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Analysis of throwing power for megasonic assisted electrodeposition of copper inside THVs

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Abstract

The deposition of increased volumes of Cu down an interconnect through-hole via (THV) of a Printed Circuit Board (PCB) is highly desirable for the fabrication of increasing component density and PCB stacks. A quality metric, called micro-throwing power, characterises the volume of Cu that can be deposited within a THV. In this paper, we analyse the influence of 1 ± 0.05 MHz megasonic (MS) assisted agitation applied to copper (Cu) electroplating baths on the micro-throwing ability of a standard, non-filling Cu electroplating solution. Our results indicate that megasonic agitation is shown to increase the Cu deposition volume within a THV by 45% for an increase of MS pressure from 225 W to 450 W, highlighting the significance of acoustic pressure as a key parameter to control MS THV plating volume. Bulk fluid flow rate within a 500 L plating tank is shown to increase by 150% due to Eckhart acoustic streaming mechanisms, compared to existing bath agitation techniques and panel movement. From MS plating experiments and COMSOL™ finite element acoustic scattering simulations, transducer orientation is shown to influence plating performance, with higher-order acoustic resonant modes forming within THVs identified as the cause. Simulations indicate that higher potential acoustic energy was coupled into a 0.200 mm diameter THV cavity, width-to-length aspect ratio (ar): 8:1, than a larger cavity of diameter 0.475 mm, ar 3.4:1. The maximum acoustic energy coupled into THV cavity is observed for a wavefront propagating along the axis of the cavity entrance, indicating an ideal alignment for the MS plating setup.
Highlights

- 45% THV µ-throwing power increase for MS pressure increase from 225 W to 450 W.
- 150% increase in bulk flow rate due to MS over conventional PCB panel movement.
- Transducer angle dependency on MS THV plating outcome due to higher order mode formation.
- Minimum transducer to PCB distance of 4.5 cm due to unwanted current thieving.

Keywords
Electroplating; Copper; Through-hole via; Printed Circuit Board; Megasonic; Current Thieving

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We would like to acknowledge discussions on the fundamentals of megasonic electroplating, with Dr. Nadia Strusevich at Greenwich University (London, UK) and Dr. Suzanne Costello from the Company MCS Ltd (Roslin, UK).

1 Introduction
The electrical interconnection between individual layers of a Printed Circuit Board (PCB) is referred to as a vertical interconnect access (via). The via enables the transmission of power and data to the individual active and passive electromechanical components, which can either be soldered on or embedded in the PCB. Reductions of the diameter of a via whilst maintaining the depth at which it is drilled into the PCB, reduces its occupying space on the board and increases its width-to-length aspect ratio ($a_r$). Such increases enable a higher density of components to be soldered to a PCB increasing its functionality and value. The global PCB market is expected to show a compound annual growth rate of 3.2% from 2018 to 2022, reaching a total value for the global market of $72.6$ Bn. This growth is driven by smart phones, tablets and by growing automation in industries such as, automotive, aerospace and defence
The UK PCB market caters to high density, high value boards and an increase to the component density, whilst maintaining the same fabrication costs, is a high priority to UK manufacturers [2].

Seminal results from the authors showed that a new manufacturing process implementing high frequency megasonic (MS) (1 ± 0.1 MHz) assisted agitation in a copper (Cu) electrolyte solution, increased Cu volume electrodeposited down PCB via interconnects, reducing the plating duration beyond current industrial capabilities [3–6]. The plating enhancement was attributed to two effects, a) reduction of the Nernst diffusion layer by acoustic streaming mechanisms [7,8], increasing the limited current plating value that opens up access to higher plating rates and faster processing times, and b) replenishment of Cu electrolyte transport down difficult-to-plate regions [9,10], due to improvements to acoustic streaming [11]. Specific enhancements have been obtained within through-hole via (THV) interconnects. A THV provides electrical interconnection through the PCB and between the internal layers as a buried via. The fabrication of THVs of different diameters (0.450 mm, 0.325 mm and 0.150 mm), is important to enable PCB designers to fit and distribute soldered electrical packages across the PCB surface. Previous studies have shown that the uniform filling of THVs of diameter 0.2 mm, *ar* 8:1, without filling chemistry, was possible through the introduction of MS plating [4,6]. Recent studies by the authors [3] have shown a variation in MS plating behaviour which is dependent on the feature size of the THV and the resonant acoustic phenomena formed within the THV. This phenomenon includes microfluidic streaming and the formation of acoustic standing waves. Plating with 1 MHz acoustic agitation and THV of diameters equal to and larger than 0.3 mm, *ar* 3.4:1, demonstrated a reduction in plating efficiency, indicative of unknown interactions between MS within certain plating scenarios. In other *ar* variants, results demonstrated a greater plating efficiency and quality in THVs of diameters smaller than 0.3 mm.

The tangential distance and orientation of the transducer are important processing conditions, that influence the pressure and mode of the acoustic wave formed within the THVs [12,13]. The current work today by the authors has focussed on tangential alignments of the acoustic transducer to the PCB. Little research has been performed to quantify changes in MS THV plating capability in response to changes in transducer orientation to the PCB, by ourselves or other research groups. Improvements to the total volume of Cu deposited down a THV during a plating cycle, can also be made from alterations to the electrical current density and the plating current waveform [14]. Reducing the current density and introducing a reverse
cycle during plating increases the total Cu volume plated, helping to reduce processing time and product turnover. Changing the acoustic pressure output and reducing the tangential distance of the transducer to the PCB, increases the acoustic forces reaching the PCB and the acoustic streaming mechanisms essential to high quality MS plating.

If an electrically conductive surface with grounding is placed into an electroplating bath alongside a PCB, applied current will be driven towards both electrical surfaces, decreasing the total current density on the PCB. This additional electrode is then said to act as a current thief. With acoustic transducers setup in a plating cell, the surface of the transducer can act as a current thief, reducing the current received at the PCB [5].

To provide further insights into the unexplained acoustic phenomena, experimental and simulation studies have been performed looking to identify:

a) the factors influencing the poor performance on THV diameters equal to and larger than 0.3 mm and

b) the changes to plating settings which can improve MS plating performance.

A series of plating trials have consequently been performed for which the angle of the transducer and its distance to the PCB surface have been altered, to identify the conditions maximising process quality. Finite element multiphysics simulations using COMSOL™ have been carried out to explore the complex phenomena that evolve during the interaction of the resonant acoustic waves within the THV. The plating trials along with the simulations help to identify which parameters are negatively influencing the behaviour witnessed down 0.3 mm diameter THVs [3]. To highlight further improvements to the plating of THVs and identify ideal operating conditions, studies are made looking to increase the Cu volume deposited by MS plating down 0.3 mm and 0.15 mm THVs, in response to changes to acoustic power, electrical current density and electrical waveform characteristics [5].

A series of plating trials were performed, to observe whether current thieving can be observed with the 1 MHz transducer. This was evaluated by looking at how plating rates on a PCB surface vary on changes to the tangential distance of the transducer from the PCB, as any Coulombic attraction by the transducer surface will decrease with distance from the source, i.e. the anode [15]. To ensure the greatest uniformity and highest output of MS streaming onto the PCB surface, investigations were also performed looking into how the transducer position alters bulk fluid flow rates.
In this paper we detail in Section 2 the experimental conditions. In Section 3, results and discussion for the different investigations are presented and lastly, Section 4 presents the conclusions of the work.

2 Experimental

2.1 Bulk fluid flow observations

The plating performance of Cu is heavily influenced by fluid convection within a bath, as the replenishment of Cu ions is provided from the forced agitation of the electrolyte solution around the PCB. Bath convections are shaped by the fluid pump, panel movement and sparge-pipe bubble agitations. The introduction of MS agitation introduces a fourth bath convection mechanism. As such the macroscale fluid flow streams in the bath can be visualised using food dye colourant flowing through the bath, with a Genius™ webcam installed above the plating bath as highlighted in Figure 1A. The trials are set up by installing the transducer in positions \( a \) to \( c \), highlighted in Figure 1B by the grey rectangles, where position \( c \) is oriented at 45° to the PCB. At each position a recording of the fluid flow is obtained, where the dye is added in front of the transducer to the positions numbered in A. MS acoustic waves are emitted from the device at 100% output corresponding to 450 W, with an orientation indicated by the arrows. From the recordings, an approximation for the fluid flow rate around the PCB is made, by measuring the distance travelled by the colourant over time. Sparge pipe agitation is not applied in the investigation as this agitation induces a chaotic flow making fluid motion observation not possibly with the dye.

![Figure 1 - Schematics of the plating bath setup for without the transducer A) and with B) as shown in different orientations and positions – a to c - by the grey rectangles. The orientation of the emitted acoustic wave is highlighted by the arrows. Two PCBs, highlighted in yellow of area 28.0 dm² have been placed stationary within the bath.](image)


2.2 MS plating setup

The plating investigations were performed on 28.0 dm$^2$, FR4 PCBs obtained from Ventec Ltd, (FR-481, Cu thickness 18 µm). The PCBs are drilled with THV features of diameters 0.475 mm, 0.325 mm and 0.15 mm (± 0.025 mm), using a Schmoll Maschinen GmbH Ltd mechanical drill. Prior to electroplating, the PCBs were uniformly plated with 1 – 2 µm of electroless Cu using the MacDermid Ltd process. Electroplating is performed in a medium size 500 L plating tank using soluble Cu anodes. An ideal Cu electroplating finish is characterised by a fine grain structure and high ductility; for this reason, the plating solution chosen in this work was the proprietary solution SLOTOCOUP CU110 supplied by Schloetter Ltd, which comprised of 80 g/L copper sulphate, 100 ml/L sulphuric acid and 80 mg/L chloride. Additional, chemical proprietary additives Cu 111 (5 mL/L) and Cu 114 (5 mL/L) were included in the solution. The electroplating schematic is highlighted in Figure 2. The tangential distance of the anode basket to the cathode PCB is 21.6 cm. This setting had been optimised previously by the collaborating company Merlin Circuit Technology Ltd. for the plating bath geometry, as it maximises plating uniformity across a PCB [16]. The distance between the transducer and PCB is represented by $x$ and the angle of orientation of the transducer is given by $\theta$. The transducer was supplied by Sonosys$^\text{TM}$ Ltd and is a square-faced submersible composed of four rectangular piezo-transducers, of size 2.5 cm by 11 cm, embedded in a steel sheet of 1.03 dm$^2$ area. The PZT outputs a 1 ± 0.05 MHz, acoustic wave with a variable power, where at 100%, 500 W of electrical power is supplied to the piezoelectric emitter, which is converted to acoustic power output with a conversion efficiency of approximately 90%. In all setups the acoustic wave within the bath was unidirectional due to the small beam spread angle attributed to high frequency acoustics [17] and covers an area approximate to the area of the transducer face.
Figure 2 – Not-to-scale schematic of the plating cell setup indicating a tangential distance $x$ from PCB to transducer and the angle orientation $\theta$, of the transducer to PCB. Acoustic waves propagate from right to left.

The Cu plating solution used was SLOTOCOUP CU110 and is formulated for direct current (DC) and reverse pulse (RP) plating. DC and RP plating modes are both used in the report with settings applied as outlined in Table 1. RP electroplating is the most common electrical waveform applied in PCB manufacturing, as it provides the largest deposition and the most uniform plating of Cu down via holes [18]. RP current comprises of reverse ($r_v$) and a forward ($f_w$) components, whose magnitude and duration are set before plating. The $f_w$ and $r_v$ pulse durations for the experiments are 10 ms and 0.5 ms, respectively, and are a standard setting for RP plating. The RP current density magnitudes applied are 0.5 A/dm$^2$ and 1 A/dm$^2$ in a 1:2, forward:reverse plating setting. In this work the magnitude settings are varied to investigate their influence as outlined in Table 1.

2.3 Plating efficiency evaluation

During electroplating, the efficiency of the plating reaction is carefully maintained through the operation of the plating rectifier and the bath chemistry. When introducing MS agitation into the plating bath the chemical behaviour is affected by the forced fluid convection through the vias. For this reason, the ability to force fluid into via features defines the plating quality. Figure 3 shows a schematic cross-section of a THV, with regions highlighted displaying different plating rates. The surfaces of the THV typically receive the highest plating rate. This rate drops further down the via. The quality of the plating was quantified either directly by measurements of time-average plating rates at a given location, or by using the micro-throwing power. Micro-throwing power is defined as,
\[
\text{Micro — throwing power in THV} = \frac{\text{Average plating rate in middle}}{\text{Average plating rate on surfaces}} \tag{1}
\]

The plating thickness was measured directly through the use of a microscope after having processed samples using microsection techniques [19].

\[\text{Figure 3 – (Colour online) 2-D Schematic of the Cu metal thickness distribution (yellow) obtained at different positions within a THV (green) for plating under DC and with non-filling chemistry.}\]

A Nikon Labophot™ was used to obtain images of the microsections. The plating rate was also evaluated across the entire surface of a test PCB. This was determined by measuring the mass of the PCB before and after electroplating, using an Ohaus Explorer measuring balance. The increase in weight provides a measurement of the amount of Cu electroplated. From this value, the amount of Cu deposited tangential to the PCB surface is evaluated by dividing by the value for Cu density, to give the volume of Cu deposited. This volume is then used to define the plating rate by using the total area plated and the duration.

2.4 Experimental conditions

To address the issues of the poor performance witnessed down THV of size 0.3 mm and larger and to improve performance, the aims of our experiments were to investigate a) the ideal configuration of the transducer within the 500 L bath; b) the streaming behaviour occurring on a macroscale within the bath; and c) the plating quality obtained down THV when processing under manufacturing conditions. In this analysis, we were looking to understand how changes to THV diameter, transducer positioning, acoustic output, electrical current density, and the variation when applying DC and RP plating, alters the quality of the
deposition. COMSOL version 4.3b was used to model the hydro-acoustic behaviours of the MS within THVs alongside some of the experiments. The simulation settings along with the plating settings used in the experiments are listed in Table 1. The plating was performed for a duration to maximise the amount of Cu plated down the THV. As such, for section 3.3, the plating was performed for each setup of the transducer until the THV entrance closed, after which Cu was no longer deposited down the THVs. For different transducer positions applied in section 3.3 the total plating time was approximately 16 hours for each setting.

Table 1 – A list of the experiments performed with their parameters and simulation settings.

<table>
<thead>
<tr>
<th>Section</th>
<th>Parameter altered</th>
<th>PCB Settings</th>
<th>Transducer</th>
<th>Plating Settings</th>
<th>Cavity feature simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PCB area (dm$^2$)</td>
<td>Via diameter (± 0.025 mm)</td>
<td>Electrical waveform &amp; Current Density</td>
<td>Duration (hour)</td>
</tr>
<tr>
<td>3.1</td>
<td>Transducer tangential Position</td>
<td>2.94</td>
<td>-</td>
<td>Position x = ∞, 1.0 cm, 4.5 cm &amp; 8.0 cm</td>
<td>DC at 1.5 A/dm$^2$</td>
</tr>
<tr>
<td>3.2</td>
<td>Position &amp; orientation of transducer</td>
<td>28.0</td>
<td>-</td>
<td>Positions a, b and c</td>
<td>Power output: 450 W</td>
</tr>
<tr>
<td>3.3</td>
<td>Transducer orientation and tangential distance</td>
<td>4.64</td>
<td>0.475</td>
<td>0° orientation, 450 W</td>
<td>DC at 1.0 A/dm$^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25° orientation, 450 W</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45° orientation, 450 W</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53° orientation, 450 W</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90° orientation, 450 W</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not in bath</td>
<td>16.0</td>
</tr>
<tr>
<td>3.4</td>
<td>Changes to the electrical current density magnitude and waveform, and acoustic pressure</td>
<td>4.64</td>
<td>0.325</td>
<td>x = 8 cm and 225 W</td>
<td>DC at 1.0 A/dm$^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DC at 0.5 A/dm$^2$</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DC at 1.0 A/dm$^2$</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DC at 0.5 A/dm$^2$</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x = 8 cm and 0 W</td>
<td>DC at 1.0 A/dm$^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DC at 0.5 A/dm$^2$</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x = 4.5 cm and 450 W</td>
<td>DC at 0.5 A/dm$^2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RP at 1.0 fw 2.0 rv A/dm$^2$</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RP at 0.5 fw 1.0 rv A/dm$^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DC at 0.5 A/dm$^2$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x = 1.0 cm and 450 W</td>
<td>RP at 0.5 fw 1.0 rv A/dm$^2$</td>
</tr>
</tbody>
</table>

3 Results and Discussion

3.1 Current thieving

Figure 4 shows the average plating rate for Cu deposited across the entire surface of the PCB with the transducer set up in the bath at different positions. No MS agitation was undertaken in order to establish a baseline deposition rate. The plating rate remains unchanged with the PCB placed at a distance of 4.5 cm and above away from the transducer. At 1 cm away from the transducer, the plating rate decreased by 8% indicating that current thieving occurs as the electrical current is attracted by the stainless steel surface of the transducer, thereby
reducing the total amount of Cu deposited on the PCB surface. The transducer acts as a current thief due to the electrical grounding. Removing the grounding is possible through the addition of a non-conductive layer upon the surface although acoustic power conversion efficiency might decrease if proper acoustic impedance matching is not carried out. The transducer distance was therefore placed at a minimum distance of 4.5 cm from the PCB in subsequent experiments.

Figure 4 - Average plating rate measured with transducer set up at a tangential distance x to the PCB surface. No MS agitation was undertaken.

3.2 Acoustic streaming movement within bulk flow

Figure 5A highlights the motion of the red dye within the acoustic streaming current at times 0 s, 5 s and 11 s for transducer setup a. The dye is transported from the left to the right by the acoustic streaming currents. The flow rates were evaluated and were summarised for all of the transducer setups as shown in Figure 5B, highlighting flow orientation and its approximate flow rate under MS agitation. With the transducer added and switched on, the maximum and minimum flow rates are 7.5 cm/s and 4.5 cm/s, respectively, which are approximately 150% and 50% faster than the flow rates obtained under standard bath agitation at the same locations, due to Eckhart streaming [11]. These results complement simulations performed in modelling the bulk fluid flow behaviour within a plating tank of similar size under MS agitation [4]. The transducer device surface is small (1.03 dm$^2$) relative to the
surface of a PCB and the bath cross section area, 28 dm$^2$ and 86 dm$^2$ respectively. The MS streaming slows by 40% at it propagates over 67 cm, which is due to attenuation and dispersion of the wave. To induce a larger streaming flow onto the PCB, close transducer distances should be applied whilst minimising current thieving effects. When the transducer is introduced at a 45° angle to the PCB, the acoustic streaming flow spreads over the surface of the PCB as indicated by position $c$ shown in Figure 5B. To achieve a larger coverage of the acoustic wave across the PCB, an angled orientation of the transducer could be applied.

![Figure 5](image_url)

*Figure 5 - A) top-down photographs of red dye added to position a. with the acoustic stream propagating from left to right and two 46 cm by 61 cm PCBs in bath, and B) a schematic summarising the direction of the fluid motion and velocity for the transducer switched on at locations a, b and c.*

### 3.3 Plating down THV in response to angle variation

Table 2 presents micro-section images of THVs cut within ± 25 μm of their diameter and plated using MS agitation under different orientations of the transducer. Cu features of differing periodic thickness are witnessed down the THV. The plated pattern shows similarity with resonant standing wave Cu features, observed for MS plating THV diameters greater than 0.3 mm [3]. More specifically, changes in the plated thicknesses along the hole of the THV are strongly correlated with the position of the acoustic standing wave pattern generated within
the THV, such that around pressure nodes (white positions) and pressure antinodes, (red and blue regions), a local decrease and increase of the plated Cu is observed, respectively. This behaviour is accredited to electrolyte transport within the die, where, at regions of low transport (pressure nodes), the plating of Cu is hindered [3]. For angles close to 90° the plated pattern resembles the plating conditions without MS plating and the application of standard bath agitations – a tear shaped void in the centre of the THV with bulging deposits at the entrance. For these angles the Cu deposit is greater down the THV.
Table 2 - Plating rate measured in the middle of 0.475 mm for ar of 3.4:1. Cross-sections of THVs in response to angle orientation of the transducer, with corresponding COMSOL simulated acoustic scattering distributions and simulation scale bar showing normalised units of acoustic pressure. Table includes THV plated under standard agitations without MS and simulation schematic.

<table>
<thead>
<tr>
<th>Angle of Acoustic agitation (± 5°)</th>
<th>Micro-section Image (± 25 μm)</th>
<th>Acoustic pressure scatter distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td><img src="image1" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>25°</td>
<td><img src="image2" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td><img src="image3" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>53°</td>
<td><img src="image4" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td><img src="image5" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>N/A</td>
<td><img src="image6" alt="Image" /></td>
<td></td>
</tr>
</tbody>
</table>

FR4 PCB

Electrolyte

FR4 PCB
COMSOL™-based modelling simulations of the 2-D acoustic scattering distribution within the THV cavity have been carried out for different orientations of the acoustic wave. The simulation output for the wave travelling from left to right at a particular orientation, is displayed in Table 2 alongside its corresponding micro-section image. The simulation modelled acoustic pressure inside and outside the FR4 PCB. The acoustic pressure distribution inside the THV indicates the formation of an acoustic standing wave, stemming from the superposition of two waves travelling in different directions. In the case of the THV, the travelling wave passing through the cavity meets its reflection, which forms due to the incoming wave being reflected at the end of the opening due to impedance mismatch between the inside and outside of the THV, to form fixed regions of varying pressure [20]. A standing acoustic pressure wave comprises of fixed positions of pressure, where at a pressure node zero change in pressure occurs and at a pressure anti-node, pressure values are at a maximum or minimum. The pressure nodes are represented in the plot by white and the antinodes by the darker red and blue regions. The simulation is static in time and as such, the localised regions of high and low pressure invert to one another over time, although remain at fixed positions within the cavity for a fixed orientation of the incident wave [21,22].

The pressure distribution varies as the angle of the acoustic agitation is changed. Absorption and transmission of the acoustic wave are influenced by the specific acoustic impedances of the FR4 structure and the water fluid medium [23]. For FR4 in the simulation, its value is $6.84 \times 10^6$ Pa.s.m$^{-1}$ and for the electrolyte medium, $1.48 \times 10^6$ Pa.s.m$^{-1}$. As the electrolyte specific acoustic impedance is higher in the FR4, it hinders the propagation of the wave, absorbing and reflecting the acoustic energy, and altering the phase of the travelling wave, to generate the pressure distribution patterns witnessed within the cavity structure, for the different orientations of the acoustic wave. As the angle of the transducer is increased towards a 90° orientation, the acoustic pressure reduces within the cavity - observed by an increase in white region areas in the pressure plots.

Measures of the total pressure are obtained within the simulated 2-D via cavities in response to acoustic propagating orientation. From these, the average potential energy density (PED) is evaluated, describing the displacement of an infinitesimal element from equilibrium position in response to the acoustic wave. It is given by:

$$PED = \frac{<p^2>}{2\rho c^2}$$  

(2)
where $<p^2>$ is the average squared pressure over an area, $\rho$ the density of the medium and $c$ the speed of sound in the medium. In the simulation the PED is evaluated over a selected area using approximated values for the sound speed and density of the medium [24]. The PED results are plotted in Figure 6 as a function of the angle of orientation of the incident MS wave, for cavities of diameters 0.2 mm, ar 8:1 and 0.5 mm, ar 3.2:1. The two sizes were chosen as they represented conditions where MS plating enhancement was and was not observed, accordingly [3]. Both cavities show that the acoustic energy is minimised when the travelling wave front is tangential to the THV cavity entrance, $90^o$ and is at a maximum when parallel, $0^o$. The two cavities were simulated with the same initial background pressures and so the data were normalised with respect to the largest value measured.

![Figure 6 - A plot of COMSOL simulated average potential sound energy density within the THV cavity in response to sonicating angle.](image)

The small cavity couples a larger PED (260 % more PED at $0^o$) than the large cavity. For both cavities the pressure coupled into the THV at this angle is significantly larger than the input pressure, which indicates that the superposition of the wave within the cavities is due to constructive interference - focusing the acoustic wave. The small cavity case is more
sensitive to misalignment of the acoustic wave, where a change from 0° to 20° results in a 50% drop in acoustic energy, compared to a 40% drop for the large cavity case.

The plated results show that a thicker plated deposit is obtained at larger angles and that Cu uniformity resembles that achieved in standard processing without MS. The acoustic PED is minimised at these angles, negating the acoustic effects on the plated deposit - which appear to negatively influence plating on 0.5 mm diameter THVs. The results highlight that changes to the transducer orientation do not yield any greater MS plating enhancements for 0.5 mm diameter THV. Plating studies were not performed changing the acoustic angle for THV 0.2 mm. It is likely that they would show the opposite - a reduction in Cu volume plated for changes of tangential orientation.

Rayleigh streaming vorticity is a resonant acoustic phenomenon observed within the fluid motions of an acoustic standing wave [22]. Standing waves formed within the THV cavity encourage the formation of vorticity motions, which are smaller than the size of the channel [25]. These motions are chaotic and can hinder the transport of electrolyte solution through the THV channel [26]. MS plating enhancement was obtained in [3] for THV of dimensions smaller than those tested here - 0.15 mm by 1.0 mm at $ar \ 5.7:1$, compared with 0.5 mm by 1.6 mm at $ar \ 3.2:1$. The smaller THVs are closer to the size of the acoustic wavelength in the electrolyte medium (1.4 mm) and the FR4 structure. When a THV cavity is of dimensions similar to the acoustic wavelength, i.e. within the long-wavelength limit [27], acoustic streaming motions are jet-like [28]. In the case of the MS plating of THVs, when its dimensions are within the long-wavelength limit of the MS wave, MS enhancements to plating are possibly obtained due to the jet-like microfluidic transport produced under these conditions. As such, the introduction of an MS wave of slightly lower frequency and longer wavelength, could lead to acoustic streaming down the 0.5 mm THV and enhanced MS plating.

This study considers acoustic wave formation with Cu deposits on the THV cavity walls, orders of magnitude smaller in size than the acoustic wavelength in solution. As such, the Cu deposit thickness has negligible influence on the acoustic wave pattern produced. During plating, the walls of the THV become thicker due to Cu build-up, to the point where its influence can no longer be neglected [3]. When the Cu walls of the THV are sufficiently thick they will reduce the diameter of the THV feature altering the acoustic mode formed within the THV and the PED coupled in, as indicated in Figure 6.

Additional resonant acoustic effects hindering the propagation of acoustic waves, is the presence of cavitation micro-bubbles formed due to pressure changes by the MS wave near to
or within the THV fluid cavity [5]. Reflections of the acoustic wave off these bubble features can excite higher acoustic modes within a pipe, altering acoustic streaming motions to unfavourable conditions [29]. Conversely microfluidic motions around cavitation bubbles can increase by several orders of magnitude enhancing fluid transport [30,31].

3.4 Micro-throwing power increase down THVs

Plating trials were performed on 0.325 mm THV to identify if MS plating enhancements could be obtained on this feature size with changes to DC current density and acoustic power output. Figure 7 shows plots of the micro-throwing power and indicates that the lowest micro-throwing is obtained for 1.0 A/dm² and 225 W acoustic output. Lowering the current density to 0.5 A/dm² reduces the plating rate on the surface and down the THV, but allows for a greater replenishment of depleted ions. As such, the MS agitation is more effective and the micro-throwing power increases for all applications of acoustic power. The electrical current density is an important property controlling the rate at which Cu is deposited. For a high current density, the plating rate is fast and the Cu deposited in the middle of the THV should be high. When using DC plating currents the opposite occurs however. The replenishment of electrolyte down the THV is controlled by the bath fluid agitation. If the replenishment rate does not increase alongside the deposition rate, then the rate of depletion overcomes repletion, reducing Cu concentration and preventing deposition [32]. This is an unwanted result as it leads to reduced plating rates in the centre of the THV relative to the PCB surface, which is counter to the goals of depositing Cu down THVs. As such, a low current density should produce an enhanced micro-throwing power down the THV.

An increase of acoustic output to 450 W enhances the micro-throwing power further for both 0.5 A/dm² and 1 A/dm². This is most likely due to increased replenishment of Cu cations due to the larger acoustic forces driving the solution through the THV [5]. The results highlight that higher MS plating efficiencies are obtained for lower current densities, when the acoustic power is maximised. Regardless, the plating efficiencies obtained are comparable to those obtained under standard plating agitation conditions without MS, which are highlighted as 0 W at 1 A/dm² on the plot. Plating was performed at 0.5 A/dm² and with 0 W. The micro-throwing power reduced compared to 0 W, 1.0 A/dm² setting. Plating with a DC current at 0.5 A/dm² induces a high plating variation due to the negative influence of low plating currents on the plated Cu finish [5], resulting in a slightly lower micro-throwing power.

The MS plating performance down the 0.325 mm THV here, shows a micro-throwing 45% greater than in [3], due to a 50% increase in MS pressure output. The 0.325 mm, diameter
THV at ar 3.4:1 is larger than the acoustic wavelength in the electrolyte solution and so, the THV is within the short-wavelength limit, and not the desirable long-wavelength limit for which MS plating enhancement is observed [3]. As such, standing waves form within the THV due to the excitation of high order acoustic modes, hindering acoustic streaming propagation and resulting in the plating being no better than the standard capability for 0.325 mm THV [26]. Despite this, some acoustic streaming does penetrate through the THV and provides electrolyte for plating, as indicated by the increases to micro-throwing with acoustic pressure. This result highlights that the standing wave effects do not entirely hinder acoustic streaming motions through the THVs.

![Figure 7](image)

**Figure 7** – Micro-throwing power evaluated from 0.325 mm diameter ar 3.4:1 THVs, with the transducer setup at 8 cm. THV plated for 15 hours. Insert, microsection images of THV at centre.

RP MS plating trials are performed on 0.15 mm THVs, making changes to the tangential setup of the PCB. The micro-throwing power results are plotted as indicated in Figure 8. At 1.0:2.0 A/dm² the micro-throwing power is approximately 20 %. The reduction of the RP current density to 0.5:1.0 A/dm² increases the micro-throwing power significantly to approximately 50 %. This is due to the slower plating rate enabling greater replenishment.
of electrolyte solution. Plating at 0.5 A/dm\(^2\) DC causes little variation to micro-throwing value. To increase the acoustic pressure down the 0.15 mm THV, the tangential distance of the transducer is reduced from 4.5 cm to 1 cm. At this distance current thieving occurs as shown previous and reduces the plating currents in the THV, but the closer distance provides increased acoustic agitation and acoustic streaming for electrolyte replenishment [5]. Despite these changes the micro-throwing power did not improve above the 0.5 A/dm\(^2\) DC setting. The results highlight that introducing a RP plating cycle, did not noticeably improve the MS deposition down 0.15 mm diameter THVs, which is likely due to the low current density producing a low deposit uniformity [5]. Further experiments applying higher current densities and RP plating, on 0.15 mm THVs, are likely to yield further improvements to micro-throwing power with MS plating.

![Figure 8](image)

*Figure 8 – Micro-throwing power for THVs of diameter 0.15 mm ar 5.7:1, MS plated for 16.5 hours with 450 W MS, for different tangential distances, plating waveform and current density. Insert, microsection images of THVs at centre.*
4 Conclusions

Experimental results presented in this article provided several insights regarding the role and interactions of MS agitation in electrodeposition of copper. Firstly, changes to the tangential distance of the acoustic transducer to the PCB indicates a minimum distance at which further reductions induced unwanted current thieving and reduce the plating rate. This is an unwanted effect due to the smaller amounts of Cu deposited down THV during MS plating and longer plating times. The observations of this limiting value help to highlight the ideal configuration of the transducer, when performing MS assisted plating.

Bulk fluid motions within the plating bath are affected by the MS streaming currents. Increases to fluid motions were recorded faster than conventional panel movement agitation applied in PCB manufacture. The MS streaming abated with distance travelled within the bath. To maximise fluid flow onto the PCB, which in turn maximises the transport into the THV, the transducer should be placed as close to the PCB surface as possible, whilst considering current thieving effects.

The influence of incident angle on the MS plating of THVs was reviewed and evidence is further provided that resonant acoustic conditions of the THV, hinder fluid transport through it and that the acoustic streaming currents inside the THV are heavily influenced by its alignment to the transducer. Suggestions for improvements are made on the alteration to applied frequency and the phase of the acoustic output.

A variety of plating conditions were altered to maximise the micro-throwing power obtained when MS plating THVs of different sizes. Down large diameter features, enhancements to the micro-throwing power are obtained for increases to acoustic pressure and reductions of the current density, although they are not beyond the capability obtained under standard bath agitations. This is attributed to the acoustic wave being smaller than the THV cavity and the acoustic streaming motions favouring vorticity rather than laminar fluid movements. MS RP plating down small THVs, of a size smaller than the acoustic wavelength, produces a similar plating quality to the DC plated results on THVs of the same size, which is attributed to the large deposit thickness variations obtained with low current densities. In further studies improvements to RP MS plated deposit thickness are likely with increases to current density.

Different resonant acoustic phenomena act to either enhance or reduce the total plating volume down THVs. Controlling which phenomena occurs influences the MS plating performance and so, the implementation of MS plating into an industrial setting can yield
enhancements, although a careful tuning of the feature size and the applied acoustic wave is required.

References


Highlights

- 45% THV µ-throwing power increase for MS pressure increase from 225 W to 450 W.
- 150% increase in bulk flow rate due to MS over conventional PCB panel movement.
- Transducer angle dependency on MS THV plating outcome due to higher order mode formation.
- Minimum transducer to PCB distance of 4.5 cm due to unwanted current thieving.
<table>
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<th>Angle of Acoustic Agitation (± 5°)</th>
<th>Micro-section Image (± 25 μm)</th>
<th>Acoustic Pressure Scatter Distribution</th>
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- **FR4 PCB**: FR4 printed circuit board components.
- **Electrolyte**: Electrolytic solution component.

*Normalized Units*

- **2.5**
- **2**
- **1.5**
- **1**
- **0.5**
- **0**
- **-0.5**
- **-1**
- **-1.5**
- **-2**
- **-2.5**