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Analysis of sinking EDM electrode deflection measurements for the manufacturing of high aspect ratio cavities

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Abstract

The use of Sinking EDM for the fabrication of filigree structures with high aspect ratio (HAR) geometries is gaining continuously more terrain not only in the area of micro machining but also for the manufacturing of highly precise HAR macro geometries for the mould- and die industry. Fundamental tests have shown that discharge forces caused by the release of energy during the electrical discharge can generate unwanted vibrations on the tool electrode damaging final desired precision of the manufactured workpieces. This work will show results of dynamic lateral deflection of HAR macro Sinking EDM slit-formed graphite electrodes. A highly precise laser-interferometer will be used to measure electrode vibration during a continuous Sinking EDM process. The pulse frequency, as well as the mechanical properties of the electrodes will be taken into account for the analysis of the results. Possible improvement strategies based on analytical modeling of the electrode vibration caused by discharge forces are presented. Further work in the area of process monitoring and control will allow the achievable workpiece precision of the Sinking EDM process to be improved, making it more viable to meet the requirements of the growing precision manufacturing industry.

Keywords: EDM; Process forces; Electrode vibration; Geometrical precision

1. Introduction

Increasing performance and design requirements of new precision parts motivate the latest developments on precision manufacturing processes. Harder or conventionally difficult to machine materials, together with tougher design restrictions like higher geometric complexity, micro-detailed features or higher aspect radii ask for more controlled and monitored machining operations. It has been shown that not only for cutting operations, but also during thermal removal processes like EDM, deflection and unstable process behavior may occur while processing high aspect ratio (HAR) components [1].

Dynamic force measurements of single discharges on micro- and macro sinking EDM made by several authors reveal that the magnitude of the force is highly dependent on variables of the process such as the discharge energy, electrode material and physical properties of the dielectric media [2-7]. Tamura [3] found that when the force measurement values were taken during impulse discharges in air, their magnitudes were almost neglectable compared with those from the discharges in hydrocarbon based dielectric. Tohi [4] and Kunieda [5] investigated the appearance of process forces during EDM using the Split-Hopkinson Bar (SHB) method for single and double discharges. This approach allows the measurements to be independent from the natural frequency of the sensing devices but can be quite complex to implement in the practice due to the length of the bars needed for the tests. Klocke et al. performed a comparison of force measurements between two types of piezoelectric sensors in order to analyse their suitability for analysing EDM forces [8]. Fig. 1 shows the results of a single square-shaped discharge on the surface of the sensor type 9213 from Kistler (Natural frequency: 200 kHz). The behaviour of the force signal resembles the results of [3] and [4] with the use of the Split-Hopkinson Bar method. Complementing the
experiment, HS-Camera recordings have been simultaneously performed during the force measurement in order to improve the understanding of the acquired measurement force signals [7, 8]. There, it has been determined that the signal peaks closely follow in μs-range the hydrodynamic effects generated during the discharge inside the working gap between electrodes.

2. Experimental Description

This paper aims to measure the effect of the discharge forces on HAR electrodes by measuring the maximal electrode’s lateral deflection caused by continuous discharges acting perpendicularly to the free end of a slender graphite electrode held as a cantilever beam, see Fig. 2. Past research has shown that even if most of the discharges during a sinking EDM process occur in the same axis of penetration, the highest deflections are expected to happen due to the discharges acting perpendicularly to the longest axis of the tool [9]. Such a case can be easily found when performing orbital motion by semi-finishing or finishing procedures.

Tests were conducted on a Charmilles Roboform 41 sinking EDM machine with 1 x 50 x 60 mm³ fine grained graphite tool electrodes (grain size 3 μm). A stainless steel needle (steel DIN Nr. 1.4305) was used as workpiece to ensure that the force was always perpendicularly applied to the electrode’s longest axis and at the same spot on the tool electrode.

A laser interferometer measured the continuous deflection of the electrode 13 mm above the point where the EDM discharges took place, in order to keep its delicate optics above dielectric level. Discharge point was located 1 mm above the free end of the electrode. The height difference between the discharge spot and the measuring point for the laser interferometer (in Fig. 2 called z) is used to calculate the maximum lateral deflection Δs at the machining point h, assuming 1st mode vibration.

![Fig. 2. Experimental set up for the measurement of lateral deflection on HAR graphite electrodes during sinking EDM](Image)

The tip of the electrode was submerged 2 mm into oil based dielectric. The influence of different types of dielectric oil on the maximum lateral deflection was also tested during this work. See Table 1 for selected relevant properties of the chosen dielectric media.

| Properties | Oil 1 | Oil 2 | Oil 3 |
|------------|-------|-------|-------|
| Density ρ / (g/cm³) | 0.77  | 0.79  | 0.82  |
| Kinematic viscosity ν / (mm²/s) at 313 K | 1.80  | 2.50  | 4.00  |

Tests were carried out while continuously monitoring the discharge current of the process. The machine was set to avoid any lifting or lateral flushing movement of the electrode in order to avoid any additional hydraulic forces other than those generated by the discharges. The digital oscilloscope was programmed to save continuous deflection and current signals for a lapse of 0.2 s once the process had been running for 1 s in order to represent a normal sinking EDM process. For statistical assurance each test was repeated 10 times.

The effect of the discharge interval time on the maximal electrode deflection was investigated for a range of t₀ values between 6.4 and 800 μs. Although some of the values chosen for the experimental range are uncommon for the use in an industrial environment (100 μs < t₀ < 800 μs), the analysis of the effect of a wider range of parameters on the mechanical behavior of the electrodes should extend the knowledge about the causes of unwanted electrode vibrations.

See Table 2 to find the process parameters used in this work.
Table 2. Process parameters chosen for the experimental phase

| Parameter                      | Value |
|-------------------------------|-------|
| Open circuit voltage, $\bar{u}_i / \text{V}$ | 120   |
| Discharge voltage, $u_e / \text{V}$     | 20    |
| Discharge time, $t_e / \mu\text{s}$    | 6.4   |
| Discharge current, $i_e / \text{A}$    | 12    |
| Interval time, $t_0 / \mu\text{s}$     | 6.4, 12.8, 25, 50, 100, 200, 400, 800 |

Relevant properties and geometrical information about the graphite electrodes can be found in Table 3.

Table 3. Relevant properties of tested graphite electrodes

| Parameter / Variable | Value |
|----------------------|-------|
| Density, $\rho / (\text{g/cm}^3)$ | 1.88 |
| Young’s Modulus, $E, / (\text{kN/mm}^2)$ | 13.5 |
| Area Moment of Inertia, $I / \text{mm}^4$ | 4.17 |
| Cross section area, $A / \text{mm}^2$ | 50 |
| Free electrode length (span length), $l / \text{mm}$ | 48 |
| Laser measuring height, $(h - z) / \text{mm}$ | 34 |
| Distance between height $h$ and discharge point, $z / \text{mm}$ | 13 |

3. Results of Electrode Vibration Tests

Fig. 3 shows the results of three different tests for continuous discharges revealing the effects of varying the discharge interval time $t_0$ on the electrode deflection in low viscosity dielectric (Oil 1). The presented signals occur each during a lapse of 0.2 s. Due to this fact, current discharges with a $t_e = 6.4 \mu\text{s}$ can only be presented as needle shaped impulses. An absence or a strong reduction in the number of discharges per time unit was generally observed simultaneously with moments when maximum deflection values occurred. This is possibly caused by the fact that the tip of the tool electrode is deflected away at a longer distance from the workpiece than the one needed for electrical breakdown at the actual process conditions.

Further on, Fig. 3a) shows the results for $t_0 = 12.8 \mu\text{s}$. Electrode deflection, $s$ measured 34 mm below the fixture point amounted to 3.5 μm. Calculating for the maximum deflection at the tip of the electrode a value of 6.1 μm was reached. In the case of $t_0 = 50 \mu\text{s}$ (Fig. 3b) values of deflection reached up to 2.3 μm. Maximum calculated deflection lowered there to values around 4 μm which is 30% lower than deflections for $t_0 = 12.8 \mu\text{s}$. On its turn, Fig. 3c) where discharge interval time increases to 400 μs, calculated maximum electrode deflection reaches values of 8 μm. Generally, it can also be seen in all cases that the tool electrode vibrates with a main frequency $f_s$ in the range of 120-160 Hz which corresponds with an acceptable error of nearly 15% to the calculated first natural frequency $f_{01}$ of the graphite electrode (See Eq. 1 and Table 4) [10]. Discrepancies with the calculated values might well come from idealized material properties and three dimensional vibration effects, not taken into account here.

$$f_{01} = \frac{\lambda^2}{2\pi^2} \sqrt{\frac{EI}{\rho A}} \quad (1)$$

Variable $l$ represents the free length of the electrode (m), $E$ is graphite’s Young’s modulus (N/m²), $I$ stands for the area moment of inertia (m⁴), $\rho$ is the density of graphite (kg/m³) and $A$ its cross section area (m²). $\lambda_i$ represents the frequency parameters that are determined by the initial conditions of the fixing situation of the electrode, in this case, as a cantilever beam [11].

Underlying the natural vibration frequency of the electrode, higher vibration frequencies in the range of several kHz with low amplitude can be seen in all cases of Fig. 3. Those might correspond to the direct reactions of the single discharge forces, or to the superimposed effect of several of them on the surface of the electrode. Fig. 4 to 6 show the complete results for the tests, including results for the main vibration frequency $f_s$ of the electrodes for each tested discharge interval time.

Fig. 3. Test results for different values of $t_0$: 12.8 μs, 50 μs and 400 μs

Table 4. Frequency parameters and natural frequencies of selected graphite electrode calculated after [10]

| $i$ | Frequency Parameter, $\lambda_i$ | Natural Frequency $f_{01}$ |
|-----|----------------------------------|-----------------------------|
| 1   | 1.87                             | 188                         |
| 2   | 4.69                             | 1177                        |
| 3   | 7.85                             | 3297                        |

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Fig. 4 shows that there is a tendency for the electrode deflection to lower its magnitude for discharge interval
times around 50 μs. Longer \(t_0\) values between 200-800 μs achieve again higher electrode deflection values probably due to the fact that pulse cycle times \(t_p\) and its reciprocal value \(f_p\) (pulse frequency) reached values near the second \(f_{o2}\) and third \(f_{o3}\) natural frequencies of the electrode as it will be shown explained below.

\[
t_p = t_i + t_0 = (t_{o2} + t_{o3}) + t_0
\]

and \(t_p = \frac{1}{f_p};\) possible resonance cases if: \(t_p = \frac{1}{f_{o2}} \text{ or } \frac{1}{f_{o3}}\) \(\text{(2)}\)

Taking a mean value for \(t_{o2}\) of 3 μs, equivalent pulse cycle times and equivalent interval times can be calculated for the first three natural frequencies of the chosen electrodes. See Table 5.

Table 5. Equivalent \(t_p\) and \(t_i\) for the first three natural frequencies of the chosen electrodes

| \(i\) | Natural Frequency \(f_0 / \text{Hz}\) | Equivalent pulse cycle time \(t_p / \mu\text{s}\) | Equivalent interval time \(t_i / \mu\text{s}\) |
|---|---|---|---|
| 1 | 188 | 5322 | 5311 |
| 2 | 1177 | 849 | 838 |
| 3 | 3297 | 303 | 292 |

The latter is further on valid when analysing Fig. 5 and Fig. 6, where dielectric’s kinematic viscosity was further increased respectively to 2.5 mm²/s and 4 mm²/s. The deflection of the electrode for the range of interval times between 200 and 800 μs is the most influenced by the effect of the working fluid. This might be explained by the fact that compared to shorter interval times, better flushing conditions reign on the working gap. A higher percentage of the area surrounding the electrodes is filled with liquid dielectric instead of gas, increasing the damping effect of the fluid by reducing the magnification effect of possible resonance cases caused by pulse cycle times \(t_p\) equivalent to \(1//f_{o2}\) or \(1//f_{o3}\).

The use of a higher viscosity dielectric (Oil 2) does not significantly reduce deflection magnitudes for \(t_0\) values below 25 μs with respect to the results for Oil 1 (see Fig. 5). In contrast, \(t_0\) values between 50 and 100 μs achieve a reduction of the maximal electrode deflection down to 3 to 4 μm. Tests made with Oil 2 for \(t_0\) values above 200 μs show a reduction on electrode deflection amplitude compared with Fig. 4.

In the case of the tests made with Oil 3, maximum average electrode deflection for values of \(t_0\) between 6.4 – 25 μs increases approx. 10-15%. Discharge forces on EDM electrodes do also depend on the properties of the dielectric fluid present in the working gap [2, 5, 7]. Dielectric liquids with higher density and viscosity do not easily permit the expansion of the generated gas bubble after each discharge, allowing a higher pressure to act on the electrode surface in comparison with lower viscosity dielectrics.

Even more, as explained by [8], not only thermodynamical processes, but also fluid-dynamical phenomena are able to create local under- and over-pressure in the system which translates into complex single discharge force signals.

In principle, every discharge does not only generate a single force peak, but rather a set of reactions depending on the way the gas bubble expands and collapses (see Fig. 1). Based on that, the following chapter will make a first approach to model the vibration of slender graphite electrodes under the effect of continuous EDM discharge forces. This model should help understanding the causes of the decrease on electrode deflection for interval times between of 25-50 μs.

4. Dynamic Modeling of Continuous Discharge Forces

In order to model the dynamical behavior of a slender electrode under the influence of continuous discharges, a model based on the Euler-Bernoulli beam equation will
be used. The influence of the viscous media and internal material dampening on the magnitude of the electrode deflection was experimentally shown. Nevertheless for comparative purposes, they will not be taken into account into this a first approach model as they do not interfere on the frequency response of the beam which is the main objective of the following discussions.

The special case with a one side clamped beam was chosen in order to resemble the conditions described in Chapter 2. At the free end of the beam, an external punctual periodic excitation force with frequency $\Omega$ and maximum amplitude $F_0$ was applied. See Fig. 7.

![Fig. 7. Modelling of a graphite electrode as a cantilever beam being excited by a periodic external force](image)

To simplify the presentation of the solution below a cosine function will be used. The deflection of the beam will be modeled using the following homogeneous fourth grade differential equation [11]:

$$EI \frac{d^4w}{dx^4} - R^4w = 0 \quad \text{with} \quad R^4 = \Omega^2 \frac{PA}{EI}$$

(3)

$R$ = Frequency parameter of the forced vibration
$\Omega$ = Excitation frequency of the forced vibration / Hz

A solution for (3) can be proposed as:

$$w(x,t) = W(x) \cos \Omega t$$

(4)

Combining (3) and (4) results into:

$$w(x,t) = (A \cos Rx + B \sin Rx + C \cosh Rx + D \sinh Rx) \cos \Omega t$$

(6)

where $A$, $B$, $C$ and $D$ are constants which can be solved with help of the following set initial condition equations:

$$w(0,t) = 0, \quad w'(0,t) = 0, \quad Q(t,t) = -EIw''''(t,t) = F_0 \cos \Omega t$$

(7)

$l$ = Length of the beam / mm
$F_0$ = Amplitude of the excitation force / N

Replacing the initial condition equations (7) into (4) for the deflection value at length $l$ gives:

$$W(l) = \frac{F_0 l^3}{EI(l)} \frac{\sin Rl \cosh Rl - \cos Rl \sinh Rl}{1 + \cos Rl \cosh Rl}$$

(8)

Successively, (8) can be replaced into (5) resulting into

the time based solution for forced vibration at length $l$:

$$w(t) = \left( \frac{F_0 l^3}{EI(l)} \frac{\sin Rl \cosh Rl - \cos Rl \sinh Rl}{1 + \cos Rl \cosh Rl} \right) \cos \Omega t.$$  

(9)

As it could be seen in Eq. 6, a different type of periodic force excitation function could have been chosen as long as it is independent of the variable $x$. For that reason, regarding the measurements and results from [7 and 8] a simplified single discharge force function of the form (10) was proposed:

$$F(t) = F_0 \sin \Omega t \cdot e^{-\frac{t}{2\tau_0^2}}$$

(10)

Constant parameters for Eq. 10 were chosen so that a maximum force peak would be found within the first 15 $\mu$s after breakdown. A negative force time-span should find its minimum around 30-40 $\mu$s and a second positive force peak related to the contraction of the gas bubble (or collapsing) should happen with a maximum value located around 70 $\mu$s after discharge breakdown.

Based on the principle of wave superposition, several discharges can be added up with determined starting delay offsets corresponding to the simulated discharge interval times $t_0$. Mechanically this would represent the effects of the expansion and contraction of several discharge bubbles and their respective shock waves located at different places inside the working gap. Fig. 8 exemplary shows that two different values of interval time result in a possible magnification of the resultant excitation force through constructive interference. (See upper part of Fig. 8 for $t_0 = 10$ $\mu$s).

![Fig. 8. Schematic representation of principle of wave addition by continuous discharge forces for a $t_0$ of 10 $\mu$s (above) and 30 $\mu$s (below)](image)

In contrast, the lower part of Fig. 8 shows how an interval time $t_0$ of 30 $\mu$s would result in a decrease of force amplitude from the second impulse onwards. This result describes the observations of Siebers [13] and Kunieda et al. [5] where forces measured for a series of discharges present a lower magnitude from the second discharge onwards compared with the first discharge. It is a known fact that the working gap fills partially with gas during a continuous EDM process [14, 15] which is a further explanation for the reduction on force magnitude [3] in comparison with single discharges in oil based dielectric. Fig. 9 presents the results for the simulation of electrode deflection for a lapse of 300 $\mu$s of continuous EDM discharge forces with an interval
time of 6 μs (left side of the diagram). Maximum values for Δτ around 10 μm are calculated (right side of Fig. 9). Mean deflection values around 7 μm stabilize at the tip of the tool. It can also be seen that such an excitation force can create higher vibration modi on the electrodes.

For t₀ = 25 μs (Fig. 10) the resultant discharge force signal lowers from a mean value around 2 N, as seen in Fig. 9, to a mean magnitude of 0.5 N causing maximum electrode deflections of 7 μm and mean deflection values around 2–3 μm resulting in a decrease of more than 50% with respect to Fig. 9.

It was therefore demonstrated that force values of the magnitude measured by [8] can result in the deflection ranges experimentally measured here, when taking into account the mechanical behaviour of the electrodes.

6. Outlook

The Euler-Bernoulli model was successfully applied as a first approach method to analyse the maximal deflection of slender electrodes as an answer to the proposed resulting force signals for continuous discharges. The authors of this work are developing a more advanced method based on the Timoshenko beam theory which does take into account factors such as material- and environmental damping effects, as well as the possibility to place acting forces on different locations of the electrode other than only at the free end which is the case of a manufacturing task inside a narrow cavity. That approach will allow a more accurate mechanical analysis of electrode deflections and vibration frequencies.

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