ACKNOWLEDGEMENT

It is my pleasure to express profound gratitude and indebtedness towards my research supervisor **Dr. G. Karthikeyan**, for his continued inspiration, motivation, support, discussions and great patience throughout this research. I admire among his other qualities, kindness and a balanced approach towards success and failure. His scientific foresight and excellent knowledge have been crucial for the accomplishment of this work. I consider myself privileged for having had the opportunity to study under his able supervision.

I also extend my heartfelt thanks to **Prof. Ranjit S. Patil**, Co-supervisor and Head, Department of Mechanical Engineering for discussions, support and providing me all the necessary facilities during my research period.

I am greatly thankful to the Doctoral Advisory Committee (DAC) members, **Prof. S. P. Regalla** and **Dr. Varinder Singh** for their critical evaluation during the progress of the work.

I gratefully acknowledge all the faculty members of the Mechanical Engineering Department, for their continuous support, care, and good wishes during the course of my work.

I am thankful to my institute **BITS Pilani, Goa** for providing the facility of Scanning Electron Microscope. I am also thankful to **IITB, IITP**, and **Walchand College Sangli** to provide the facility of EDM and high-speed camera. I am also thankful to my institute **ADCET Ashta** and all the faculties of Mechanical Department, for giving me sufficient flexibility in completing my research work.

I am very much thankful to all my friends and fellow research scholars for their company, support, and encouragement during my stay in BITS Goa.

Finally, I wish to express my love and affection to my Parents, Sisters, Brother, wife Megha and my loving daughter Drishya, thank you for being with me during good and bad times.

Last but not least, I am grateful to everyone who has helped me during this research work.

Satish Anand Mullya

ABSTRACT

In the present manufacturing scenario, miniaturization is the basic strategy all over the world. Mechanical and electronic products are in great demand having small size and lighter weight. The development of high-strength alloys in biomedical and aerospace industries necessitates the use of precision machining with advanced technology. Micromachining techniques are used to create micro features or miniature parts in micro devices such as micropumps, microvalves, microactuators, etc. Machining in the microdomain is difficult and requires precise and sophisticated technique. Among various advanced machining techniques, micro-electric discharge machining (μEDM) finds its importance because of its unique advantages of low cost and clean environment.

Micro electric discharge milling (μED-milling) is the advancement in the μEDM which is specifically used to create complex features with high aspect ratio. It utilizes a simple cylindrical rotating tool to cut the microchannel (μchannel) while moving along the predefined path. The phenomenon happening at the inter-electrode gap (IEG) of the tool and workpiece is complex. The IEG size formed between the two electrodes mainly depends on the input energy supplied and the value happens to be less than 50 μm. At this small gap, multiple numbers of plasma channels are formed with very high temperature and pressure which contributes to the removal of material due to melting. This plasma channel on collapsing ejects the molten metal from the crater which cools due to surrounding dielectric to form debris particles. This debris has to be removed instantly from the IEG to avoid secondary sparking. Among the different approaches of flushing, rotation of tool is a simple and effective method. The rotation will also provide sufficient stiffness for the tool during the process. But the rotation of the tool in the process will further add to the complexity. The literature survey shows that μED-milling has a history of nearly 40 years. Most of the research in this area is focused on the material removal rate (MRR), tool wear rate (TWR), and tool wear compensation. Many aspects of the μED-milling process such as the shape of plasma channel, crater geometry, temperature distribution model, etc. are studied. However, only a limited research work is reported on the flow behavior of dielectric flow and its interaction with the molten metal or debris at the IEG at different conditions of the μED-milling process. This phenomenon is important in achieving desired performance on MRR, TWR and surface finish and the process is

attractive for micro features. Hence it has been decided in the present research to focus on the flow behavior at the IEG in the microdomain.

The complex phenomenon happening at the IEG is a multiphysics problem involving different phases such as dielectric, debris and bubbles occurring in microseconds. Such a multiphysics problem is very complex to simulate or capture through instruments experimentally. So, it has been decided to simulate this problem in different stages using various tools of computational fluid dynamics (CFD). For the first stage of simulation, only the dielectric fluid is considered and the flow behavior is analyzed. In the subsequent stages, the interaction of the dielectric fluid with debris particle at room temperature is solved and followed by the interaction behavior at a high temperature. Molten metal is injected and its interaction with the dielectric fluid is investigated. All the simulations are performed on the standard Fluent software.

To simulate the dielectric flow, the realizable k-epsilon (k–ε) model is selected. This model responds more accurately to the flow features involving turbulence. The geometrical model of the study is a 2D representation of the cutting process by μED-milling. This is shown as partially cut straight channel with rotating tool positioned in the direction of machining. The tool is represented as a solid circular domain and the μchannel excluding the tool represents the fluid domain which is finely meshed. Moving reference frame is used to provide the rotation to the tool. The entire fluid domain surrounding the tool is filled with kerosene which is selected as a dielectric fluid because of low viscosity. The inlet and outlet for the flow of dielectric are provided in the boundary of the geometry that represents the edge of the work. Through the detailed review, various parameters which are critical for dielectric flow such as tool rotation speed, IEG size, inlet nozzle velocity, and tool diameter are selected with initial reference of simulation. The critical range for each parameter has been decided by the initial simulation study and a total of 51 simulations are performed considering 4 variables to cover all the conditions.

Among all the variables discussed, tool rotation is the most influencing parameter which affects the dielectric velocity in the gap. It is observed that with the increase in the tool speed the dielectric velocity in the gap increases. Rotating tool exerts a centrifugal force on the dielectric near the tool which drags the fluid in the gap. The velocity pattern observed in the IEG is uniform along the gap and the vortex formation is observed at the back of the tool. The pressure distribution also varies in the gap due to tool rotation. This effect of velocity pattern, vortex, and pressure distribution are largely affected by the other input parameters such as IEG size and inlet nozzle velocity. With the decrease in the size of IEG, the velocity is found to increase but the vortex is not significantly affected. On the other hand, with the increase in the inlet nozzle velocity the velocity in the IEG increases and also the vortex size is affected.

In the second stage of the simulation, debris is introduced in the IEG to study its interaction with the dielectric flow. The model which is used for dielectric flow simulation is retained for debris analysis. Besides, discrete phase modeling (DPM) is used where the dielectric is a primary phase and the debris are the secondary phase. During the simulation, generation of debris is represented by injecting micro-sized particles from the workpiece surface. The geometrical model selected is also the same where the inlet and outlet are assigned with escape boundary condition for the particles to move out of the domain. The tool and workpiece surface are assigned with reflect boundary condition. The injection points on the workpiece surface are assigned wall jet boundary condition to provide injection velocity to the particles. Particles injected with a different velocity reaches various positions in the IEG and is dragged from this position due to dielectric flow. These particles follow the dielectric flow and travel as a single particle or a group of particles. The grouping of particles shows chain-like structure, clustering, and accretion on the workpiece surface. These trajectory patterns observed are reasonably in accordance with the results reported in the literature. During motion, particles make multiple rotations around the tool before accreting. The distance traveled by the particle before accretion is calculated by tracing the path followed. The particles accrete on the workpiece surface inside the IEG and outside the IEG. Accretion outside the IEG can affect the geometry of the μchannel whereas the accretion inside the IEG will not affect as it will be removed by the subsequent sparks. The study is further extended by introducing particles with a high temperature and finding the distance traveled by the particle before cooling. The simulation results are compared with the analytical method and it is observed that the results are reasonably similar. Like the particles, molten metal is injected at a high temperature during the simulation. It is observed that the molten metal gets cooled rapidly and solidify in a few milliseconds. Hence, the multiphase study of the molten metal flow is carried by injecting solid particles at high temperature.

The next objective is to study the effect of the slotted tool on flow behavior. The slotted tool consists of a peripheral slot along the surface of the tool. These slots provided on the tool helps in collecting the particles and reducing their concentration in the IEG. The stages of simulation explained before is now applied for the slotted tool. All the models selected for the simulation study is similar except the geometry of the slotted tool. Different shapes of the tool with various slot size and the number of slots are studied. The width and height of the slot are varied to study its effect on the particle removal rate. It is observed that the dielectric velocity in the gap is less for all the slotted tools as compared to the cylindrical tool due to a disturbance in the flow around the slots. Also, a large variation of pressure is seen in the slots. Among various slotted tool shapes considered, the tool which as a deep slot is efficient in the removal of particles. The vortex observed in the slot is responsible to collect the particles in the slot and reduce its concentration in the IEG. While the accretion is majorly observed on the corners of the slot which does not affect the workpiece surface.

Different tools are fabricated with the slotted shapes considered for simulation to conduct experiments. The experimental study is the investigation of the machining performance of the slotted tool over the conventional cylindrical tool. Here the machining performance such as MRR and TWR is calculated using 9 different tools consisting of different slot size while cutting a channel. Out of 9 tools, 3 tools are similar to simulation study and the other 6 tools are used to find the effect of slot width, height and the number of slots on the MRR. It is observed that the MRR is higher using a slotted tool as compared to the cylindrical tool. The surface topography of the machined surface and the tool surface is captured to observe the accumulation of debris particles on various slotted tools. The simulation results are correlated with the experimental findings.

An attempt is made to capture the actual process images at the IEG of the μED-milling using a high-speed video camera. As the field of view (FOV) is few microns and the process is submerged under the dielectric it is difficult to capture the micro size debris particles ejecting from the crater. However, the images of spark and dielectric flow are captured at a high resolution with a high frame rate of 2277 fps. The images show sparking is continuous along the periphery of the tool and its size changes with the input energy. The vortex flow is also observed at the back of the tool. The obtained images of the spark and the bubble motion are used to calculate the IEG size and the velocity of the dielectric. The scanning electron microscope (SEM) images show spherical debris particles deposited on the machined surface which is the direct validation to the assumption of spherical particles for simulation. The experimental results are reasonably in accordance with the simulation results.

The detailed investigation conducted at the IEG of the μED-milling process helps to understand the flow behavior at the IEG and improve the machining performance. In addition, the study of tool geometry can be applied to improve flushing characteristics. For various microfabrication sectors, the slotted tool can provide a large opportunity for improving the process performance and suggest approaches to achieve higher performance of machining. The above discussion will justify a better understanding of the process phenomenon happening at the IEG of μED-milling for machining complex shapes.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Abbreviation	Description
ρ	Fluid density
ρ_p	Density of particle
μ	Dynamic viscosity
μ_∞	Dynamic viscosity of kerosene
μ_s	Dynamic viscosity of steel
μ_t	Turbulent viscosity
υ	Kinematic viscosity
ε	Dissipation rate
γ	Rotational rate
β	Coefficient of thermal expansion
ω	Specific dissipation rate, angular velocity
σ_k	Turbulent Prandtl number for k
σ_ε	Turbulent Prandtl number for ε
$\bar{\bar{\tau}}$	Stress tensor
a_1, a_2, a_3	Constants
a	Radius of the cylinder
A_s	Surface area
A_{face}	Area of cell face at wall
C_2, $C_{1\varepsilon}$, $C_{3\varepsilon}$	Constants
C	Capacitance
C_D	Drag coefficient
C_p	Specific heat
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
CMOS	Complementary metal-oxide-semiconductor
d_p, D	Particle diameter, cylinder diameter
DPM	Discrete Phase Modelling
E	Energy
$\vec{F}$	Additional force

F_D	Drag force
FOV	Field of View
g	Gravitational acceleration
G_b	Turbulence kinetic energy due to buoyancy
G_k	Turbulence kinetic energy due to the mean velocity
h	Average heat transfer coefficient, slot height, sensible enthalpy, normalized gap
H	Gap between cylinder and plane wall
I	Unit tensor
IEG	Inter-electrode gap
J_j	Diffusion flux of species j
k	Thermal conductivity of kerosene
kl, k_L	Laminar kinetic energy
k, k_T	Turbulent kinetic energy
k_t	Turbulent thermal conductivity
k_{eff}	Effective conductivity
LED	Light Emitting Diode
m	Mass
$\dot{m}$	Mass flow rate of particles
MRR	Material removal rate
N_u	Nusselt number
p	Pressure
P_r	Prandlt number
$\dot{Q}_{avg}$	Average heat transfer rate
$\dot{Q}_{total}$	Total heat transferred
r	Radius of sphere
$R_{accretion}$	Accretion rate
R_e	Reynolds number
R_E	Relative Reynolds number
S, S_k, S_m, S_ε	Source terms
S_h	Heat of chemical reaction
SEM	Scanning Electron Microscope
T	Temperature

T_{avg}	Average temperature
T_{∞}	Temperature of kerosene
t	Machining time
TWR	Tool wear rate
u	Velocity along X direction
$\vec{u}$	Fluid phase velocity
$\overrightarrow{u_p}$	Particle velocity
$\bar{u_i}$	Mean velocity component
$\dot{u_i}$	Fluctuating velocity component
U	Inflow velocity
v	Velocity along Y direction
$\vec{v}$	Velocity vector
V	Voltage, Velocity
V_w	Volume of material removal from workpiece
V_T	Volume of material removal from tool
w	Velocity along Z direction, width of slot
Y_M	Fluctuating dilatation in compressible turbulence to the overall dissipation rate