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Viscosity control of dense suspension by ultrasound

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ABSTRACT

The production of consumer and industrial electronics is dependent on the precise deposition of conductive fluids onto printed circuit boards (PCBs) in order to provide electrical contact between the board and components that populate the board. The demands on volume delivery and positioning accuracy for solder paste deposits are increasing as the size of components shrink and the complexity of circuits continue to develop in the electronics industry. The development of next-generation electronics will demand greater control of solder paste deposition onto PCBs and new methods to finely tune the viscosity of solder paste during printing. Control of the thixotropic characteristics of solder paste is critical to achieve consistently repeatable solder paste deposits on the PCB. This work investigates the possibility of using ultrasound as an actuation method to control the viscosity of a dense suspension in a microfluidic context.

Rheological measurements were performed to determine the thixotropic flow behaviour of a sample of the solder paste. To study the effect of ultrasound on the viscosity of solder paste, a piezo-element was used to apply ultrasonic vibrations to solder paste flowing through a capillary tube. These measurements were repeated with a set of combinations of actuation frequencies and amplitudes. The amplitude of the ultrasound determines the magnitude of change of the viscosity, but the effect is relatively small for the tested amplitudes. The frequency of the ultrasound did not have a clear effect on the viscosity change.

INTRODUCTION

Surface mount technology (SMT) is the standard production method for contemporary electronics. The SMT process includes the deposition of precise volumes of conductive material, such as solder paste, onto the conductive pads on a printed circuit board (PCB), the subsequent placement of components, and finally the reflow of the PCB in order to produce conductive joints on the PCB. For the producers of SMT products, the ability to deliver high-precision solder joints is of major importance. The application of solder paste onto the PCB has traditionally been performed using a screen-printing methodology. An alternative method has grown in popularity where deposits are produced by pneumatic of piezo-actuated drop-on-demand printing heads, see Figure *1*. This technology offers high deposit volume repeatability and accuracy together with a digital, software-controlled work flow. The accuracy and repeatability of the volume and positioning of the droplets are key performance indicators for these machines.

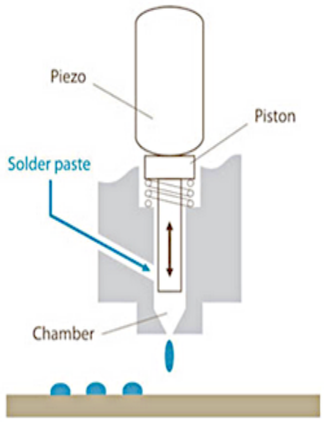

Figure 1. Schematic of a drop-on-demand jetting device used to deposit high viscosity fluids.

The thixotropic properties of the solder paste affect the deposition process in jet printing. A thixotropic fluid is a fluid that exhibits time-dependent shear thinning: the viscosity of the fluid decreases with an increase in shear rate, but returns to its original viscosity over time when the shear is removed [1]. This is caused by the break-down and build-up of its microstructure. Weak attractive forces between components (e.g. metal particles, organic molecules, etc.) leads to the creation of flocs, which increases the viscosity. During flow, these flocs are broken down by the hydrodynamic forces, thus lowering the viscosity. After the flow is stopped or slowed down, the attractive forces will start the formation of flocs again, thus increasing the viscosity again. However, the hydrodynamic forces can change the structure of the flocs, permanently lowering the viscosity [9].

During the passage of paste through the ejector head, the fluid will be exposed to a range of shear rates from very low while in the paste reservoir tube to extremely high when exiting the ejection nozzle. When the solder paste is pumped into the ejector chamber, the viscosity will be relatively low due to the shear introduced during pumping. In the ejector chamber, the solder paste will start to become more viscous again. The viscosity of the ejected droplet thus depends on the specific combination of shear rates and stagnation times experienced by the fluid volume to be ejected. It is reasonable to believe that these variations in viscosity reduce the accuracy and repeatability with which droplets can be deposited. The ability to control the viscosity of the solder paste in detail would thus improve the performance of the deposition process. An improved performance of the jet printers may lead to less failed circuit boards and thus less waste.

Since the solder paste is shear thinning, it is proposed that the viscosity of the solder paste can be affected by inducing vibrations, and thus shear, by means of ultrasound. Ultrasound has already proven to be effective in reducing the viscosity in various other non-Newtonian fluids [2–5]. Many researchers have reported on the rheological properties of solder paste [6–8].

Rheology of solder paste

Solder paste is a thixotropic suspension of metal-alloy particles in a carrier fluid called flux, which is a resin-based material. The particle size distribution is specified by the type of the solder paste, but is approximately Gaussian. The solder paste used in this work (type 6) had a size distribution where 80% of the solder particles are between 5 to 15 μm [9]. One of the most common alloys used for solder pastes is SAC305, a lead-free alloy composed of 96.5% tin, 3% silver and 0.5% copper. The flux consists of a mixture of (among others) solvents, activators, binders and thickeners [10]. The volume fraction of metal particles was 86% by weight.

METHOD

To measure the effect of the ultrasonic excitation on the solder paste, the material is pushed through a glass capillary pipe subsequently actuated by an annular piezo-element mounted around the capillary tube (manufacturer X, city X). The fluid is fed through the tube by a linear motor that in turn pushes a plunger of a syringe filled with solder paste forward at a constant speed. A pressure sensor (manufacturer Y, city Y) measures the pressure drop over the capillary tube, see Figure *2*.

For a Newtonian fluid the relation between the pressure drop and flow rate in a capillary tube is given by the Hagen-Poiseuille equation, such that

$$\Delta P = \eta Q \frac{8L}{\pi R^4} \tag{1}$$

where ΔP is the pressure drop, η is the fluid viscosity, Q is the volumetric flow rate, L is the length of the pipe, and R is the pipe diameter. The viscosity is linearly proportional to the ratio between the pressure drop and the flow rate. Although the relation between pressure drop and flow rate is more complicated for a non-Newtonian fluid, the pressure drop can be used to estimate the average viscosity in the non-Newtonian fluid.

A wave generator (manufacturer Z, city Z) is used to generate square waves at ultrasonic frequencies to drive the piezo-element. The wave generator output is limited to 15 V, but an amplifier is used to increase the signal to 60 V.

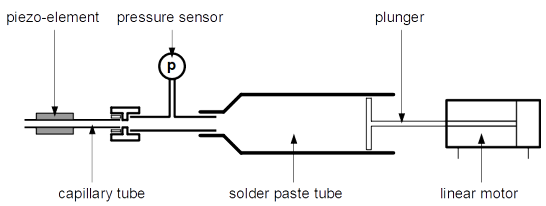

Figure 2. Schematic of the experimental setup.

The experimental study probed the effect of ultrasonic frequency and voltage according to the combinations presented in Table 1.

Table 1. Compilation of experimental trials.

Measurement	Frequencies (kHz)	Voltage (V)	Avg. flow speed ($\mathrm{mm\,s^{-1}}$)
A	40, 20, 60 and 80	15	2.5
B	20, 40, 60 and 80	15	2.5
C	80, 60, 40 and 20	15	2.5
D	40	15	0.5
E	40	15	2.5
F	40	15	2.5
G	40	20, 40 and 60	2.5
H	40	60, 40 and 20	2.5

RESULTS AND DISCUSSION

The preliminary experiments included tests of the effect of amplitude and frequency of the ultrasonic actuation on the flow of fluid through the capillary.

<u>Effect of actuation frequency</u>

In Figure *3*, the pressure measured in the capillary is shown as an effect of the frequency of the ultrasonic actuation. In all tests, the pressure drops noticeably when the ultrasound is turned on and increases again when the ultrasound is turned off. The absolute levels of pressure change are relatively small. The largest pressure reduction is 2.2 kPa at a frequency of 40 kHz and the smallest pressure reduction is 1.1kPa at a frequency of 60 kHz.

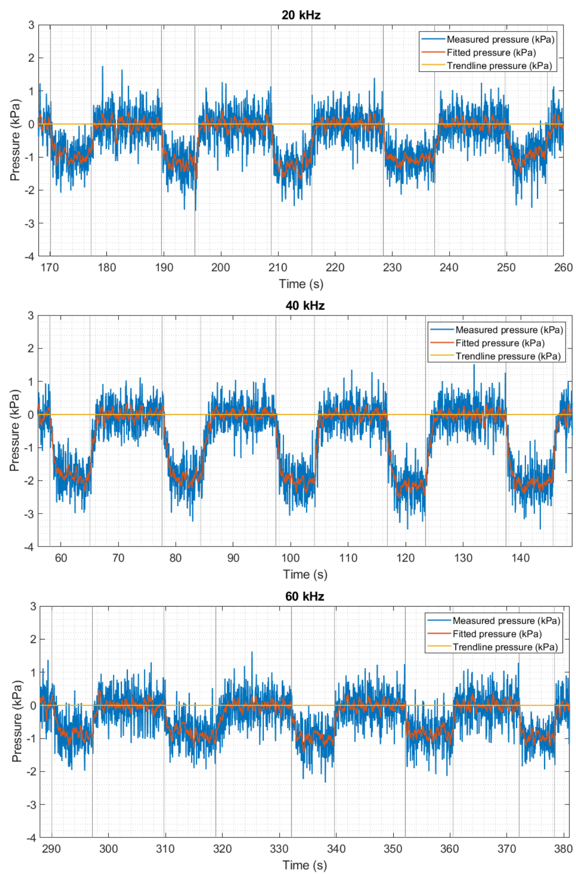

Figure 3. (continued)

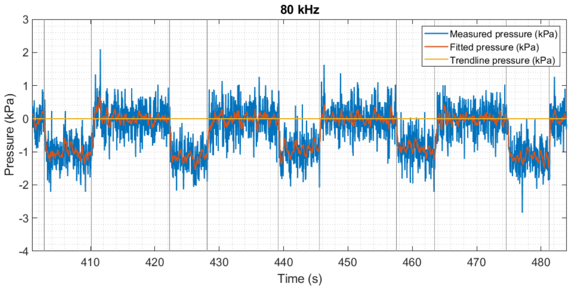

Figure 3. Measured pressure over the capillary tube under a constant flow rate while the ultrasound is switched on and off. The grey lines indicate the times at which the ultrasound was switched. The frequencies for each marked region are 20 kHz, 40 kHz, 60 kHz, and 80 kHz.

The variability of measurement series is relatively large. For all three of the measurement series, the 40 kHz actuation performs the best and 60 kHz the worst, while 20 kHz and 80 kHz perform similarly. It is unclear what causes this behaviour.

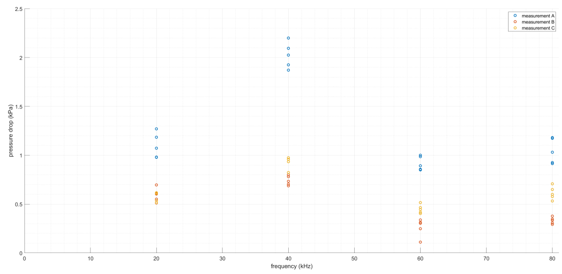

Figure 4. Pressure drop as a function of actuation frequency.

<u>Effect of actuation amplitude</u>

In Figure 5, the pressure drop is plotted as a function of the actuation amplitude. These measurements show that a higher voltage amplitude results in a larger pressure drop. The largest pressure drop observed is 4.17 kPa at a voltage of 60 V and the smallest pressure drop was 1.39 kPa at a voltage of 20 V. The variation between different measurements once again is quite large.

The largest pressure drop corresponds – after subtracting atmospheric pressure – to a decrease of 3.81% in pressure. The average decrease at 60 V is 2.74% and the lowest is 1.94%. This is quite small and even higher voltages are probably needed to achieve an appreciable pressure reduction. The piezo-element is specified for voltages up to 300 V, but this was not done for safety reasons.

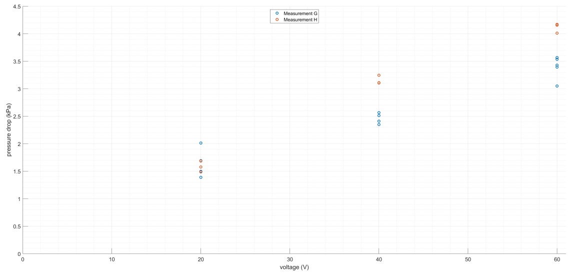

Figure 5. Pressure drop as a function of actuation amplitude.

CONCLUSIONS

Ultrasound actuation was evaluated as a method to manipulate the viscosity of dense suspensions in order to enable detailed control of pumping of functional fluids for industrial microfluidic applications. From the measurements, it was found that the viscosity of solder paste was reduced by the application of ultrasound. It was found that increasing the amplitude of the ultrasound leads to a larger viscosity reduction. The pressure drop over the capillary tube decreased on average by 1.6kPa, 2.8kPa and 3.7kPa for piezo-voltages of 20V, 40V and 60V. These pressure reductions correspond to an average decrease of the equivalent Newtonian viscosity of 1.3%, 2.1% and 2.7%, respectively. The largest pressure reduction observed was 4.2 kPa or 3.8 % viscosity reduction at a voltage of 60 V.

The ultrasound measurements did not provide evidence that the frequency of the ultrasound has an influence on how much the ultrasound affects the viscosity of the solder paste. However, the measurements are not sufficient to conclude that a change in frequency has no systematic effect.

In order for ultrasound to be a feasible method to control the viscosity of solder paste, the amplitude of the ultrasound has to be high enough to have a sufficiently large effect on the viscosity. The viscosity change observed at the tested amplitudes is large enough to counteract the standard deviation in the viscosity during a deposition sequence. However, it is not large enough to counteract the viscosity difference at the beginning of the jetting sequence.

Further measurements are planned with a number of new sample fluids, as well as improved pressure monitoring over the capillary.

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