Study of Molten Metal Flow and Debris Movement at Inter Electrode Gap in Micro Electric Discharge Milling Process using CFD

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Abstract

Micro Electric Discharge milling (µED milling) process is widely used for micro machining of hard to cut conductive materials. In this process, sparking occurs at the Inter Electrode Gap (IEG) of few microns. Sparking occurs intermittently at the bottom and along the periphery of the tool electrode. Rotation of the tool increases the frequency of spark generation at the IEG. Repetitive sparks at the same location locally melt the metal and due to high temperature maintains it in the molten state. As the temperature of the molten metal is very high it does not cool rapidly and gets flushed away in the form of molten metal flow by the dielectric fluid. Agitation of the dielectric fluid due to rotating tool segregates large globules of metal into small globules of metal. These globules cool rapidly to form debris particles. The flow behavior of the molten metal expelled and the debris particles are not well discussed in the literature and this will be useful to understand redeposition phenomenon on the tool and work surface. The objective of this work is to investigate molten metal flow and debris particle movement at IEG using Computational Fluid Dynamics (CFD). Multiphase modeling and discrete phase modeling in ANSYS FLUENT is used to analyze molten metal flow and debris particle movement in the gap. The effect of tool rotation speed, metal injection position, and size of electrode gap on the molten metal flow and debris movement in the gap is investigated and the contour plots are plotted.

Keywords: Micro electric discharge milling, debris, dielectric, redeposition, simulation, computational fluid dynamics.

1. INTRODUCTION

Among various advanced manufacturing processes, Electrical Discharge Machining (EDM) is a popular technique to machine hard to cut conductive materials. The heat generated by spark due to the dielectric breakdown between two electrodes over small Inter Electrode Gap (IEG) can melt practically any material. The complex phenomenon occurring at IEG of EDM is a multi-physics problem attracting the scientific community. In EDM the phenomenon of electrical discharge occurs in micro seconds over a narrow gap of few micro meters. The machining area is submerged under dielectric fluid and is polluted with bubbles, debris and carbon making it extremely difficult for observation and theoretical analysis [1]. Micro Electric Discharge milling (µED milling) is the advancement in the EDM technology in the micro domain. In µED milling process cylindrical tool electrode rotates and moves along the predefined path to machine complex geometry. CNC servo control is used to program the motion of tool along the different axis. This avoids manufacturing of complex tools required for machining 3D profiles. High machining aspect ratio, the capability to machine any hard-conductive material, low machining cost and a simple cylindrical tool to manufacture complex shapes are the advantages of the µED-milling process. Currently, µED-milling is mostly used to produce micro cavities with high aspect ratio and tools such as micro molds for micro injection molding [2]. To understand the physics of the process, it is very important to understand material removal (debris), the crater formed and dielectric fluid flow with molten metal. Accumulation of debris in discharge gaps usually causes a poor discharge, which not only causes a low material removal rate but also severely damages the machined surface [3]. Material removal occurs intermittently during or just after the discharge duration. Material removal occurs while the generated bubble is expanding, whereas no debris particle is removed while the bubble is contracting [4].

It is agreed that the physics of the EDM process is complex. It is the classical example of the multi-physics problem. Most of the researchers used CFD method to simulate and study the EDM process. Stefan et al. [5] used CFD simulation to study the fluid flow in grinding process and obtained the distribution of temperature, pressure, velocity and liquid volume fraction and determine the flow patterns, including useful and wasted flows. Okada et al. [6] investigated the fluid flow from the machined kerf of wire EDM. The flow field, debris motion and better jet flushing conditions of working fluid from the nozzles were analyzed by CFD simulation. Haas et al. [7] designed and analyzed dielectric injection nozzles of wire EDM process by CFD simulation for improving the cleaning process in the gap. When the spark frequency and power are high, the machining speed is governed mainly by hydrodynamics. Pontelandolfo et al. [8] investigated the dynamics of the dielectric fluid in the die sinking EDM process. Researchers have studied the use of different dielectric in µEDM and their effect on its performance. But very few studies have been reported in the literature on the molten metal flow and debris movement in the gap of µED-milling. The pattern of fluid flow, agitation of fluid determines the size and shape of debris particles, its movement and subsequent redeposition of molten metal in the gap. So, it becomes important to study the molten metal flow and debris movement at IEG.

The objective of this paper is to study the molten metal flow and debris movement in µED-milling process on machining of micro channels. The molten metal flow and debris movement in the discharge gap were analyzed by computational fluid dynamics (CFD) analysis. The results are presented considering different machining conditions such as injection position, electrode speed, and size of the gap. Microscopic observation has shown that unlike µEDM process, µED-milling experience different flow pattern due to rotation of the tool electrode. Rotation of the tool electrode causes a stirring action in molten

Table 1. Properties of the molten steel and dielectric fluid (kerosene)

	Density g/cm^3	Thermal conductivity W/m K	Specific heat J/Kg K	Dynamic viscosity Kg/m s	Molecular Weight Kg/Kgmol	Temperature K
Molten steel	8.03	16.27	502.48	0.007	55.85	10000
Kerosene	0.78	0.149	2090	0.0024	167.31	300

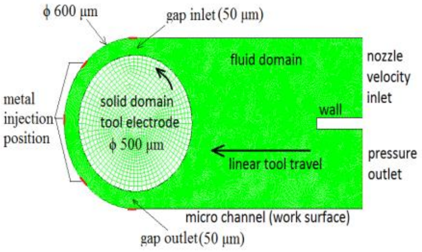

Fig. 1. Model description

metal flow and agitates the fluid with corresponding flushing and non-uniform deposition.

2. PROBLEM FORMULATION

Top view of a 2D model used for CFD analysis of molten metal flow and debris movement is shown in Fig. 1. Tool electrode of diameter 500 µm is rotating in counter clockwise direction and fed from right to left direction. The constant IEG of 50 µm is maintained between a tool and the work piece. The width and length of the micro channel are 600 µm and 1300 µm respectively. In conventional µEDM, electrodes are submerged under dielectric and additional dielectric for circulation enters through the nozzle. For simulation, inlet and outlet of fluid flow are considered on either side of the wall. For ease of simulation wall (partition) of 200 µm is located at the center to distinguish between inlet and outlet. The presence of wall does not affect the flow pattern near the tool electrode. Rotating tool electrode, which is solid domain meshed with quadrilateral elements and the fluid domain that is micro channel gap meshed with triangular elements as shown in Fig. 1. As the dimensions are in micro meters the entire domain was finely meshed to improve the accuracy of results. The fluid flow simulation of 2D geometry was done by Finite Volume method. Realizable K-Ɛ model with standard wall functions was used for simulation. The main algorithm was SIMPLE (Semi – Implicit Method for Pressure Linked Equations) for pressure-velocity coupling. Moving Reference Frame is used to provide rotation speed to tool electrode. The effect of gravity was neglected as tool and work piece is submerged under dielectric fluid. The boundary conditions used were velocity inlet, pressure outlet, and no slip condition.

Due to the rotation of the tool, the velocity of the dielectric fluid is varying across the gap. To study the flow of molten metal in the gap, five equidistant points were considered along with the circumferential surface of the workpiece as shown in Fig. 1. Two conditions are considered where the injection points are near to each other and far from each other. The CFD simulations are performed with commercial ANSYS FLUENT software. The governing differential equations are Navier – Stokes equations of the flow physics solved numerically on a computational mesh.

3. MULTIPHASE MODELING

In the µED-milling process, as tool electrode is rotating at high speed, the spark is generated along the circumference of the tool. Spark is generated between two electrodes where the gap size is minimum. Repetitive sparks occur at the same location on the workpiece due to surface irregularities and the rotation of the tool electrode. Due to repetitive sparks, the crater of a larger volume is generated on the workpiece. Globules of molten metal are ejected from the workpiece and are flushed away by the dielectric fluid. Due to large energy, a large volume of material is melted and it flows as a molten metal flow. As the temperature of the volume of ejected metal is high, it does not solidify and travels as a molten metal flow with the dielectric fluid.

Multiphase modeling is useful to model the flow of molten metal flow in the dielectric fluid. Multiphase modeling in ANSYS FLUENT has two approaches: Euler Lagrange approach and Euler-Euler approach. In Euler-Euler approach, different phases are treated as interpenetrating continua. The volume of a phase cannot be occupied by another phase; hence phase volume is considered for calculations. The volume fractions of the phase are assumed to be continuous functions of space and time and their sum is equal is one. Three different Euler-Euler multiphase models are available: Volume of fluid, Mixture and Eulerian. The Eulerian model is the most complex of the multiphase models. It solves a set of momentum and continuity equation for each phase. Coupling is achieved through the pressure and interphase exchange coefficients. The Eulerian model provides more accurate results than the mixture model, but as it solves several equations it is computationally expensive.

In the present study, two fluids are considered primary fluid is a liquid dielectric (kerosene) and the secondary fluid is molten steel. The properties of both fluids are given in Table 1. Volume fractions are the space occupied by each phase. Volume of a phase is given by

$$V_p = \int_V \propto_p . dV \qquad (1)$$

And the summation of the volume of all phases is equal to one.

$$\sum_{p=1}^{n} \propto_p = 1 \qquad (2)$$

The value for the phase velocity ratio is the ratio of secondary phase to primary phase velocity

$$Velocity\ Ratio = \frac{secondary\ phase}{primary\ phase} \qquad (3)$$

The value of one for velocity ratio indicates the same velocity for both phase (no slip condition). Velocity ratio greater than one indicates larger secondary phase velocity and the ratio less than one indicates smaller secondary phase velocity. In the present study, velocity ratio is taken as one that is kerosene and molten steel has same velocities.

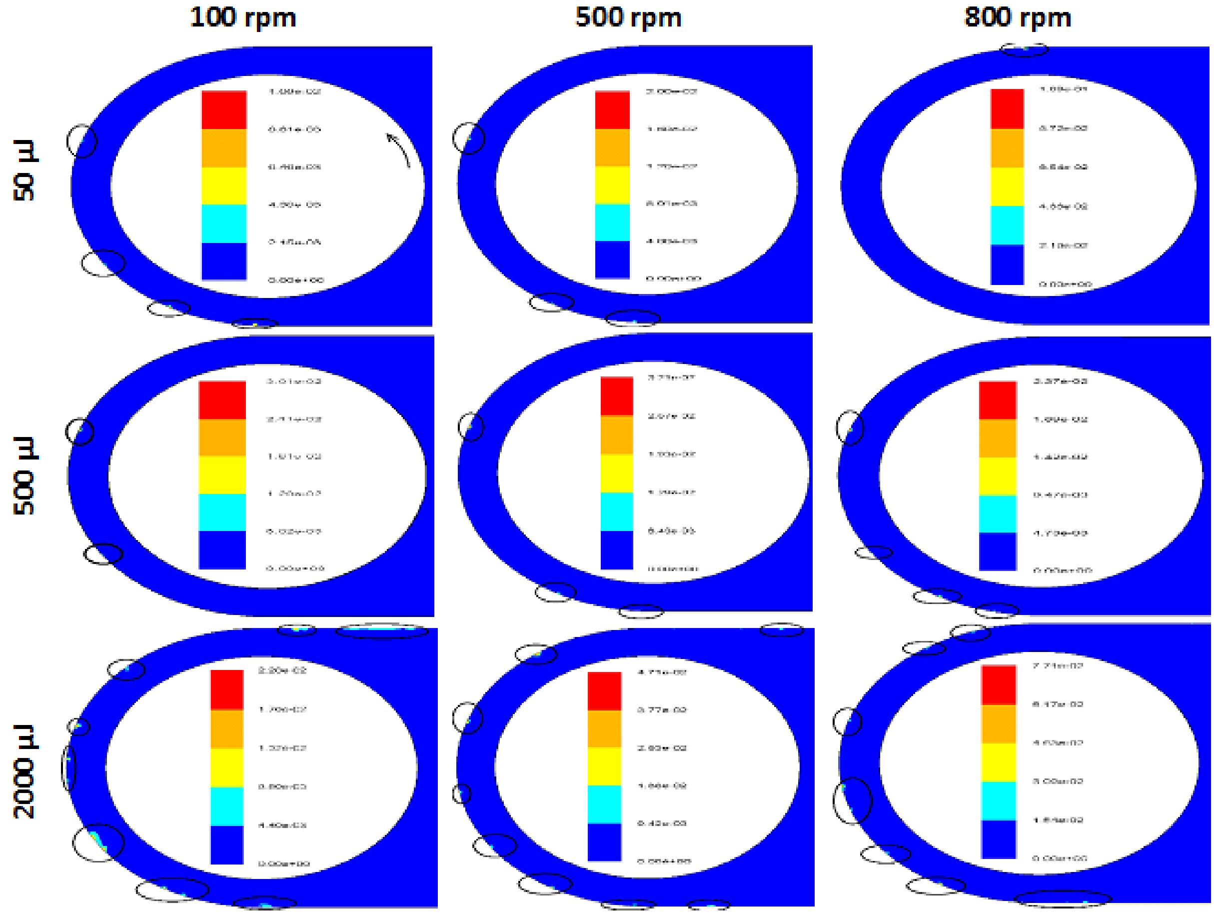

Fig. 2. Contour plots showing volume fraction of molten steel depositing to the work surface for different tool electrode speed and volume of metal injection which is a function of input energy conditions.

4. RESULTS AND DISCUSSION

4.1 Effect of injection position

The injection position of molten metal can be referred as the position of craters in the actual process. It is possible to have an infinite number of craters along the workpiece surface and all these points could be the source of molten metal and debris. In the first case, five equidistant positions are considered far from each other as shown in Fig. 1. In second case five equidistant positions are considered near to each other. The energy in the gap is given by

$$E = \frac{1}{2}\, C\, V^2 \qquad (4)$$

When this energy is supplied, erosion of metal occurs due to melting and vaporization due to heat conducted by the electrode. The actual energy used to erode the material to form a micro crater due to melting is given by

$$E_e = V_{exp} \cdot \rho \; . \; H_m \qquad (5)$$

where E_e is actual erosion energy due to melting, V_{exp} is the experimental erosion volume, ρ is the density, H_m is the enthalpy of melting [9]. The volume of the crater for different energy 50, 500 and 2000 µJ is calculated using the above equation and is injected from the injection position for 100 ms during simulation. The injection for a specific time is done using DEFINE_PROFILE user defined function (UDF). The molten metal injection and its subsequent deposition on the work surface for different machining conditions is shown in Fig. 2. It is observed that globules of metal injected from injection position far from each other travels some distance and combines to form large globule of metal at the bottom of the gap. At the bottom of the gap, void spaces are created due to rotating tool and the vortex created at the back of the tool. The molten metal is dragged from this position and travels to the gap inlet where it is divided into two flows: one flowing inside the gap again and the other flowing towards the vortex at the back of the tool as shown in Fig. 3. When injection positions are near to each other small globules of metal combine to form large globules of metal after traveling a short distance.

4.2 Effect of tool rotation speed and electrode gap

Rotation of tool is an inherent part of the µED-milling process. Due to tool rotation, the velocity of dielectric fluid across the gap varies. The velocity of the dielectric fluid is maximum near to tool electrode and minimum near the workpiece. Molten metal injected travels with higher velocity when tool speed increases. At the speed of 100 rpm and 50 µJ energy, the volume of molten metal is small and it does not travel a longer distance and stick to the adjacent surface. With the increase in

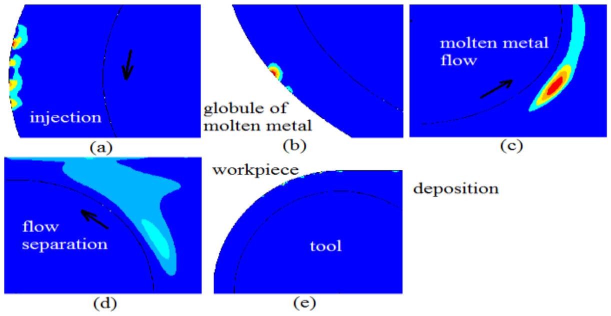

Fig. 3. Contour plots of the volume fraction of molten steel showing (a) molten metal injection (b) globules of metal combine to form single globule (c) molten metal flow (d) molten metal segregates into small globules due to agitation and (e) molten metal gets deposited on the work surface.

energy to 500 and 2000 µJ and with a lower speed of 100 rpm, continuous flow of molten metal is observed as the flow is not agitated due to lower electrode speed [2]. Also, molten metal is dragged along the vortex at the back of the tool. After making one complete rotation globules of molten metal gets segregated into small globules and gets stick to the workpiece as shown in Fig. 3. The considerable effect of the size of electrode gap on molten metal flow is not observed. Fig. 4 is the velocity vector of the dielectric flow field in the micro channel which clearly shows the vortex and the void spaces created in the micro channel.

4.3 Debris particle movement

In CFD analysis, discrete phase modeling (DPM) is used to study the movement of solid particles in the fluid. Debris particles are solid spherical shaped particles, size varying from nanometers to few micrometers. The Lagrangian discrete phase model follows the Euler Lagrange approach. The fluid phase (primary phase) is treated as a continuum by solving Navier Stokes equations, while the dispersed phase (secondary phase) is solved by tracking many particles through the calculated flow field.

In µED milling process, a spark can happen at any location where the gap size is minimum. High-temperature spark melts and vaporizes the metal to form crater on the work surface. Molten metal in the form of debris particles is ejected from the IEG by the dielectric fluid. Spherical particles of size 8 µm are injected with a velocity of 150 cm/s from work surface. Particles are injected after 20 seconds of initial iteration of fluid flow. Due to high injection velocity particle penetrates the moving fluid and attains the position at the center of the gap. These debris particles get dragged from that position by the rotating dielectric fluid and make complete rotation with a decrease in temperature at the gap inlet. It is observed that particles near to tool make multiple rotations as compared to the particles near to work surface. Debris particles get accreted on top, bottom and circumferential surface of the workpiece. Debris particle closely follows the movement of the dielectric fluid; hence it traps in the vortex and void created in the dielectric fluid flow.

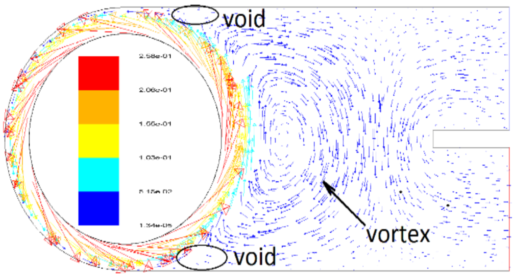

Fig. 4. Velocity vector of dielectric fluid flow.

5 CONCLUSIONS

Effective flushing of debris and unwanted particles from the gap improves the machining efficiency of EDM process. Most of the materials eroded from the crater are deposited on the work and tool surface. In the µED-milling process, rotation of tool enhances flushing of debris from the gap. In this study, debris movement and molten metal flow in the gap were investigated by using CFD tool. The effect of injection position, electrode speed and gap size on the molten metal flow in the gap was analyzed. With the increase in energy, the volume of metal ejected increases and at a lower speed, continuous flow of molten metal is observed. At higher electrode speed, agitation of dielectric fluid segregates large globules of molten metal into small globules and stick to the work surface. The debris particle follows the dielectric fluid flow and gets accreted on the work surface.

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