in EDM in order to achieve desired form precision and to reduce the surface roughness. The main advantage of orbiting is the superimposition of micro peaks of the electrode and the workpiece surface, where the peaks are removed by the small energy discharges. In the current work, this electrode orbiting is made stochastic within the given form contour. The electrode movement can be either restricted within the undersize of the electrode, or it can be made to machine a contour as in the case of EDM milling or micro-EDM milling. Compared to the conventional planetary orbiting movement, stochastic movement of the electrode brings random microscopic regions of the electrode and the workpiece in vicinity for machining. Also, it may improve the flushing and debris distribution conditions in the machining gap.

Fig. 1. Stochastic orbiting movement of the electrode in XY plane.

As shown in fig. 1, for machining a square shaped cavity in the workpiece using a square electrode, the electrode centre (represented by black dot) is displaced within a square contour using a vector. This vector randomly changes the magnitude and angle in the given XY (Z) plane in order to generate a stochastic movement of the electrode. The rate of change in vector magnitude and angle is influenced by a parameter defining how many times the defined contour is completed per minute.

2.2. Low stray capacitance EDM power circuit

It is well known that in EDM, higher pulse energy results in higher surface roughness compared to the pulses with lower energy. The pulse energy is dependent on current, voltage and pulse duration. RC type generators are typically used for finishing operations, where used capacitance mainly determines the pulse energy. The smallest pulse energy achievable depends on the stray capacitance of the circuit, also known as the parasitic capacitance. Within this work, a state-of-art power circuit was used for generating super-finishing pulses solely using the stray capacitance. Although measurement of the stray capacitance is difficult, based on the calculated cable inductance, the obtained shortest pulse durations (refer, fig. 2) suggest stray capacitance of the used power circuit to be below 3nF.

Fig. 2. Smallest energy pulses achieved using novel power circuit, where pulse duration is below 50ns and peak current is 0.3A.

2.3. EDM parameters and conditions

Die sinking EDM machine Form 1000 from AgieCharmilles was used for this work. Prototype for the stochastic orbiting movement of the electrode and the low stray capacitance power circuit were realised on the machine. Dielectric oils Oelheld IME110 and Steelfluid AD90 were used with kinematic viscosity of 3.4 mm²/s and 2.3 mm²/s (at 20°C) respectively. No powder additives in the dielectric fluid were added.

Copper was used as the tool electrode and hot-work steel 1.2343 was used as the workpiece. Conventional layer approach was used, where starting with the highest pulse energy for roughing, decreasing pulse energies are used for semi-finishing and finishing operations. Pulses with the smallest possible pulse energy (see, fig. 2) were used for super-finishing operation. Depth of erosion for most of the machined cavities was kept at 0.1mm to ease the measurement process. Copper tool electrodes were machined using turning or wire-EDM. No pre-treatment of the tool electrodes such as polishing was carried out after electrode machining.

2.4. Surface characterisation

Surface roughness measurement of meso-micro scale surfaces is a challenging task, as the tactile measurement is either infeasible or the micro probing instruments are too expensive. On the other hand, optical measurement technologies for surface roughness measurement have
difficulties such as longer measurement durations and restrictions regarding the complexity of the machined geometries, e.g. vertical walls. Also related standards ISO 25178 were unavailable during current research, to use standardised parameters such as cut-off length.

Mainly two surface roughness measurement methods have been used during this work. For tactile measurements, Talysurf from Taylor Hobson was used, whereas Alicona Infinitifocus microscope, which is based on focus variation technique, was used for optical surface roughness measurement. In order to compare reliability of the optical measurements, a comparison study was carried out using 8 different wire-EDM surfaces, machined on hard metal with dielectric oil, to different surface roughness. Fig. 3 presents obtained results indicating good repeatability of the two tactile measurement instruments, whereas optically measured values correlate with tactile measurement values for $R_a < 0.1 \mu m$. The main reason for the deviation in measured values for higher surface roughness is attributed to the characteristic length of the surface roughness measurement and chosen cut-off length. Keyence optical laser microscope was used to test the repeatability and reliability of the measured values for sample 6 with $R_a: 0.048 \pm 0.003 \mu m$. For all the measured values, std. deviation ($\sigma$) was found to be below 0.02$\mu m$.

3. Results and discussion

3.1. Comparison of orbiting strategies

Conventional planetary orbiting strategy was compared to the novel stochastic orbiting strategy for finishing of 100mm$^2$ surface areas using copper electrodes. Both strategies were applied for the same machining time of 360 min. The square electrodes were prepared with facing operation to achieve a fine frontal surface. Surface roughness of the electrodes before and after erosion machining is presented in table 1. It can be seen that the surface roughness at the end of super-finishing operation increases when using planetary orbiting, compared to a decrease in the electrode surface roughness for the stochastic orbiting. For the same process technology parameters, surface roughness achieved on the workpiece is lower when using stochastic orbiting for super-finishing. The maximum electrode movement for both orbiting strategies was kept same as the undersize of the electrode, i.e. 0.2 mm.

Table 1. Results for achieved surface roughness for different orbiting strategies (cut-off length Lc: 0.25mm)

| Orbiting strategy | Surface roughness | Electrode roughness $R_a$ ($\mu m$) |
|-------------------|-------------------|-----------------------------------|
|                   | $R_a$ ($\mu m$)   | $R_a$ ($\mu m$)       |
|                   | Before erosion    | After erosion     |
| Planetary         | 0.078             | 0.681               | 0.077 | 0.195 |
| Stochastic        | 0.054             | 0.422               | 0.068 | 0.051 |

The surfaces thus generated are optically inhomogeneous as can be seen in fig 4, where lightly shaded regions have higher surface roughness compared to the dark shaded regions. This inhomogeneity results from dirt distribution over the surface during machining, further discussed in 3.3. It is seen that the stochastic orbiting improves the distribution of dirt and homogeneity of the machined surfaces.

3.2. Super-finished surfaces in meso-micro scale

With further improvements in the process technology regarding flushing cycle times, flushing speed, servo regulation and adaptive process control, super-finishing of meso-micro scale surfaces using stochastic orbiting was demonstrated. With the optimized technology, tool wear was reduced to a few micrometres for finishing operations. Since it was not feasible to measure surface roughness using the tactile method for micro scale surfaces (1mm$^2$, 0.25mm$^2$ and 0.09mm$^2$), surface roughness was measured using Alicona Infinitifocus. It can be seen in table 2 that the meso-scale surfaces with $R_a \leq 0.06 \mu m$ have been machined. For the micro-scale surfaces, measured $R_a$ values vary highly depending on the used sample length and cut-off length for $R_a$ calculation. Although decrease in the surface area of the electrodes results in lower stray capacitance, higher surface roughness is obtained for micro scale surfaces mainly due to higher wear of the tool electrode.
3.3. Surface defects

During the course of this research work, various surface defects have been encountered and analysed. While on one hand, these defects are undesirable concerning the aesthetic aspects of the final product, on the other hand, it may also adversely affect the life-time of machined dies and moulds. Thus, it is necessary to completely avoid or minimise such defects to achieve high surface quality.

3.3.1. Matt – Glossy surface

Conventionally mirror or brilliant finish surfaces are machined using transistor type pulses by melting the machined surface in order to achieve glossy surface finish. Also, it is well known that the surface roughness $R_a<0.05\mu m$ yields optically functional surfaces with high light reflectivity, atypical for die sinking EDM surfaces. During current research, using the same process technology parameters, two different types of surfaces have been produced. While the difference in $R_a$ values is marginal, surface shown in fig. 7 (left) has optically matt finish compared to the surface shown in fig. 7 (right), having glossy finish and lower $R_a$. The main difference between these two machining is the timed erosion strategy. The surface with matt finish was eroded without time-bound erosion and the surface with glossy finish was machined with time-bound erosion. Time bound erosion is a strategy where maximum erosion time for the process is defined by user, at the end of which the machining is stopped automatically. The underlying cause for optical difference in the surface finish is considered to be the crater shape and the surface topography. This can be observed in fig. 8, where left image is SEM image of a matt finish surface and on the right side is SEM image of a glossy finish surface. Here, the discharge craters consist of outer rims on the matte finish surface, whereas glossy finish surfaces have no or minimal discharge craters with the outer rims. The surface topography as shown in fig. 8 (right) reveals continuous surface with crater marks, assumedly produced by discharges with thermal runaway causing diminutive erosion of the micro regions.

As can be seen in fig. 5, extreme fine surfaces machined in meso-micro scale have crater diameter below 5µm, with no surrounding rims, resulted from the extremely low energy pulses with pulse duration in the order of a few nanoseconds. Because of the low discharge energy and ultra-short pulse durations, the subsurface influence of EDM is reduced to white layers (also known as re-solidified layer) of less than 1µm thickness (see fig. 6). Also, consistent crater diameter, shape and minimal surface defects signify high performance of the power generation circuit. The gap width during the machining is estimated to be below 3µm, however precise measurements are needed to validate this value. Apart from the arithmetic average value $R_a$, average distance between the highest peak and lowest valley in each sampling length represented by $R_z$ (DIN) indicate average $R_z$ value 0.5±0.2 µm or lower.

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Table 2. Results for achieved surface roughness for respective surface areas (cut-off length $L_c$: 0.250mm) * cut-off length $L_c$: 0.080mm

| Electrode surface area ($mm^2$) | Surface roughness $R_a$ ($\mu m$) $\sigma$ <0.02µm | Machining time (min) |
|--------------------------------|---------------------------------|---------------------|
| 100                           | 0.066                           | 350                 |
| 56                            | 0.052                           | 330                 |
| 25                            | 0.044                           | 220                 |
| 9                             | 0.043                           | 180                 |
| 1                             | 0.085*                          | 120                 |
| 0.25                          | 0.100*                          | 60                  |
| 0.09                          | 0.120*                          | 60                  |

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Fig. 5. SEM images (left: 500x; right: 2000x) of achieved super-finished surface by meso-micro EDM, featuring low energy pulses and stochastic electrode orbiting.

Fig. 6. Polished cross section of achieved super-finished surface using die-sink EDM showing white layer with average thickness below 1µm.

Fig. 7. Surfaces achieved using finish machining pulses in die sinking EDM. Left: matt surface finish; Right: glossy surface finish.
While intentionally generating completely matt or glossy finish surfaces is advantageous, this effect is further exemplified in this work regarding the surface inhomogeneity. Matt and glossy regions are eroded on the same surface during a machining leading to an optical effect of a cross in case of the square electrodes and a ring in case of the cylindrical electrodes, as shown in fig. 9.

Fig. 8. SEM images showing different crater characteristic for surfaces shown in fig. 7. Left: matt finish surface; Right: glossy finish surface.

3.3.2. Surface inhomogeneity

In fig. 10, it can be observed that for the same technology parameters, crater shape in the matt region of the surface (fig. 10, left) differs from that of the glossy region (fig. 10, right). The optical effect originates predominantly due to the crater shape, compared to surface roughness of the regions. Although super-finished surfaces are achieved without using any additives in dielectric, a sub-micrometre thick dirt layer is generated over the surface during the finishing operations. This layer of dirt mainly consists of a fine dielectric decomposition product and the electrode materials. It is this layer because of which the super-finish surfaces can be generated using sinking EDM. It is believed that a part of the discharge energy dissipated in the work-piece is shared by this dirt layer, reducing the crater volume. For super-finishing operations, if this dirt layer is not distributed homogeneously, the end machined surface shows inhomogeneity regarding surface roughness and optical appearance, e.g. a cross like appearance mainly due to the fluid flow induced transportation of the debris. It is in this region that one observes glossy effect and lower surface roughness. On the other hand, matt regions have thinner layer of the dirt during machining resulting in higher energy dissipation in the workpiece material and thus different crater shape, surface roughness and the optical appearance. Using simple fluid dynamic simulations by COMSOL Multiphysics, it was found that the cross or ring like inhomogeneity are dependent on the electrode shape and are caused due to the fluid dynamic effect. During flushing operation when the electrode jumps out of the machining region, submicron sized dirt particles are arranged over the surface according to the fluid velocity vectors. Process parameters such as flushing speed and servo regulation gain were analysed which affect the dirt distribution in order to achieve homogeneous surfaces. It was found that this inhomogeneity was prevalent mostly while machining on the surface or at low depths, such as 0.1mm depth. While machining at the depth of 1mm or more, no such inhomogeneity was found for super-finished surfaces except for the regions where electrode wear is high, such as on the corners and the edges.

3.3.3. Surface cracks

Surface cracks is one of the biggest challenges for ED-Machined surfaces and a considerable amount of dedicated literature can be found, especially due to its importance in machining of aerospace parts, deterioration in the aesthetic appearance and lower tool life. The main reason for the surface cracks in EDM is thermal residual stresses induced due to rapid cooling and heating cycles. It was observed that the surface cracks after super-finishing operation were much larger compared to the surfaces with higher surface roughness.
In fig. 11, the top image shows a surface with \( R_a = 1.03\mu m \) magnified, where a micro crack can be identified within the yellow box. The bottom image of fig. 11 shows much larger cracks indicating higher thermal residual stresses in case of poorly selected process parameters, especially the pulse shape. It has been observed that a higher inductance in the power circuit causes longer pulse durations for the same discharge energy, leading to the surface cracks.

### 3.3.4. Arc spots and black spots

Arc spots (see, fig. 12 left) are often encountered during the roughing operations; however for ultra-short pulses such as in the case of super-finishing, it is difficult to control arc transition which may lead to the damage of surface and in some cases rejection of the machined part. Such arc spots have been minimized by power supply circuit of EDM machine and adaptive process control. Also, black spots are encountered on the machined surfaces (see, fig. 12 right) resulting from melting of the dirt layer due to concentrated discharges in a local region. With adaptive process control based on pulse monitoring and stochastic orbiting strategy, such black spot defects on the super-finished surfaces have been reduced.

### 4. Conclusions and outlook

Super-finished surfaces having \( R_a < 0.06\mu m \) have been generated using die sinking EDM in meso-micro scale using a novel stochastic orbiting strategy and a low stray capacitance power circuit. The stochastic orbiting strategy reduces the pre-polishing requirement of the tool electrode. \( R_a \) values as low as 0.05\( \mu m \) and evenly distributed white layer (re-solidified layer) with thickness of less than 1\( \mu m \) can be achieved with milled, turned or wire-eroded copper electrodes having \( R_a \leq 0.2\mu m \). Furthermore, surfaces with \( R_a < 0.03\mu m \) have been machined using the pre-polished copper electrodes of 10\( \mu m \) diameter. Surface defects such as inhomogeneity, cracks and arc spots have been analysed and minimized, aiding both the aesthetic and functional aspects of the machined surfaces. Due to the absence of dielectric additives and small machining gap widths, sub-micrometre accuracy can be achieved for the machined features. For the same erosion times, reduction in pre-polishing of the electrode delivers higher energy and economic efficiency in die sinking EDM to machine free-form super-finished surfaces in meso-micro scale.

In addition, stochastic orbiting can also be developed for finishing operation in micro-EDM milling to reduce the electrode feed marks. Extreme small energy discharges generated using developed power circuit paves the way for nano-EDM. As further work, process analysis need to be carried out in order to further reduce surface defects and tool wear during finishing and super-finishing operations. Clearly, nano-metrology requires further effort in order to reliably measure high precision structures with super-fine surfaces in meso-micro scale.

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