Study of particle size and position on debris evacuation during Wire EDM operations

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Abstract: Wire Electrical Discharge Machining (WEDM) is a well-known non-conventional machining process for those applications that require both good finishing and tight tolerances. One of the main problems that occur during EDM operations is wire breakage, which leads to stops in the machining process and lowers process productivity. Recent findings have revealed that discharge accumulations near the same spot of the wire are the main cause for wire breakage. If this discharge accumulation is not stopped, the wire finally breaks. In the present work CFD simulations have been effectively used to simulate dielectric flow and particle movement. The effect of particle size and position, together with the effect of high and low pressure flushing conditions have been analyzed. The studied variables have a clear effect on debris evacuation, and it can be concluded that particle size and position, together with nozzle position affect process stability and wire breakage. This work can help to develop new WEDM strategies that consider the relation between mentioned variables and wire breakage.

Keywords: Wire Electrical Discharge Machining, CFD simulation, Debris evacuation.

1. Introduction

Wire Electrical Discharge Machining (WEDM) is a well-known non-conventional machining process for those applications that require both good finishing and tight tolerances. The main advantage of the EDM process is that it relies on a thermal material removal mechanism which makes machinability independent from material hardness. This characteristic makes this process suitable for machining hard and brittle materials as long as they have enough electrical conductivity [1]. One of the main problems that occur during WEDM operations is wire breakage, which leads to stops in the machining process and lowers process productivity, especially in machines without automatic wire threading. One of the biggest challenges of current EDM research is to maximize material removal rate while preventing wire breakage.

Recent findings have revealed that discharge accumulations near the same spot of the wire are the main cause for wire breakage [1]. This effect is increased due to the fact that new discharges tend to take place on the border of previously formed bubbles, where debris is accumulated [2]. When sparks tend to concentrate around the same zone of the wire, they both erode the wire, reducing its cross-section area, and increase wire material temperatures, reducing their mechanical resistance. If this discharge accumulation is not stopped the wire finally breaks due to this combination of wire wear and high local...
temperatures. Modern WEDM machines use different control techniques to detect and interrupt discharge accumulation, but these techniques tend to decrease machining speed [3]. The most usual technique used to prevent wire breakage is to increase the pause time (sometimes called off-time) between consecutive discharges in order to give more time to the recovery of the initial conditions in the dielectric fluid. These initial conditions are met when the conductive plasma channel formed during the discharge is completely extinguished and when debris particles generated by the discharge have been adequately evacuated (or at least flushed away from the discharge zone). Some authors have used Computational Fluid Dynamics (CFD) to try to understand how the dielectric flow during the EDM process affects debris evacuation. Tanjilul [4] simulated Sinking EDM operations using a novel vacuum system combined with traditional flushing and evaluated debris removal efficiency. They find this system as a good alternative to improve debris flushing in Sinking EDM (SEDM) operations, and they also mention the influence of discharge current on debris particle size, in such a way that higher discharge currents lead to bigger debris particle generation. Ebisu [5] analyzed the dielectric flow in corner cutting using WEDM in order to understand and minimize corner errors produced. This work relates dielectric flow with wire deflection and find that debris stagnation area disappears just after the corner but is observed again when the wire has advanced a couple of millimeters away from the corner. In another article, Wang [6] analyzes debris movement during continuous (multi-spark) SEDM operations, being the main contribution of this work the fact that it takes into account gas bubble formation and evolution inside the SEDM gap. The main conclusion drawn is that debris particles are mainly evacuated due to bubble expansion and movement. Similar observations have been also made by Yoshida [7], Okada [8] and Takeuchi [9]. Experiments show that particle sizes differ depending on EDM media and discharge parameters and that they tend to accumulate in the vicinity of bubble borders.

The mentioned works have simulated debris movement under different conditions and have assumed particle diameters of 10 µm [5] and 25 µm [6]. It is well known that debris particle diameters can vary significantly [8]. Tanjilul [4] studied particle diameter distribution for different SEDM conditions and obtained a size distribution function used for the numerical analysis of particle movement. Particle diameters ranged from tenths of microns to submicron, being submicron particles responsible for less than 8% of total debris volume. In another work. Most of available data about particle sizes in EDM is focused on SEDM. In order to fill this information gap Wang [10] also studied debris particle size distribution in WEDM using Energy Dispersive X-Ray Fluorescence Spectroscopy (EDXRF) and laser diffraction together with TEM and SEM images. Results reveal that most of the particle diameters are in the 1 – 20 µm range, but TEM images showed that up to 98% of the particles are submicron scale. A large number of them having diameters lower than 100 nm. The influence of these submicron particles on the process is not yet well understood but particle movement simulations should consider them in the future since they could have an active role in discharge concentration leading to wire breakage.

In this paper CFD (Star CCM+) is used to simulate dielectric flow and particle movement under different WEDM conditions. The objective of the performed simulations is to study the effect process variables on debris evacuation.

2. Methodology
Simulations have been carried out using Star CCM+ software. The main variables considered have been the following ones: particle size (diameter), particle angular position around the EDM wire, particle height and nozzle positions.

Three different particle sizes have been considered based on previous work [10]. After analyzing the properties of debris particles formed during WEDM of steel parts, it was found that particle diameters range from tenths of microns to sub-micron sizes. Therefore, particle diameters of 10, 1 and 0.1 µm have been considered in the present study. Particles have been introduced at five different initial angular positions close to the EDM wire as shown in figure 1. When it comes to the initial height of the introduced particles, they have been introduced at five different heights spaced between the minimum and maximum workpiece thickness, workpieces of 10mm and 50mm have been analyzed (being particle injection plane heights of 0, 2.5, 5, 7.5 and 10 mm for 10 mm thickness, and 0, 12.5, 25, 37.5 and 50 mm
for the thickest workpiece). And finally, two different nozzle positions have been considered: nozzles positioned close to the workpiece (for optimum high pressure conditions) and nozzles far from workpiece surface in order to reflect bad cleaning conditions (this situation is usually found when EDM-ing workpieces that present height variations in the section being cut). The effect of all mentioned variables on debris evacuation has been studied.

![Figure 1](image.png)

**Figure 1.** (a) Initial angular positions of particles around the EDM wire. (b) Different initial particle heights for a 10 mm workpiece.

3. Results and Discussion

In this section obtained results will be presented and the main conclusions will be drawn. This section will also describe the CFD model developed for the analysis of debris evacuation during different WEDM conditions.

3.1. CFD model

The CFD software used has been Star CCM+. This software tool has been employed for mesh generation, flow calculations and particle tracking simulation. In order to adequately represent the physics of the process, realistic boundary conditions have to be established. Figure 2 shows the geometry of the model, the example shown corresponds to workpiece height of 10 mm and dielectric nozzles are located close to the workpiece.

![Figure 2](image.png)

**Figure 2.** Boundary conditions established for CFD calculations.

Given the geometry of the problem, a symmetry plane has been used in order to minimize mesh size and computational cost. Surfaces far from the wire have been modeled as pressure outlets at atmospheric pressure and both nozzles have been represented as velocity inlets with constant velocity flow. Velocity
data for the nozzles has been obtained from flow rates calculated by the WEDM machine manufacturer, ONA Electroerrosión S.A., and taking into account their actual diameter. Resulting flow velocities have been of 5 m/s and 5.8 m/s for the upper and the lower nozzle respectively.

When it comes to the meshing of the simulated fluid volume, an optimum balance between precision of the obtained results and computational cost has to be found. Different mesh sizes of 20, 10 and 5 µm have been tested in order to select the most appropriate one. It was found that, when using a minimum mesh size of 5 µm, the obtained results varied less than 3% if compared to the previous mesh size of 10 µm, and it was therefore concluded that further reductions in mesh size were not necessary, so minimum mesh size used for the present simulations has been of 5 µm.

As mentioned before, three different particles have been considered. Particles have been modeled as spheres with diameters of 0.1, 1 and 10 µm and their density value has been established equal to 7,800 kg/m³, that is, equal to a typical density value for steel.

3.2. Simulation results

The first parameter analyzed has been particle size. Figure 3 presents particle tracks, colored based on particle residence time (time after particle injection inside the EDM gap). In all cases workpiece thickness is 10 mm and both upper and lower nozzles are located close to the workpiece (0.2 mm) which represents high pressure conditions needed for optimum gap cleaning. It can be observed that after 0.07 seconds all particles of 10 µm diameter are still in the vicinity of the EDM wire (a), while most of the particles with 1 µm diameter have been evacuated after 0.02 seconds (except for some particles in the central zone). In the case of the smallest particles considered (0.1 µm diameter) all of them are far from the EDM gap after 0.007 seconds of flow time. As explained in section 2, particles have been injected at five different heights along workpiece thickness and at five different angles around the wire. These results reveal that even in the case of a low thickness part (10 mm) debris evacuation is difficult for larger particle sizes, while smaller particles can be easily flushed away from the EDM gap.

![Figure 3](image-url)

**Figure 3.** Particle residence times and particle tracks for particle diameters of 0.1 µm (a), 1 µm (b) and 10 µm (c). Workpiece height is 10 mm and nozzles are close to its surface (high pressure conditions).

The next parameter studied was the angular position of the injected particles. Particles tracks and residence times for particles of equal diameters of 1 µm have been plotted in figure 4. It can be observed that only particles located in the central height have not been affectively evacuated. Particles injected at
angular positions defined as 1, 4 and 5 in figure 1 are the ones that have not moved away from the vicinity of the EDM gap. Position 1 is located in front of the EDM wire, whereas positions 4 and 5 correspond to particles situated behind the wire. These findings could indicate that dielectric flow presents vortices behind the wire, which could lead to particle accumulations and that the flow just in front of the wire is less able to track particles away.

![Figure 4](image-url)

**Figure 4.** Particle tracks and residence time for 1µm diameter particles located at angular positions 1 (a), 2 (b), 3 (c), 4 (d) and 5 (e). Some particles at positions 1, 4 and 5 are not effectively evacuated.

And finally, the effect of particle injection height has been analyzed. The next figure (figure 5) shows particle tracks and residence times for particles at different heights, five angular positions have been simulated for each injection plane. After studying the obtained results, the tendency of particles in the center of the workpieces thickness to not evacuate the EDM gap is observed once again. Even for a workpiece thickness that can be considered as a low value for industrial standards, particle debris is not easily evacuated from the discharge zone.

![Figure 5](image-url)

**Figure 5.** Particle tracks and residence time for 1µm diameter particles injected at five different heights. Particle heights are 0mm (a), 2.5 mm (b), 5 mm (c), 7.5 mm (d) and 10 mm (e).
All simulations results shown before correspond to high pressure flushing conditions, but some industrial applications require cutting workpieces of variable thickness, which forces the use of low pressure flushing. In order to assess the effect of this configuration, particle tracks were simulated for the separated nozzle configuration. In this new geometry, the distance between both nozzles and workpiece surface was set to 10 mm, and workpiece thickness was kept constant and particle size of 1 \( \mu m \) was simulated. Some results are presented in figure 6.

![Figure 6](image)

**Figure 6.** Velocity fields for high pressure conditions (a) and for low pressure conditions (b). Particle tracks and residence time for low pressure flushing conditions, particle heights of 7.5 mm (c) and 5 mm (d).

After studying particle residence times, it can be concluded that if nozzles are far from workpiece surface, particles can be finally evacuated from the gap zone close to the wire, but this requires much longer times. In some cases, especially for particles located in the central zone of the workpiece, times up to 0.1 seconds are required for debris cleaning, while particles of the same size are evacuated in less than 0.05 seconds in low pressure conditions.

This is closely related to flow speed values in high pressure and low pressure flushing conditions. In the case of high pressure conditions, flow speed at the lower and upper workpiece planes presented values of around 30 m/s, while for low pressure conditions this speed had values of approximately 4 m/s. If flow velocity in the centre height is analyzed high velocity variations are also observed: 18 m/s are achieved if the nozzles are close to the workpiece, while much lower speeds of 1.3 m/s are obtained in the central zone around the wire. This explains the difference in the time required for an effective particle evacuation.

**4. Conclusions**

CFD simulations have been effectively used to simulate dielectric flow and particle movement. The studied variables have a clear effect on flushing, so it can be concluded that particle size and position,
together with nozzle position affect process stability and wire breakage.

The effect of particle size has been addressed, bigger particles (10 µm diameter) are more difficult to evacuate, while smaller ones (0.1 µm diameter) can be easily flushed away. Even for a low workpiece thickness of 10 mm, particles located near the central plane have also presented problems for their evacuation. All these trends are reinforced for low pressure conditions (if nozzles are far from workpiece surface), in this case, much longer times have been needed for an effective evacuation of debris particles.

This work can help to develop new WEDM strategies that consider the relation between mentioned variables and wire breakage, since this problem is closely related to discharge accumulations due to debris concentration around the EDM wire.

**Acknowledgements**

This research was funded by the Spanish Ministry of Economy and Competitiveness through the project DPI2017-82239-P.

**References**

[1] Kunieda M, Lauwers B, Rajurkar K P and Schumacher B M 2005 Advancing EDM through fundamental insight into the process *CIRP Annals* 54 (2) pp 64–87

[2] Kunieda M and Kitamura T 2018 Obsevation of difference of EDM gap phenomena in water and oil using transparent electrode *Procedia CIRP* 68 pp 342–346

[3] Saini H, Khan I, Kumar S and Kumar S 2017 Optimization of material removal rate of WEDM process on mild steel using molybdenum wire *International Journal of Advanced Engineering* 3 pp 1001–1005

[4] Tanjilul M, Afzaal A Senthil M and Rahman A 2018 Study on EDM debris particle size and flushing mechanism for efficient debris removal in EDM-drilling of Inconel 718 *Journal of Materials Processing Technology* 255 pp 263–274

[5] Ebisu T, Kawata A, Okamoto Y and Okada A 2017 Influence of jet flushing on corner shape accuracy in wire EDM 19th CIRP Conference on Electro Physical and Chemical Machining (Bilbao, Spain)

[6] Wang J amd Han F 2014 Simulation model of debris and bubble movement in consecutive-pulse discharge of electrical discharge machining *International Journal of Machine Tools & Manufacture* 77 pp 56–65

[7] Yoshida M and Kunieda M 1998 Study on the Distribution of Scattered Debris Generated by a Single Pulse Discharge in EDM Process *International Journal of Electrical Machining* 3 pp 39–46

[8] Okada A, Uno Y, Onoda S and Habib S 2009 Computational fluid dynamics analysis of working fluid flow and debris movement in wire EDMed kerf *CIRP Annals - Manufacturing Technology* 58 pp 209–212

[9] Takeuchi H. and Kunieda M 2007 Effects of volume fraction of bubbles in discharge gap on machining phenomena of EDM *Proceedings of the 15th International Symposium on Electromachining (Pittsburgh)* pp 63–68

[10] Wang J, Sánchez J A, Wang Z, Izquierdo B and Ayesta I 2020 Observations on Debris Composition and Size Distribution in WEDM *Procedia CIRP* 95 pp 331–336