Chapter 5

SLOTTED TOOL

5.1. INTRODUCTION

This chapter focusses on using a slotted tool to enhance the performance of μED-milling process. As discussed earlier, rotation is only one aspect of debris removal, but there are several other flushing techniques such as high velocity jet, tool vibration and tool jump which have been devised in the past to maintain low level of debris concentration in the gap. However, this necessitates additional attachment/setup which are expensive and requires maintenance. Therefore, geometric features provided on the cylindrical tool as compared to the plain tool can provide effective push for removal of debris from the gap. Various tool shapes such as peripheral slot, tubular, semi-cylindrical, helical and inclined slots have been used by the various researcher among which slotted tool find many applications for complex geometries. In addition, they are easy to fabricate than the other shapes.

In this chapter, study of the dielectric flow-field and the debris movement in the gap is extended using slotted tool. The influence of various parameters that are considered previously such as tool rotation speed, gap width (IEG), nozzle inlet velocity, and tool diameter are also considered here and the similar responses such as the average dielectric velocity and flow patterns taken for observation. The time taken by the debris particles to move out of the gap is calculated for different slotted tools at various tool speed to study the removal rate. The accretion happening at various region in the slots of the tool is analyzed.

5.2. MODEL DESCRIPTION

The schematic diagram showing various slotted tool is shown in Figure 5.1. As shown in the figure, four different tools of various shapes represented as slotted tool 1, slotted tool 2, slotted tool 3, and slotted tool 4 are selected for simulation. The shape of the tool is varied by changing the number of slots and the size of slots. The details of different shapes of tool in terms of number of slots, slot width, slot height is listed in Table 5.1. The width represents the circumferential distance of slot and the height represents the depth of slot. The diameter of the tool, µchannel width and gap width are 500 µm, 600 µm and 50 µm respectively and they are kept constant. The tool is rotating in counter clockwise direction. The gap between the external surface of the tool and workpiece surface is

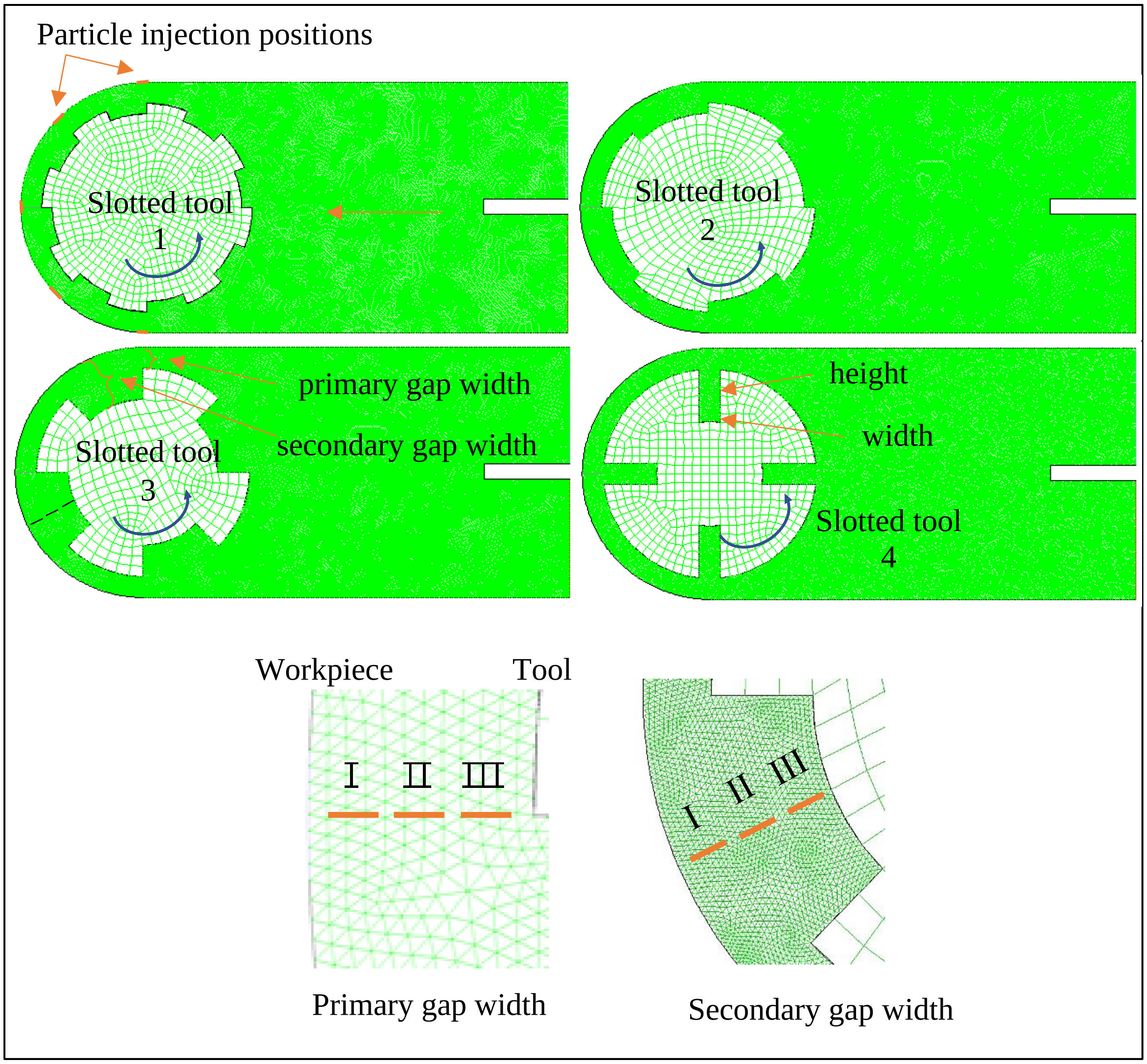


Figure 5.1 Schematic diagram representing the slotted tool and analysis points

represented as primary gap width (IEG) and the gap between bottom surface of the slot and the workpiece surface is represented as secondary gap width (IEG + slot height). The primary and secondary gap width is divided into equal divisions and the average dielectric velocity is measured at three different positions as shown in figure. In order to study the trajectory of the particles, five different positions on the workpiece is used to inject the particles. The meshing and boundary conditions are similar as discussed before for cylindrical tool in chapter 3.

Table 5.1 Tool geometry and μchannel size

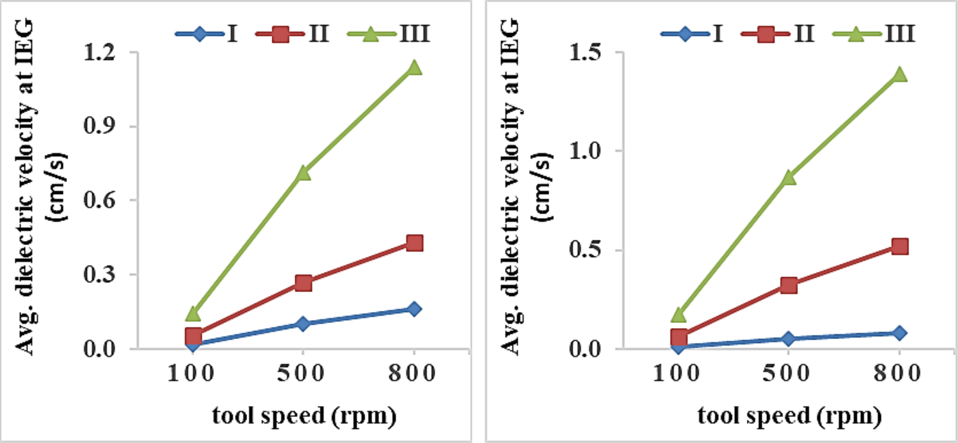
Tool No.	Tool dia. (μm)	No. of slots	Slot width (μm)	Slot height (μm)	μchannel width (μm)
1	500	8	98	25	600
2	500	4	197	25	600
3	500	4	197	75	600
4	500	4	50	125	600

5.3. INFLUENCE OF PARAMETERS ON DIELECTRIC FLUID FLOW

The effect of different parameters on the dielectric flow in the gap is studied using different slotted tools. The average dielectric velocity is calculated at the primary and the secondary gap and all the results at the secondary gap width is presented here. The table showing the average dielectric velocity at the primary gap width is given in the Appendix.

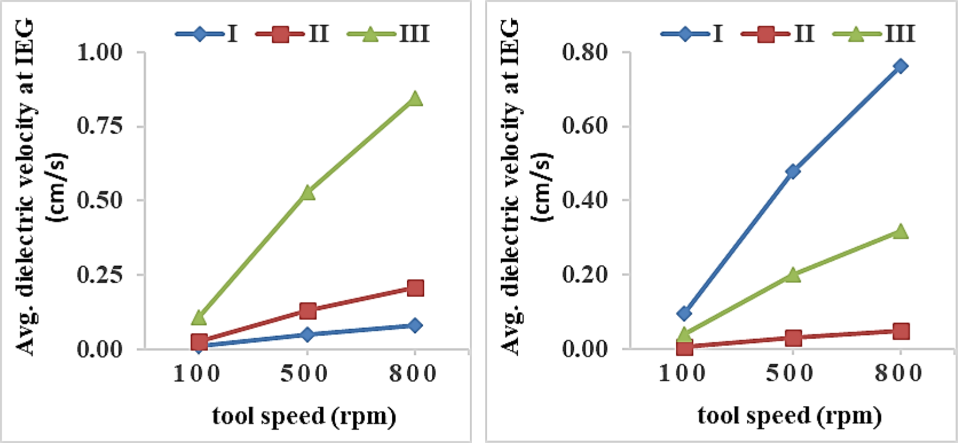
5.3.1 Effect of tool rotation speed

The major factor that affects the average dielectric velocity at the IEG is the tool rotation speed. The values of the average dielectric velocity at the IEG for different slotted tools when the gap width is 50 μm is given in Figure 5.2. The inlet velocity of the dielectric is constant at 0.01 cm/s and the tool speed is 100, 500 and 800 rpm. It is observed that the average velocity at the tool surface is maximum and it is minimum near the workpiece surface for all the tools except the slotted tool 4 as shown in figure. At lower speed the variation in velocity is less while it is large at higher tool speed. The fluid layer in contact with the tool surface inside and outside the slot experiences higher centrifugal force and hence its velocity is higher. The next subsequent fluid layers get necessary drag from the fluid layer in contact with the tool and due to this the velocity reduces towards the workpiece. As the centrifugal force depends on the speed and radius of rotation, the velocity of fluid in the slot is less as compared to the velocity outside the slot due to decrease in the radius equal to slot height. The presence of slot reduces the velocity of the



(a) Slotted tool 1

(b) Slotted tool 2



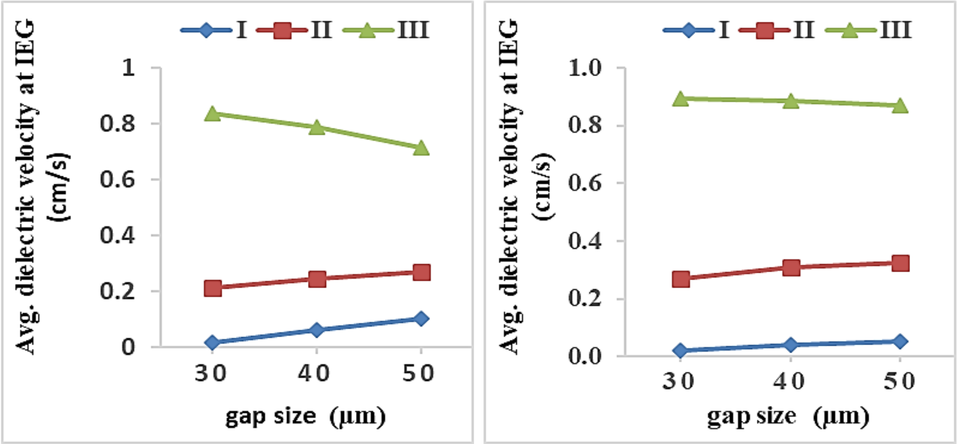
(c) Slotted tool 3

(d) Slotted tool 4

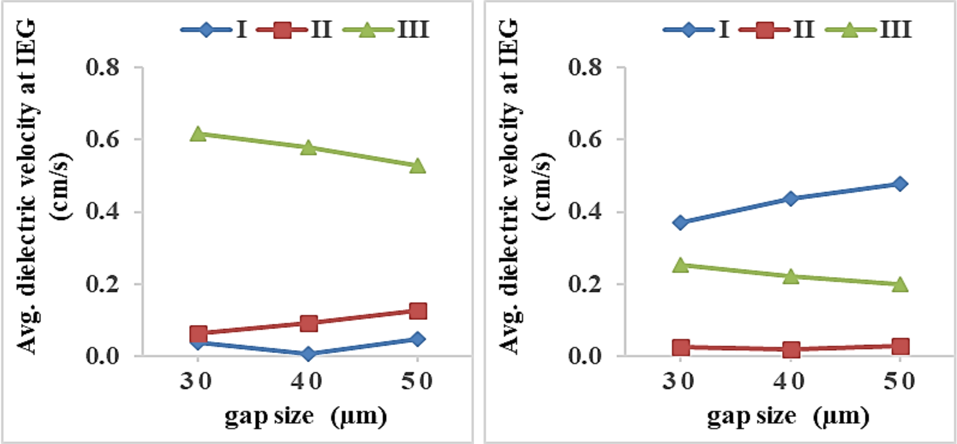
Figure 5.2 Effect of tool rotation speed on the average dielectric velocity at the IEG dielectric in the gap. In case of slotted tool 4, the average dielectric velocity at the workpiece surface is more as compared to near the tool which is exactly opposite for all other tool. The velocity at the centre of the slot is minimum and this is due to the vortex flow created in the slot as the height of slot is more as compared to width.

5.3.2. Effect of interelectrode gap

The gap width is varied and its effect on the average dielectric velocity at the IEG is studied at the tool speed of 500 rpm as given in Figure 5.3. The gap size considered are 30, 40 and 50 µm with the corresponding tool diameters of 540, 520 and 500 µm



(a) Slotted tool 1 (b) Slotted tool 2



(c) Slotted tool 3 (d) Slotted tool 4

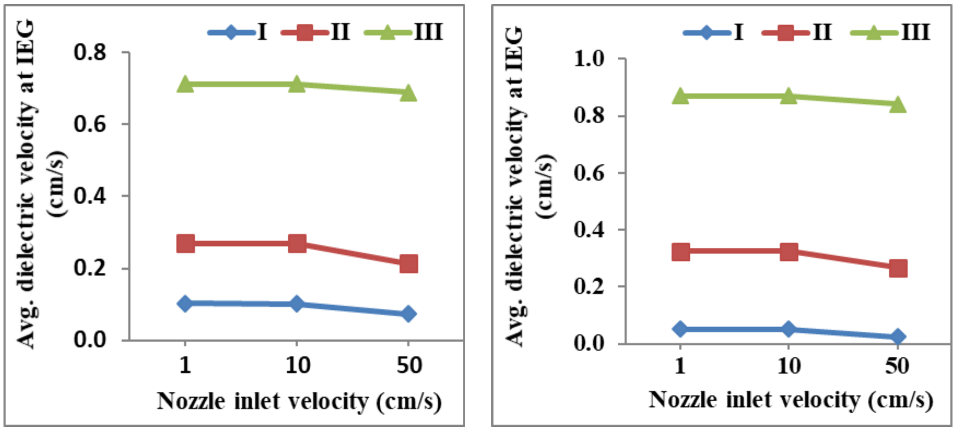
Figure 5.3 Effect of gap size on the average dielectric velocity at IEG respectively to have a constant µchannel width of 600 µm. The inlet velocity of the dielectric is kept constant. It is observed from the figure that at position III near the tool as the gap size increases the average dielectric velocity decreases for all the slotted tools. This is due to the decrease in the tool diameter and the corresponding decrease in the centrifugal force acting on the dielectric. At position I and II, the average dielectric velocity slightly increases with the increase in the gap size. This is due to the higher flow of dielectric in the gap due to larger gap width. The flow-field in case of slotted tool 4 is different as compared to other tools as discussed earlier due to vortex flow in the slot. As the variation in velocity is less even with the small gap width, the flushing will be effective.

5.3.3. Effect of nozzle inlet velocity

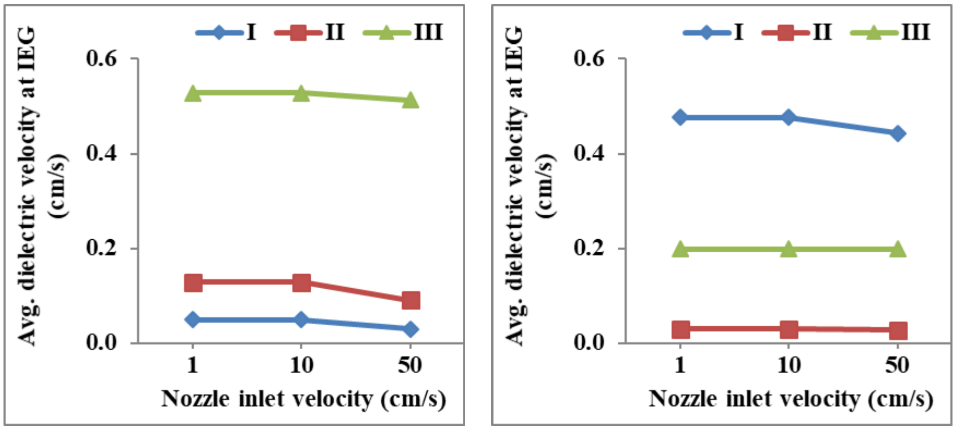
The nozzle inlet velocity is the jet velocity of the dielectric at the entrance of the µchannel to ensure recirculation and flushing of debris. The effect of nozzle inlet velocity on the average dielectric velocity at the IEG is studied. The value of the velocity at the inlet is varied from 0.001 to 50 cm/s and the gap width is kept constant at 50 µm. It is observed that for the inlet velocity between 0.001 and 10 cm/s, the average dielectric velocity in the IEG is constant irrespective of the tool speed as shown in Figure 5.4. However, when the value increases above 10 cm/s, there is a small drop in the average dielectric velocity. This shows that the tool rotation is the major driving force to increase the dielectric velocity in the gap. The slots provided on the tool creates stirring action and disturbs the uniform rotational flow. Due to this, the direction of the fluid changes and it reduces the velocity of the flow. The velocity contour plots of dielectric flow of slotted tool 1 for various nozzle inlet velocity is shown in Figure 5.5. At low inlet velocity, vortex is seen at the back of the tool. The vortex is not symmetrical, it is elongated at one end towards gap inlet and its center is slightly shifted. This happens for all other slotted tools and hence contour plot of only slotted tool 1 is represented here. In case of cylindrical tool, the vortex formed is always symmetrical for different input conditions. At higher nozzle inlet velocity above 1 cm/s, most of the dielectric flows back from the outlet section without affecting the velocity at the IEG.

5.3.4. Effect of change in dimension of tool

The size of the µchannel and the tool is changed without changing the IEG. The size of the tool considered is 300, 400 and 500 µm with the µchannel width of 400, 500 and 600 µm respectively with a constant IEG of 50 µm. This condition can prevail while machining different µchannel width with the same energy conditions. The average dielectric velocity in the gap for different tool diameter using various slotted tool is given in Figure 5.6. With the increase in the diameter of the tool, the average dielectric velocity in the IEG increases at different positions as expected due to higher centrifugal force. In



(a) Slotted tool 1 (b) Slotted tool 2



(c) Slotted tool 3 (d) Slotted tool 4

Figure 5.4 Effect of nozzle inlet velocity on the average dielectric velocity at the IEG

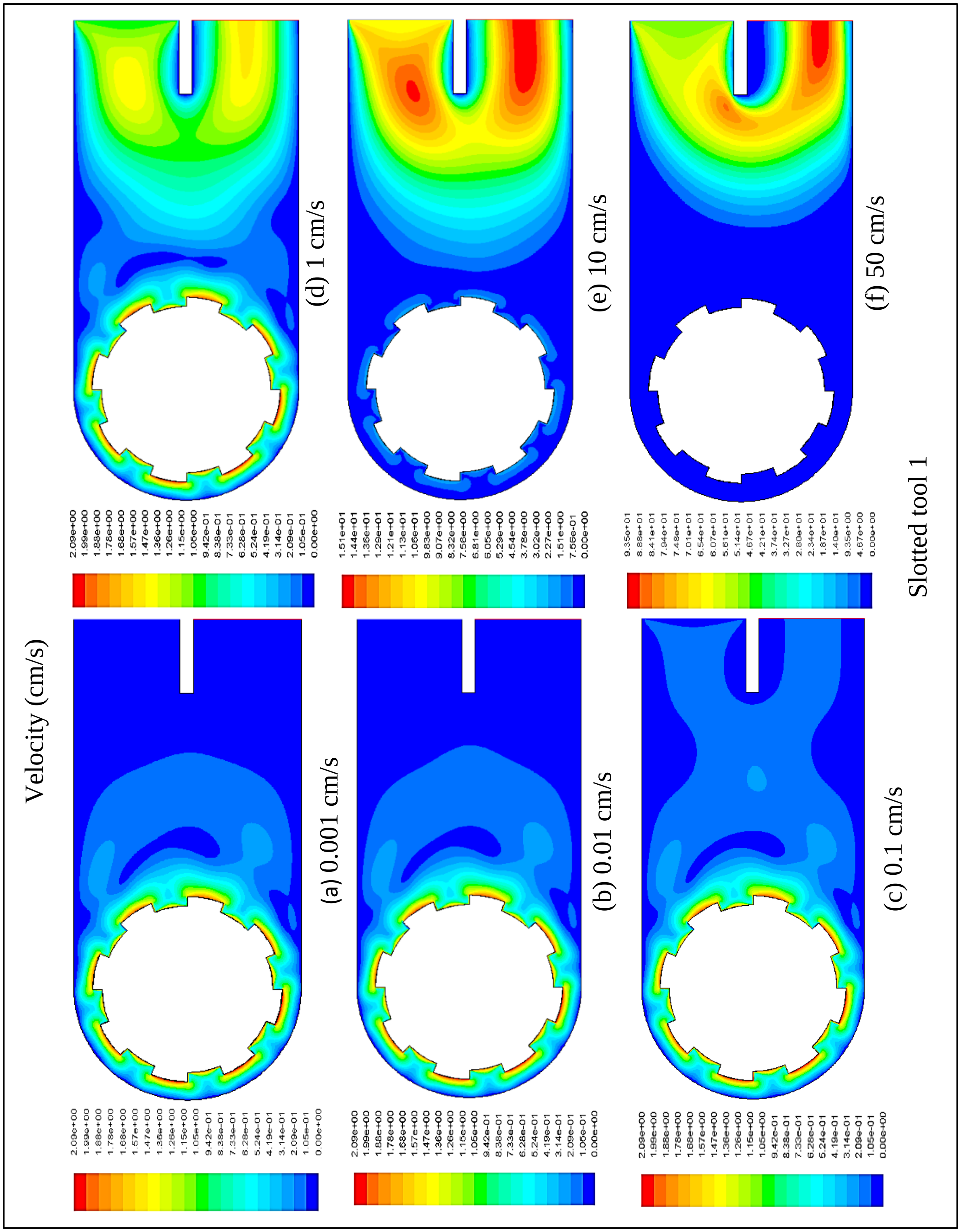
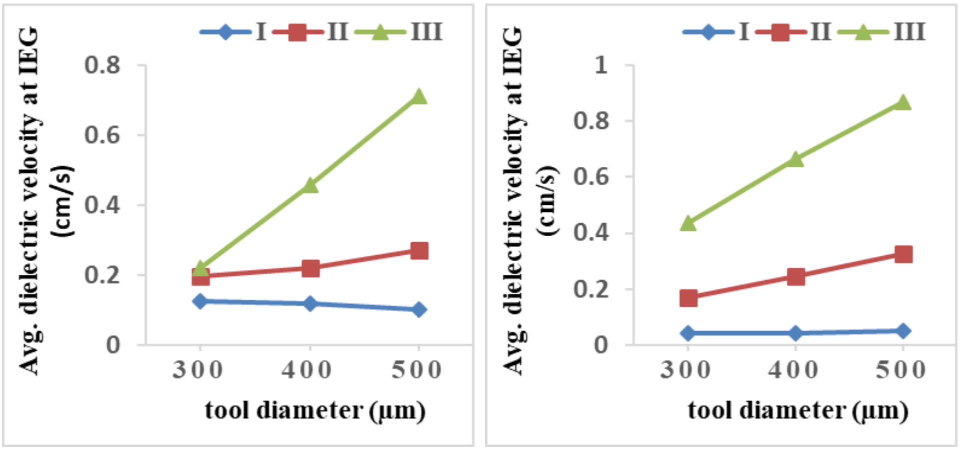
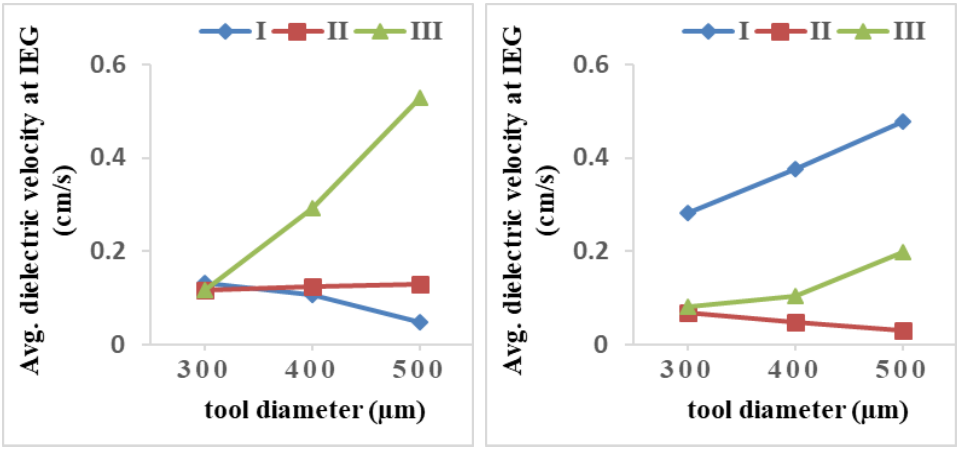


Figure 5.5 Contour plot showing velocity of the dielectric at various nozzle inlet velocity

case of slotted tool 3, where the slot width and height are large the velocity near the workpiece drops with increase in the diameter of the tool. As the slot size increases the dielectric flow in the slot increases creating the void near the workpiece. Due to this, velocity decreases and this is further reduced with the increase in the diameter of the tool as shown in Figure 5.6 (c).



(a) Slotted tool 1 (b) Slotted tool 2



(c) Slotted tool 3 (d) Slotted tool 4

Figure 5.6 Average dielectric velocity at IEG for different tool diameter

5.4 EFFECT OF DIFFERENT SHAPES OF TOOL

The effect of different shapes of tool as represented in Figure 5.1 on the flow-field in the IEG is studied. The contour plots showing static pressure and velocity of the dielectric in the slots of different tools at a tool speed of 800 rpm is shown in Figure 5.7. Large pressure difference is observed in the slot of all the tools. The pressure is maximum on the corner and the edge of the slot (representing the height) in the direction of the flow. While the vacuum or negative pressure is observed on the opposite edge of the slot. This is because the dielectric fluid entering the slot fails to contact the sharp corner due to perpendicular slot edges. In addition to that, when the fluid moves from larger section to smaller section there is vortex flow at the corners reducing the pressure in that region. When the width of the slot is more (slotted tool 2) the pressure in the slot is equally divided into low and high pressure. With the increase in the height of slot (slotted tool 3) pressure in the slot increases.

The velocity contour plot shows large variation of velocity in the slot and it is observed that the velocity near the tool surface is maximum as explained earlier. The velocity at the corners of the slot is less due to inability of the dielectric to flow in that region. Figure 5.8 shows the velocity vector and the values of the average dielectric velocity in the gap at a tool speed of 800 rpm. The average velocity at the primary gap is more as compared to secondary gap for all the cases. The dielectric velocity in the gap varies due to slot size and the number of slots. When the number of slots is more (slotted tool 1) the velocity is minimum due to sudden change in the flow direction of the fluid. The reduction in the number of slots keeping the slot size constant (slotted tool 2) increases the average velocity in the gap. However, increasing the height of slot decreases the average velocity in the gap. In case of slotted tool 4 where the height of slot is considerably more than the width, the average velocity near the workpiece is maximum and it is minimum at the center. The vortex flow is observed in the slot as shown in Figure 5.8.

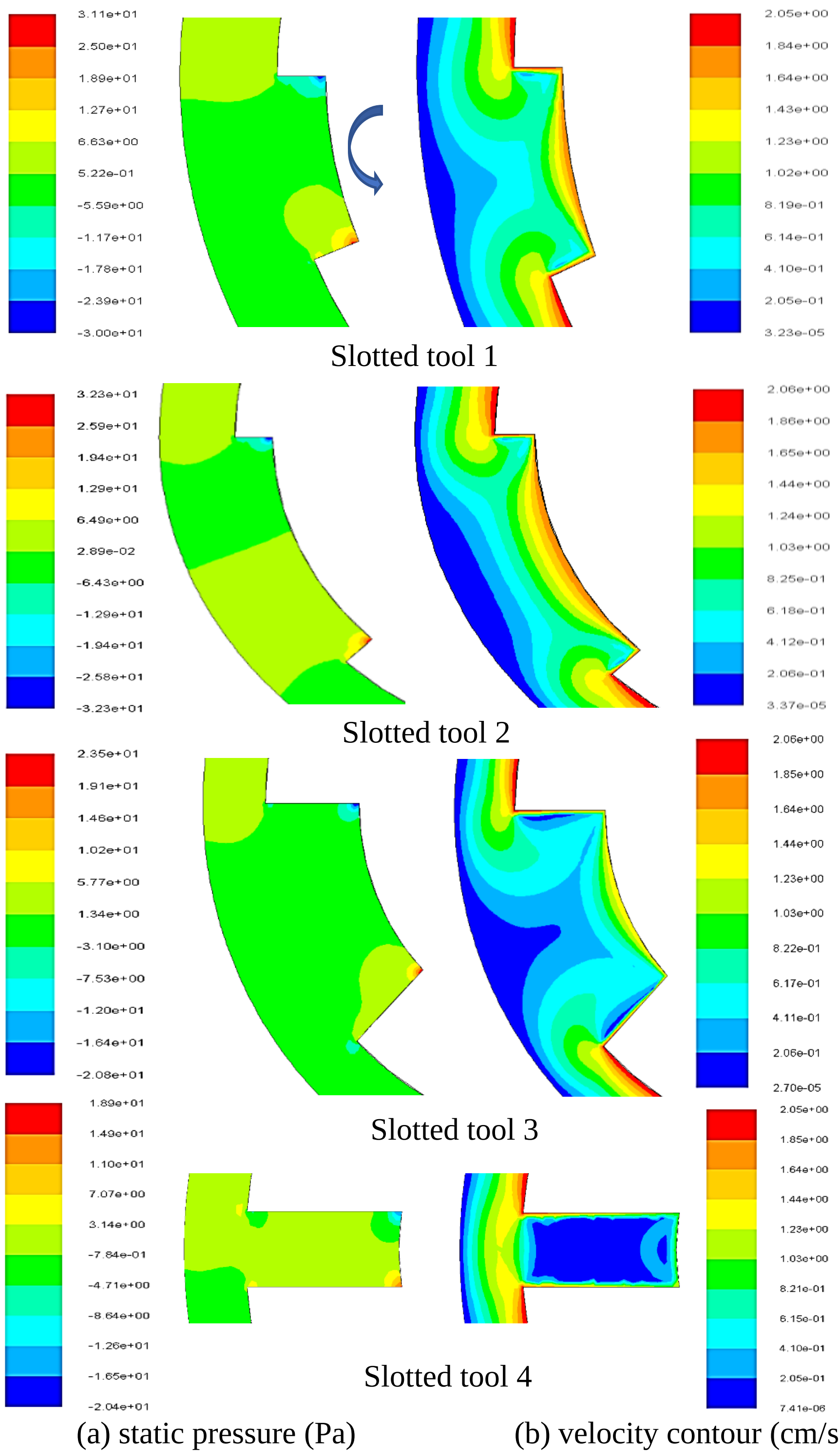


Figure 5.7 Contour plots showing (a) static pressure and (b) velocity of dielectric in the slots of various slotted tools

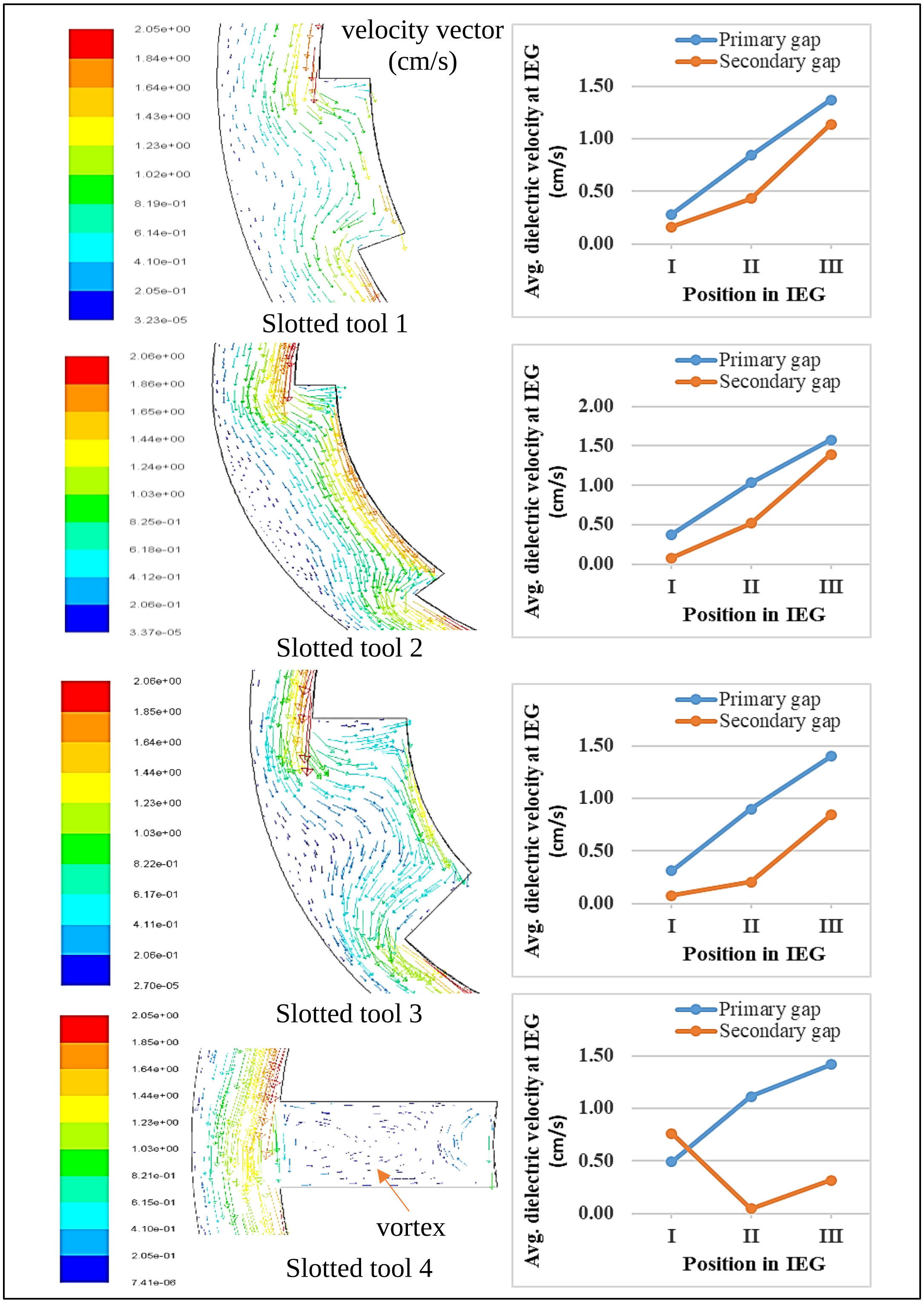


Figure 5.8 Vector plot showing dielectric velocity in the slots of various slotted tools

5.5. PARTICLE TRAJECTORY

The trajectory and accretion of the particles are studied by injecting the spherical steel particles of 8 μm diameter from different positions of the workpiece surface as shown in Figure 5.1. The trajectory of the particles in the gap and the slot of tool is represented in Figure 5.9. When the particles are injected normal to the surface with low velocity, then it travels few distance in the gap and gets dragged from that position due to dielectric flow. In this case, particles do not enter the slots of the tool as the dielectric velocity at the periphery of the tool is higher. It continues to rotate along the periphery of the tool to make multiple rotations and finally gets trapped in the vortex at the back of the tool. However, when the particles are injected with a high velocity of 0.8 m/s it enters the slot as shown in Figure 5.9. This can happen in the μED-milling process where the debris are ejected with a very high velocity due to sudden breakdown of the bubbles.

In case of slotted tool 1 and 2, as the slot height is small the particles injected from the workpiece are not collected in the slot. They travel along the periphery of the tool and get scattered due to stirring action of the tool. In case of slotted tool 3 as the width of the slot is more the particles gets collected in the slot at the IEG and with the rotation of the tool it gets ejected at the back of the tool. This enhances the removal of particles from the IEG. In slotted tool 4, the particles collected in the slot are unable to move out of the slot as the velocity is higher at the outer periphery of the tool. This is necessary to collect and remove maximum particles from the IEG. Particles are continuously collected in the slot reducing the concentration of particles in the IEG. These particles collected in the slot do not affect the sparking process as the gap width is higher near the slot.

Figure 5.10 shows the time taken by the particles and the percentage of particles removed from the gap for different slotted tools. Total 28 particles are injected for 10 ms with a velocity of 0.8 m/s normal to the workpiece surface. Few particles are injected to keep track of individual particles and to avoid flooding of particles in the gap. The time taken by the particles from the injection point to move out of the gap outlet is considered as the removal time and it is calculated for different tool speeds. It is observed from Figure

5.10 (a) that with increase in tool speed the time required to remove particles from the gap reduces and it happens for all the tools. This is due to higher dielectric velocity at higher tool speed. Minimum time is taken by slotted tool 2 to remove the particles from the gap at a tool speed of 800 rpm. However, all the particles are not removed from the gap and 10 % of the particles remain in the gap as shown in Figure 5.10 (b). Among all the tools, slotted tool 4 is able to remove all the particles from the gap irrespective of the tool speed.

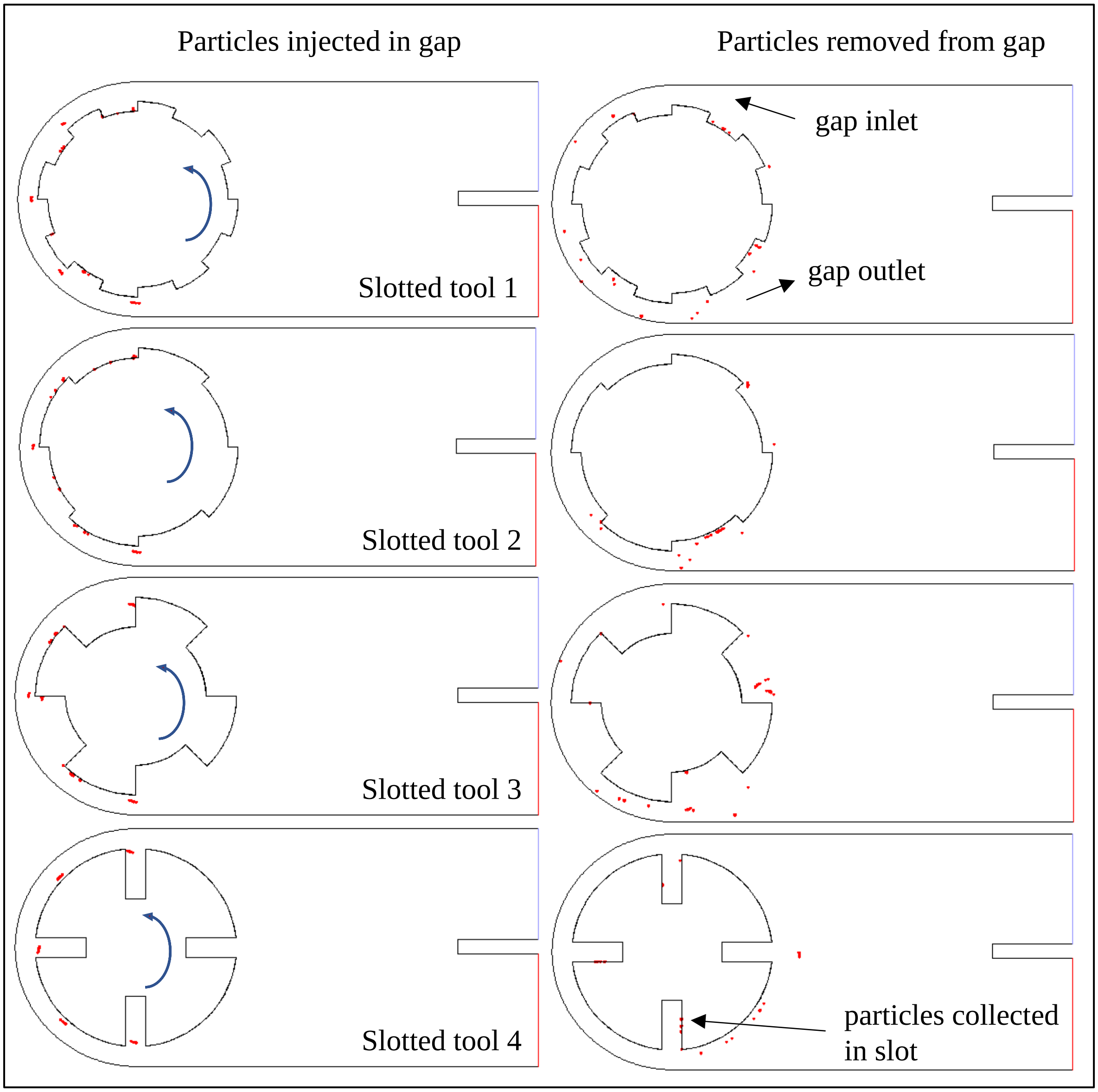


Figure 5.9 Trajectory showing particles injected and removed from the gap

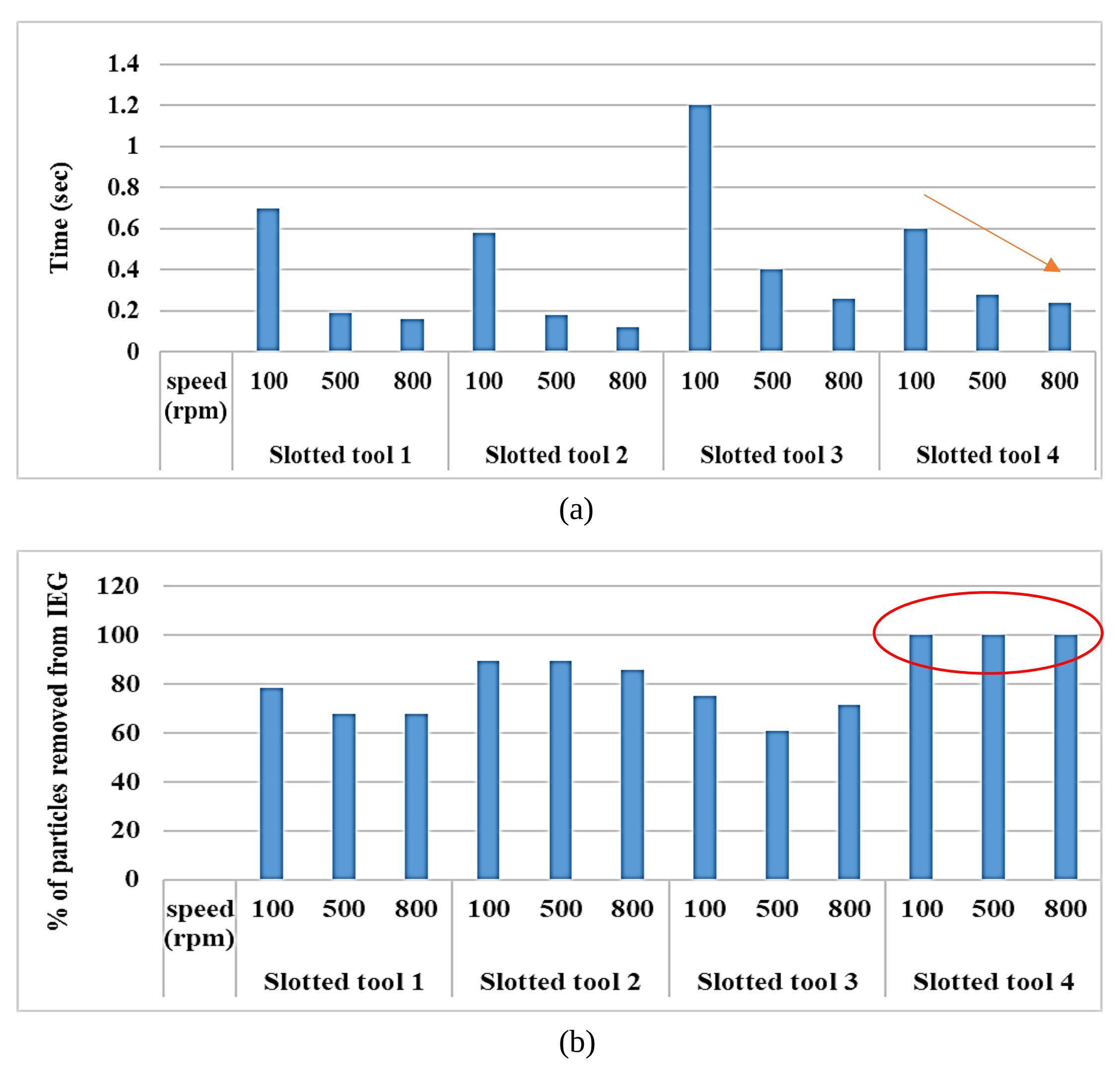
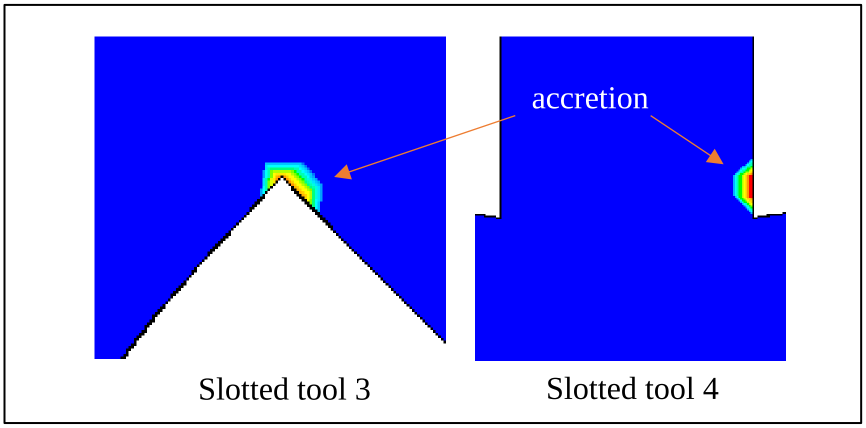


Figure 5.10 Plot showing (a) Time taken by the particles to move out of the gap and (b) percentage of particles removed from the gap for different slotted tools

The contour plots showing the accretion of particles in the slots of slotted tool 3 and 4 is shown in Figure 5.11 and the values for different tool speed are listed in Table 5.2. When the particles are injected at high velocity it hits the corner of the slot and gets accreted in that region. The accretion of particles is mostly observed on the corners of the slot which helps in reducing the redeposition of the particles on the workpiece surface. The particles accreting (accumulating) in the slot does not affect the sparking process as it is not in the sparking zone. The accretion values are recorded at the respective time when the particles are removed from the gap. The values given in table shows that slotted tool 1 and 4 has less accretion.



Slotted tool 3 Slotted tool 4

Figure 5.11 Accretion of particles on the edge of the slot

Table 5.2 Removal rate and accretion of particles

Tools	**Speed (rpm)**	**Time (s)**	**Particles removed (%)**	**Accretion $\times 10^{-4}$ (g/mm^2)**
Slotted tool 1	**100**	0.7	79	0.007
	500	0.19	68	0.120
	800	0.16	68	0.239
Slotted tool 2	**100**	0.58	89	18.045
	500	0.18	89	7.728
	800	0.12	86	22.770
Slotted tool 3	**100**	1.2	75	99.917
	500	0.4	61	2.613
	800	0.26	71	5.696
Slotted tool 4	**100**	0.6	100	0.004
	500	0.28	100	6.498
	800	0.24	100	1.101

5.6. SUMMARY

The study of dielectric flow-field and debris particle movement in the gap is extended to slotted tool. The input variables studied are tool rotation speed, effect of gap size, nozzle inlet velocity, and the diameter of tool. In case of slotted tools, the average dielectric velocity is less as compared to cylindrical tools. The velocity in the primary gap is more as compared to the secondary gap. Large variation of pressure and velocity is observed in the slot due to sharp change in the flow direction of the dielectric. The effect of slot size and shape on the dielectric flow and debris movement is studied. The slotted tool 4 is found best option as the average dielectric velocity is maximum near the workpiece as compared to other tools. In addition, the vortex flow observed in the slot collects the particles entered the slot and the particles are not ejected as high dielectric velocity surrounds the periphery of the tool. Due to this, maximum particles are removed from the gap and the accretion of the particles is considerably less in the slot. The CFD analysis results helped in optimizing the tool geometries. The slotted tools are effective in flushing the debris particles as the slot provided accumulates the debris particles.