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Particle hydrodynamics of the electrical discharge machining process. Part 2: Die sinking process

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Abstract

The objective of this work is to investigate the dynamics of the dielectric fluid in the die sinking electrical discharge machining (EDM) process. Different methods were developed to investigate the fluid dynamics of the dielectric and particles. Both computational fluid dynamics (CFD) and experimental tests were performed.

The most important achievement of this project is the improvement of the evacuation of the waste particles within the gap workpiece-electrode. An exhaustive understanding of the processes was crucial to obtain a uniform particles distribution which leads to a more efficient discharging and particle evacuation. A CFD analysis was used to figure out the characteristics for the electrode, such as its shape and dimensions and its kinematic properties. In particular, different combinations of axis Jerk, acceleration, speed and movement of the electrode were studied in detail. Different dielectric liquids were also considered.

The experimental tests on full scale and increased scale models were performed at the AgieCharmilles laboratory and at the CMEFE laboratory in Geneva, in order to validate the CFD results. A test rig was built to perform study at a scale of 50:1 has been built, and a particle image velocimetry (PIV) was developed in order to study the effect of the fluid flow. The analysis of the trajectories of the waste particles inside the dielectric was performed for several configurations. The effect of the gas bubbles generated during the process is also under investigation.

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*Keywords:*EDM; hydrodynamics; particles; die sinking

Nomenclature and symbols

u	Reference speed, m/s
D	Reference length, m
μ	Dynamic viscosity, kg/(m·s)
ρ	Density, kg/m^3
ν	Kinematic viscosity, (m^2/s)
σ	Surface tension, N/m
Re	Reynolds Number
Fr	Froude Number
y_{max}	Amplitude of the electrode movement, mm
v_{max}	Maximal speed of the electrode movement, m/s
a_{max}	Maximal acceleration of the electrode, m/s^2
J_{min}	Minimal derivate of the acceleration, or Jerk, m/s^3
J_{max}	Maximal derivate of the acceleration, or Jerk, m/s^3
$\phi_{B\text{-}exp}$	Bubbles diameter in experimental tests, m
$\phi_{B\text{-}real}$	Bubbles diameter produced during the EDM process, m
$V_{B\text{-}exp}$	Volume of the bubbles generated with the test ring, m^3
g	acceleration due to gravity, m/s^2
Π	Non-dimensional number

1. Introduction

During the die sinking electrical discharge machining (EDM) process, waste particles produced within the gap tend to remain in the dielectric fluid. Local concentration of the produced particles leads to a poor surface quality,

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decreasing the machining accuracy and influencing the dimension of the gap [1]. The analysis of the fluid inside the gap during the gap cleaning is therefore important to understand how to obtain high EDM speed and high surface quality.

The objective of the present work is to improve the performances of EDM process.

The aim of this work is understand how evacuate a large volume of waste particles, cleaning of the gap during the machining, minimal time for the gap cleaning and study the effects of the bubbles created during the process on the waste particle cleaning. In order to analyze and solve these problems, the understanding of the hydraulic phenomena inside the gap is the main object of this work and, in particular, how the electrode[2], [3], [4], [5], the electrode shape, the fluid proprieties move the waste particles inside the gap.

The effects of electrode jump time, jump high, jump frequency, jump maximum speed, jump maximum acceleration, jump maximum Jerk, electrode shape and size and the dielectric fluid proprieties are investigated by means of a Computational Fluid Dynamics (CFD) analysis [6].

The CFD model is validated by an experimental tests carried out at the AgieCharmilles laboratory on an increased scale model of the electrode [7]. This scale model was designed and built at the CMEFE (groupe de Compétences en MEcanique des Fluides et procédés Energétiques) laboratory in Geneva and it is 20 times larger than the real scale electrode, so that fluid dynamics field inside the gap can be better visualized using coloured small particles.

During the EDM process, bubbles are created inside the gap can influence the outcome of the entire process. In particular, their influence on the evacuation of the waste particles is analysed through an experimental approach. A test rig has been developed at CMEFE laboratory, with an electrode scale model increased by 50 times the real size of the electrode. A Particle Image Velocimetry (PIV) has been developed in order to compare the trajectories of the waste particles inside the dielectric with and without the bubbles presence. The effect of gas bubbles generated during the process is also under investigation.

2. The similarity

In CFD simulations, both geometrical and physical proprieties are set identical to the real case, whilst, the experimental investigations are performed with increased scale models to allow better visualisations.

The physical similarity between the electrode increased scale model with the real geometry is performed by the Reynolds Number and the Froude Number:

$$\Pi_1 = Re = \frac{\rho u D}{\mu} = \frac{uD}{\nu} \qquad (1)$$

$$\Pi_2 = Fr = \frac{\rho_1 u^2}{(\rho_2 - \rho_1) g D} \qquad (2)$$

where, u is the reference speed, D is the reference length, μ is the dynamic viscosity, ρ is the density, kg/m^3 and ν is kinematic viscosity and g is the acceleration due to gravity.

Therefore, the Reynolds Number represents the ratio of the inertial forces to the viscous forces and, consequently, it gives the relative importance of them for given flow condition.

The Froude Number represents the ratio of the inertial forces to the gravitational force and, consequently, it gives the relative importance of them for given flow condition.

3. The numerical simulations

In this part of the study, the problem is approached using CDF calculations, performed using commercial software Ansys Fluent. Three different 2D geometries are analysed ("Blade", "Pocket" and "Complex Pocket" geometry) and one 3D geometry ("3D Pocket") to investigate the 3D effects on the particles evacuations.

3.1. Geometries and calculations setting

The "Blade" geometry has a very high electrode with a thin section. The lateral gap between the electrode and the workpiece is 60 μm and the bottom gap is 50 μm. The cavity dimensions are 70.05 mm x 15.12 mm x 1.12 mm, the roughness of both electrode and workpiece is 10 μm. The representative 2D geometry is of 70.05 mm x 1.12 mm for the workpiece cavity, lateral gap of 60 μm and bottom gap of 50 μm, seeFigure 1.

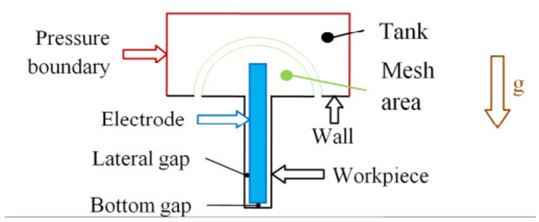

Figure 1: "Blade" 2D geometry

The "Pocket" geometry has a large electrode with dimensions of 49.9 mm x 14.9 mm x 4.95 mm. Both lateral gap between the electrode and the workpiece and the bottom is 50 μm. The cavity dimensions are 50 mm x 15 mm x 5 mm, the roughness of both electrode and workpiece is 10 μm. The representative 2D geometry is a section of 70 mm x 1 mm for the electrode and 15 mm x 5 mm for the workpiece, seeFigure 2.

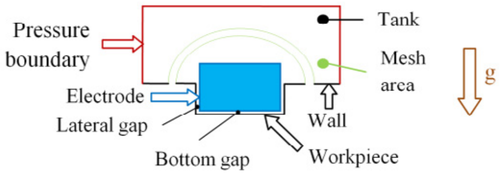

Figure 2: "Pocket" 2D geometry

The "Complex Pocket" geometry is an evolution of the pocket geometry where the workpiece has three teeth of 0.5 mm height and 3 mm of width and the electrode has the negative shape. The bottom gap is of 50 µm and the wall roughness of both electrode and workpiece is 10 µm.

One geometry has been chosen to investigate the 3D effects: the pocket geometry (for this geometry the 3D effects are bigger than the blade geometry). The geometry has two planes of symmetry, see Figure 3. The roughness of both electrode and workpiece is 10 µm.

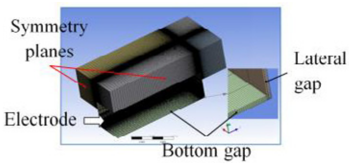

Figure 3: Mesh of the 3D pocket geometry at the beginning of the movement.

Two different fluid petroleum products are tested as dielectric fluid in order analyse the effect of the dielectric fluid viscosity: "DIEL MS 5000" and "DIEL MS 7000". In case of no nomenclature, the fluid "DIEL MS 5000" is used.

For all geometries, the mesh has to be a "dynamic mesh" where some cells are added and others are removed during the transient calculation because of the moving boundary of the jumping electrode inside the workpiece. The mesh dimension of all the 2D geometries is around $2 \cdot 10^6$ elements at the beginning of the jump and $8 \cdot 10^6$ elements for the 3D geometry.

The numerical analysis was performed with the assumption that the liquid density and viscosity is constant and uniform in the field during the simulated time and the gravitational acceleration is 9.81 m/s^2 and it is parallel to moving of the electrode. The chosen viscous model is the "k-ω SST, low Reynolds correction" viscous model and the main algorithm used was SIMPLE (Semi-Implicit Method for Pressure-Linked Equations). Depending of the geometry, the time step is between 0.035 ms and 0.25 ms.

In order to simulate the behaviour of the waste particles generated during the EDM process, some spherical steel particles are injected inside the bottom gap (particle density of 7800 kg/m^3 and diameter of 3 µm). The discrete phase is injected at the beginning of the jump on two different surfaces, on the workpiece in the bottom gap and on the electrode in the bottom gap. The phase of the particles is not coupled to the continuous phase and the particle trajectories are computed in Lagrangian frame by integrating the particle force balance equation, the forces on the particles are the drag force and the gravity force.

3.2. Kinematic parameters

The electrode movements are vertical, as shown in Figure 1 and Figure 2, and the analysed kinematic parameters are: amplitude of the electrode movement (y_{max} [mm]), maximal speed of the electrode (v_{max} [m/s]), maximal acceleration of the electrode (a_{max} [m/s^2]), minimal and maximal acceleration derivate, or Jerk, (J_{min} and J_{max} [m/s^3]).

The implemented movement allows to the electrode to achieve y_{max} as soon as possible limited by the other kinematics parameters v_{max}, a_{max}, J_{min} and J_{max}.

4. Experimental tests

In order to validate the numerical simulations, some experimental tests are carried out and compared to the CFD results. An electrode increased scale model of the "blade" geometry has been built 20 times larger than the electrode real size.This increased scale model represents the cavity created in the workpiece with the tank for the dielectric fluid. The experimental tests were conducted at AgieCharmilles' laboratories.

To visualise the fluid trajectories inside the cavity in the workpiece, coloured sand is used. The sand can follow the fluid trajectories because of their small diameter [6]. The validation of the numerical simulations has been carried out analysing and comparing the fluid trajectories, traced by the sand in the experimental tests, with the velocity contours of CFD simulations.

In order to have Reynolds similarity and obtain a good visualisation with the coloured sand, a mixture of water and glycerine (40% of water and 60% of glycerine) was used. Increasing the water viscosity by adding glycerine, the experimental tests can be carried out at a speed of half time the numerical simulations. The jump amplitude is 20 times larger than the jump amplitude of the numerical simulations.

The kinematic parameters for the experimental test are: "blade" geometry with y_{max} = 9x20 mm =180 mm, v_{max} = 0.05/2 mm = 0.025m/s, a_{max} = 10 m/s^2, J_{min} = -400 m/s^3 and J_{max} = 400 m/s^3.

The kinematic parameters for the CFD simulation corresponding to the experimental test (imposing the Re similarity) are: "blade" geometry with y_{max} = 9 mm, v_{max}

= 0.05 m/s, a_{max} = 10 m/s^2, J_{min} = -400 m/s^3 and J_{max} = 400 m/s^3.

In order to compare a 2D simulation with the experimental tests, the 3-D effect has been eliminated in the electrode in the increased scale model. The increase scale model has only the lateral and bottom gap and no the frontal gap. Therefore, that the electrode is always in contact with the transparent surface of the workpiece increased scale model.

The electrode increased scale model has been built in Polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) material.

5. Bubble test rig and bubble experimental tests

The bubble test rig is composed of different parts. In order to have a better visualisation inside the fluid, the electrode size is 50 times larger than electrode real size. It has been built in Polyvinyl chloride (PVC) and polymethyl methacrylate (PMMA) material. This increased scale model represents the cavity created in the workpiece with the tank for the dielectric fluid. The movement of the electrode is guaranteed by a servo-motor. In order to simulate the formation of the bubbles during the EDM process an air injection system, with a pressure regulator and volume air flow valve, is developed. The air injection is from the bottom of the cavity in the workpiece, see Figure 4.

A simplified Particle Image Velocimetry (PIV) has been developed in order to compare the trajectories of the waste particles inside the dielectric with and without the bubbles. A high speed camera (*Phantom v1210*, recording speed of 100 fps) is used to film the coloured sand trajectories during the electrode jump and two image treatment software ("ImageJ" and "Video to picture") have been used to analysed the movie file.

In particular, two different diameters of the bubbles produced during the EDM process have been considered: $\phi_{B\text{-real-1}}$ = 1.8 mm and $\phi_{B\text{-real-2}}$ = 2.2 mm. In order to have Froude similarity, the corresponding bubble diameter for the experimental tests are: $\phi_{B\text{-exp-1}}$ = 3.9 mm and $\phi_{B\text{-exp-2}}$ = 4.8 mm.

The effect of the gas bubbles generated during the process is also under investigation.

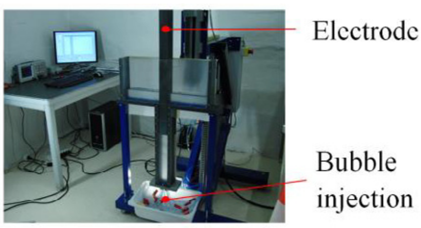

Figure 4: Bubble test rig image

6. Experimental test results

According with the analyse of results of the experimental and CFD results, acceptable correspondence can be observed both of the particle and fluid behaviour. The Figure 5 shows the recording picture of the dielectric fluid flow of an electrode jump, compared with a CFD image of the speed of the fluid at the same instant. The behaviour of the vortex formation and the fluid dynamics inside the dielectric are described in *"Results"* chapter.

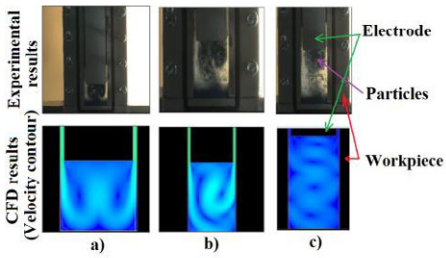

Figure 5: Comparison between experimental and CFD resultants in different instants: a) Beginning of the ascending period with the formation of a couple of vortexes, b) Instability of the vortexes during the ascending period, c)

7. Results

7.1. Numerical simulation results for "blade" geometry

For the "blade" geometry, different simulations are carried out with different values for the kinematics parameters.

The parameters most important for this geometry for the evacuation are y_{max} and v_{max}. The effects of all the others kinematics parameters have less influence both on the evacuation and on the homogenisation. The y_{max} is important to increase the efficiency of the movement. In particular, if the jump amplitude is low (less than 6 mm), the waste particles remain inside the gap, and all the particles are moved from the bottom gap to the lateral gaps.

During the beginning of the ascending period, the fluid behaviour inside the bottom gap is symmetrical with formation of two big vortexes aligned horizontally, see Figure 5. The intensity and the position inside the bottom gap of these vortexes are the causes of the waste particles movements inside the bottom gap. When the electrode continues with the movement, these first two big vortex structure, became longer and other smaller vortexes appear under them, see Figure 5. All the vortexes in the bottom gap are unstable, so, if the velocity of the electrode is high, they can change their positions from aligned horizontally to aligned vertically, see Figure 5.

During the of ascending period, if the speed is less than 0.1 m/s, the waste particles will remain glue down the electrode and easily can go out during the descending phase, see Figure 6. Otherwise, if the speed is more than 0.1 m/s, the waste particles are suspended inside the bottom gap and only a part of them go out after one jump, see Figure 6.

Analysing the particle density inside the bottom gap after one electrode jump, a small electrode jump (less than 3 mm) provides a good homogenizations. A series of more electrode jumps accumulates all the particles in the middle of the cavity.

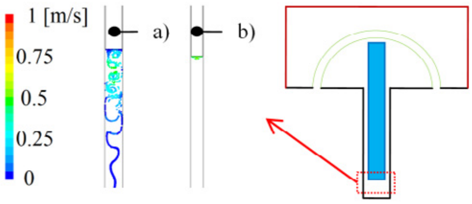

Figure 6: Particle distribution coloured by particle speed in the CFD analysis for the "blade" geometry when the electrode is at y_{max} = 14 mm: a) Electrode speed more than 0.1 m/s, b) electrode speedless than 0.1 m/s.

7.2. Numerical simulation results for "pocket" geometry

For the "pocket" geometry, as for the "blade" geometry, during the ascending period,thevortexes which are the causes of the movements of the waste particles inside the bottom gapappear inside the bottom gap.

During the beginning of ascending period of the electrode the fluid behaviour inside the bottom gap is symmetrical with formation of two big vortexes aligned horizontally after the electrode. When the electrode continues with the movement, other smaller symmetrical couples of vortexes appear beside them, see Figure 7.

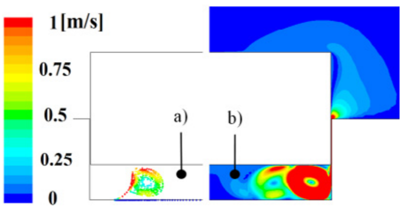

Figure 7: "Pocket" geometry CFD results at 0.075 s: a) Contours of velocity [0; 1] m/s, b) Injected particles coloured by velocity of the particles [0; 1] m/s

Both y_{max} and v_{max} are important for the waste particles evacuation. Increasing the ymax, the waste particle evacuation increases, but the time to complete one jump increases too, so the jump efficiency decreases. Otherwise, if the v_{max} increases, the jump efficiency increases, because the waste particles evacuation increases, but the time to complete one jump decreases. The effects of all the others kinematics parameters have less influence both on the evacuation and on the homogenisation.

The problem of the homogenization is very important for this geometry, several accumulations of waste particles can be observed after a series of more than two jumps, in particular in the central zone of the cavity.

7.3. Numerical simulation results for "complex pocket" geometry

For the "complex pocket" geometry, only one simulation has been carried out: y_{max} = 5 mm, v_{max} = 0.05 m/s, a_{max} = 5 m/s^2, J_{min} = -50 m/s^3 and J_{max} = 50 m/s^{3}and it has been compared to the "pocket" geometry.

Inside the bottom gap, the fluid flow is similar to the fluid flow of the "pocket" geometry. The teeth of "complex pocket" geometry inside the bottom gap fix the position to the vortexes created inside the gap and they decrease the efficiency of the movement for the evacuation (around 22% less), compared to the "pocket" geometry, seeFigure 8.

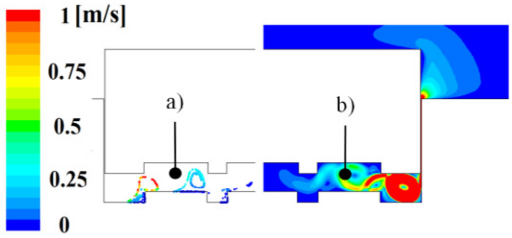

Figure 8: "Complex pocket" geometry CFD results at 0.0625 s: a) Contours of velocity [0; 1] m/s, b) Injected particles coloured by velocity of the particles [0; 1] m/s.

7.4. Numerical simulation results for "3D pocket" geometry

For the "3D pocket" geometry, one simulation has been carried out: y_{max} = 1 mm, v_{max} = 0.015 m/s, a_{max} = 5 m/s^2, J_{min} = -400 m/s^3 and J_{max} = 20 m/s^3.

The results show that all the sections of the geometry parallel to the lateral gap have the same fluid behaviour of the 2-D "pocket" geometry.

The four coins of the electrode produce four lines inside the bottom gap where the waste particles are accumulated. The speed of the fluid in these zones, inside the bottom gap, is higher than the speed forecasted in the 2-D geometry. The shows the cavity generated by the electrode with thee iso-surfaces of velocity where the particles are accumulated.

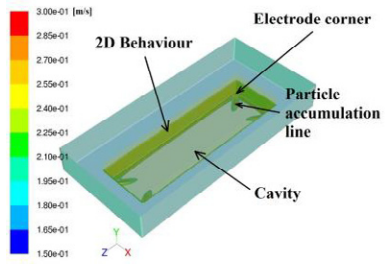

Figure 9: Velocity iso-surface of 0.15 m/s, 0.225 m/s and 0.3 m/s inside the workpiece cavity

6.5. *Effect of the viscosity of the dielectric fluid*

The "pocket" geometry has been chosen to analyse the effect of the dielectric fluid viscosity and the kinematic parameters of the simulations are: y_{max} = 2.5 mm, v_{max} = 0.03 m/s, a_{max} = 5 m/s^2, J_{min} = 20 m/s^3 and J_{max} = 400 m/s^3.

For the evacuation, if the kinematic viscosity increases, the jump efficiency (defined as the ratio of waste particle number out the gaps at the end of the jump to the jump time) decreases and less particles go out. The Figure 10 shows the efficiency of the movement for a series of three consecutive jumps. For the homogenisation, no particular difference can be observed between the two simulations.

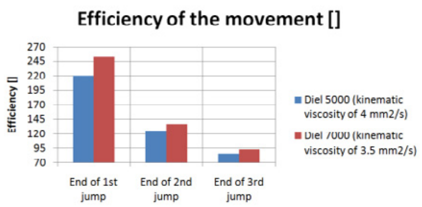

Figure 10: Efficiency comparison between different dielectric fluids

8. Bubble test rig results

In order to evaluate the effect of the bubble presence on evacuation of the waste particles, 15 tests are carried out: 5 without bubbles, 5 tests with bubbles of $\phi_{B\text{-}exp\text{-}1}$ and 5 tests with bubbles of $\phi_{B\text{-}exp\text{-}2}$.

The presence of the bubbles increases the evacuation of the waste particles, around 30% for with bubbles of $\phi_{B\text{-}exp\text{-}1}$ and 46% for with bubbles of $\phi_{B\text{-}exp\text{-}2}$.

9. Summary

A CFD analysis can be used to analyse the dielectric fluid flow and the waste particles distribution in a EDM process.

The kinematics parameters most important for "blade" geometry for the evacuation are v_{max} and y_{max}. The y_{max} is important to increase the movement efficiency and a small electrode jump provides to have a good homogenizations.

For the "pocket" geometry, the parameter v_{max} is important to increase the efficiency of the evacuation of the waste particle. A series of two small jumps can produce a good waste distribution at the end of the jump. The homogenization problem is very important for this geometry.

If the electrode presents a surface inside the gap with teeth, they fix the position to the vortexes created inside the bottom gap and they also decrease the efficiency of the movement.

All the sections of the "3D pocket" geometry parallel to the lateral gap have the same fluid behaviour of the 2-D "pocket" geometry. In the coins of the electrode there is an accumulation of the waste particles (effect 3D).

For the evacuation, if the kinematic viscosity of the dielectric fluid increases, the jump efficiency decreases while, for the homogenisation, no particular difference can be observed.

The presence of bubbles increases the evacuation of the waste particles.

Further statistical studies and experimental investigations will be conducted on the waste particles distribution with a different sizes, shapes of them, density (in the reality the produced particles can be hollow), and uniformity of density and viscosity of the liquid during the simulated time in order to decrease the error source.

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