INTRODUCTION
Non-contact material removal processes offer numerous advantages over traditional machining approaches and no where is this more apparent than in the fabrication of micro devices. Current micromachining techniques such as microgrinding and micromilling have limitations with respect to their positioning accuracy and tool deflections. Electro thermal processes such as microEDM and laser machining usually result in a heat affected zone being produced. Other approaches such as etching and non-contact ultraprecision polishing are either costly or are not suitable for high throughput. In order to address these limitations, alternative micromachining techniques are required.

In this paper, a non-contact material removal technique based on the electrokinetic phenomenon is proposed for precise material removal at rates in the order of nanometers/min. The aim of this research is to have a better understanding of the electrokinetic material removal technique by studying the trajectory of the particles and the influence of the frequency of the electric field on the material removal rate.

CONCEPT OF PROPOSED TECHNIQUE
The two primary mechanisms that are involved in the material removal technique are the electrokinetic and hydrodynamic effects. Electrokinetic effect on the particles is based on the movement of suspended colloids under an electric field while the hydrodynamic effect is based on the movement of the particles under a fluidic flow.

When a particle is submerged in an aqueous solution, it is charged as the solid interfaces of the particles carry electrostatic charges where a difference in potential is developed across the interface between the two phases. The charged interface of the particle will attract counter-ions and repel co-ions to form an electric double layer. The surface charge of the particles is related to the particles’ zeta potential, size and dielectric constant which can be determined by [1]:

\[ Q_e = 4\pi\varepsilon a\zeta \]  

where \( Q_e \) is the surface charge of the particle, \( a \) is the radius of the particle, \( \varepsilon \) is the dielectric constant, \( \varepsilon_0 \) is the permittivity of vacuum, and \( \zeta \) is the zeta potential of the particle.

As mentioned earlier, one of the primary forces that acts on the particles (normal to surface of the workpiece) to cause surface wear is the electrokinetic force which is mainly governed by electrostatics, given by equation (2) [1].

\[ F_E = Q_e E_{AC+DC_Bias} \]

\[ = 4\pi\varepsilon a\varepsilon_0 \left[ \frac{V_{AC} \sin(2\pi f t)}{d} + \frac{V_{DC\_Bias}}{d} \right] \]  

where \( V_{AC} \) is the AC voltage of the electric field, \( V_{DC\_Bias} \) is the DC voltage of the electric field, \( d \) is the distance between the two electrodes through which an AC electric field with DC bias is applied and \( f \) is the frequency of the AC electric field.

Besides the influence of the electrokinetic effect on the material removal, the other determining factor that acts on the particles (along the surface of the workpiece) to cause surface wear is the hydrodynamic effect of the fluidic flow that is mainly given by the expression:

\[ u = 6U \left[ \frac{1}{4} + \left( \frac{y}{H} \right)^2 \right] \]

where \( u \) is the localized fluid velocity, \( U \) is the general fluid velocity, \( y \) is the height of the localised element of the fluid at the centre of the channel and \( H \) is the height of the microchannel.

In addition, the horizontal component of the particle motion exerted by the flowing fluid was
used to ensure constant, uniform material removal during the material removal process. Figures 1(a) and 1(b) show the idealized movement of the particles when they are under the influence of the fluidic flow with no electric field and an AC electric field respectively. With an AC electric field applied to the particles only, the particles are expected to have relatively few collisions and interactions with the workpiece. Figure 1(c) shows the movement of the particles when they are subjected to DC electric field only where the particles are expected to move towards the workpiece and deposit on the surface of it. It is suggested that the particles would experience cyclic collisions with the surface of the workpiece only under the influence of a combination of AC and DC electric field coupled with the effect of the hydrodynamic flow. During the experiments conducted, dielectrophoresis was considered negligible as there were no electric gradients between the electrodes. Electroosmotic flow was also considered to be negligible as the fluid was a non-electrolyte.

**FIGURE 1.** The expected behaviour of the particles when they are under the influence of fluid flow velocity and (a) no electric field (b) AC electric field only (c) DC electric field only (d) AC electric field with a DC biased.

**EXPERIMENTAL PROCEDURES**

The schematic of the experimental setup is illustrated in Figure 2. A base substrate consisting of a channel for fluid flow that was made of polydimethylsiloxane (PDMS) was fabricated. The base substrate was attached to a gold workpiece with a metallic clamp. The channel in the PDMS was 500 µm wide and 25 µm deep (20 µm after compression during clamping). A voltage potential was subsequently introduced to the electrodes via voltage probes and wires that were soldered onto them. An AC electric field with a DC offset was supplied to the electrodes in such a manner that the workpiece was positively biased while the electrode was negatively biased with the DC electric field. The workpiece then underwent the material removal process for one hour with a syringe pump regulating the flow of the particle (1.5 µm diameter silica particles from Alfa Aesar) suspended fluid (ethanol from Sino Chemical) across the micro-channel. Experiments were carried out to study the influence of the frequency of the electric field on the material removal rate. Throughout the experimental processes, an oscilloscope was used to monitor the voltage that was supplied across the electrodes to ensure that the electric field was of the prescribed amount. Table 1 lists the experimental conditions which were varied and the values selected.

<table>
<thead>
<tr>
<th>DC electric field (kV/cm)</th>
<th>AC electric field (kV/cm)</th>
<th>AC electric field frequency (Hz)</th>
<th>Fluid velocity (m/s)</th>
</tr>
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<tbody>
<tr>
<td>12.5</td>
<td>50</td>
<td>100 ~ 500</td>
<td>0.4</td>
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Material removal was determined by using a combination of white light interferometry (Wyko NT2000 from Veeco), stylus profilometry (Dektak®ST from KLA-Tencor) and scanning electron microscopy (Hitachi S-3500) to determine the depth of material removal. The material removal rate was calculated by dividing the depth of the material removed from the workpiece by the span of time (usually one hour) taken during the material removal process. For each data point on the graph, a total of 10 measurements were made. Outliers from each set of measurements were removed such that a more robust and accurate account on the material removal rate could be reflected. The sample mean and standard deviation of the wear depth for each data point was then calculated and plotted along with a best fit line.

**RESULTS AND DISCUSSION**

Preliminary results seemed to be promising as initial results showed that the electrokinetic...
phenomenon was capable of creating nanometric material removal. This is demonstrated by the results as shown in Figure 3. From Figure 3 (c), it was observed that there was greater material removal at the edges of the channel. This was due to the non-homogeneities of the electric field in the channel where the electric field lines are more concentrated at the edges as the electrical resistivity of the PDMS \((4 \times 10^{13} \text{ } \Omega \text{ m})\) is much greater than that of the ethanol \((1.8 \times 10^{8} \text{ } \Omega \text{ m})\) [2]. This observation corroborated with the profiles that were taken from the workpieces that underwent the process.

![Figure 3](image)

**FIGURE 3.** (a) SEM picture with white arrows pointing to the channel walls (b) WYKO top view image of the material removed from a gold workpiece (c) 2-D profile on the material removed from the gold workpiece in the X direction (direction perpendicular to the channel) (d) 2-D profile on the material removed from the workpiece in the Y direction (along the channel).

A Matlab mathematical model for the vertical trajectory of the particle by solving Newton’s second law under the electrokinetic effect and a multiphysics (COMSOL) simulation based on the fluid velocity acting on the particles were made. The trajectory of the particles obtained mathematically appeared to follow the same trend as the predicted and observed motion of the abrasive particles during the experimentation as shown in Figure 5. Modelling results showed that the velocities in the vertical direction of the particles, when they were in close proximity to the surface of the workpiece, were in the range of around 1 mm/s to 20 mm/s during the experimental processes. On the other hand from the COMSOL simulation, the horizontal velocity of the fluid that exerts on the centre of the particle, when it is in close proximity with the surface of the workpiece, is approximately fifteen percent of the fluidic velocity at the centre of the channel (which is approximately twenty percent of the general flow velocity) as shown in Figure 6. With the resultant velocity of the two components, the particle has sufficient energy to break the metallic bonds of the atoms on the workpiece to create material removal with a relatively similar mechanism as the elastic emission machining where the minimum velocity required for a 1.5 \(\mu\)m diameter particle to break the metallic bond is about 16 mm/s. During the experiments, the influence of the temperature due to the electric field may have an effect on the viscosity and may affect the material removal rate. However, at this stage of the experiment it was not considered.

During characterization of the material removal from the workpiece, the observations obtained suggested that the primary material removal mechanism was a mechanical one. Any other material removal mechanisms were high, the particles were unable to react with the electrokinetic force fast enough to collide with the surface of the workpiece. Fagan et al noted this behaviour as well where they reported that the height levitation of the particles decreased with increasing frequency in a similar setup [3]. It was also observed that the particles were not able to create material removal beyond a frequency of 300Hz. This is likely due to the effect of inertia where the particles’ mass on the electrokinetic response was not great enough to create an impact for the removal of the material from the surface of the workpiece before being pulled in the opposite direction.

![Figure 4](image)

**FIGURE 4.** The influence of the frequency of AC electric field on the wear rate of the workpiece.

Figure 4 shows the experimental results that relate the influence of the AC electric field frequency on the material removal rate of the workpiece. It is observed that there is a clear trend in decreasing material removal rate with increasing electric field frequency. At higher frequency, more particles were expected to collide with the workpiece within a fixed amount of time. However, when the frequency was too
regarded insignificant as there were insufficient evidence. Some of the possible material removal mechanisms include electro discharge machining (EDM) and galvanic corrosion. However, EDM could not be identified as the material removal mechanism as there is insufficient presence of craters to suggest so. Galvanic corrosion could not be the main mechanism also as the fluid that was utilized during the process was a dielectric one. This consequently led us to suggest the mechanical mechanism to be the most prevalent method for the material removal as the net resultant velocity of the particles far exceeds the energy to break the metallic bonds of the workpiece.

CONCLUSIONS

In this paper, the novel technique of using electrokinetic phenomenon for precise material removal was presented. The work demonstrated the influence of the electric field frequency on the material removal rates. By varying the frequency of the electric field, it provided a degree of control over the electrokinetic material removal process. The technique allows precise material removal without the limitations of most traditional approaches.

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REFERENCES