Ink drop deposition and spreading in inkjet-based printed circuit board fabrication

Wen-Kai Hsiao, Graham D. Martin, Stephen D. Hoath, and Ian M. Hutchings, Inkjet Research Centre (IRC), Institute for Manufacturing, Department of Engineering, University of Cambridge, Cambridge, UK

Abstract

Droplet deposition phenomena have been studied over a wide range of timescales under conditions relevant to direct printing of etch resist patterns on printed circuit boards. UV-curing and phase-change inks were jetted from commercial drop-on-demand print heads on to copper-clad boards. Early-stage impact-driven spreading of 80 pl ink drops was imaged by 20 ns flash-based photography, while a 27,000 fps high-speed camera was used to study the later stages of spreading up to 130 ms post-impact. The initial stage was generally free from excessive drop oscillation or splashing. The effects of liquid-surface wetting and substrate temperatures were investigated. Quantitative image analysis was used to study the transition from impact-driven to capillary spreading and to derive the power law exponents for capillary spreading, which can be used to predict printed track widths.

Introduction

Printed circuit boards (PCBs) form core components in today's affordable consumer and commercial electronics. Fabrication of PCBs is currently a multi-step process involving photolithographic masking and etching of copper-clad laminated boards to create conductive tracks. This process not only utilizes costly equipment but is also inflexible to design changes and adapts poorly to variations in process parameters (e.g. to compensate for board distortion). There is therefore a growing interest in applying the etch resist patterns directly by using inkjet printing methods, eliminating the need for custom masks as well as greatly improving flexibility in design and manufacture.

Although inkjet printing is a relatively mature technique for graphical applications, the knowledge developed in this area is insufficient to meet the higher-precision demands of PCB fabrication. Specifically, ink drop deposition on non-absorbing, high-energy metallic surfaces typically results in excessive spreading of the printed tracks, and some aspects are poorly understood.

Liquid drop impingement on solids has been a well-studied phenomenon since Worthington's pioneering studies more than 130 years ago [1]. Drop deformation and spreading are controlled by inertia, capillary force and viscous dissipation. These phenomena may be characterized by dimensionless parametric groups such as the Weber number (We), Reynolds number (Re) and Ohnesorge number (Oh) which are defined as follows:

$$\mathrm{We} = \rho U_o^2 D_o / \sigma; \quad \mathrm{Re} = \rho U_o D_o / \mu; \quad \mathrm{Oh} = \sqrt{\mathrm{We}} / \mathrm{Re} \qquad (1)$$

where ρ, σ, μ, D_o and U_o are the liquid density, viscosity, surface tension, initial drop diameter and impact velocity, respectively. Based on these parameters, a drop deposition regime map can be constructed, as shown in Figure 1 [2].

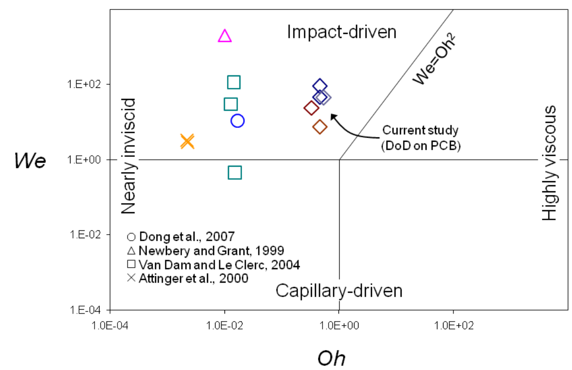

***Figure 1**. Map showing regimes of drop behavior on impact (adapted from [2]) with the conditions used in the present work indicated*

In comparison with the parametric ranges of previous studies shown in Figure 1, it is clear that for printing on PCBs, although initial drop spreading is still predominantly driven by the impact inertia, viscous damping and capillary effects may be more significant [3-6].

The spreading of an ink drop on a solid surface can be characterized by its normalized contact diameter: $D^* = D(t)/D_o$. Figure 2 illustrates how the spreading of a liquid drop deposited on a wetting surface evolves with time and can be described in terms of the progressive influences of impact inertia and capillary force [3].

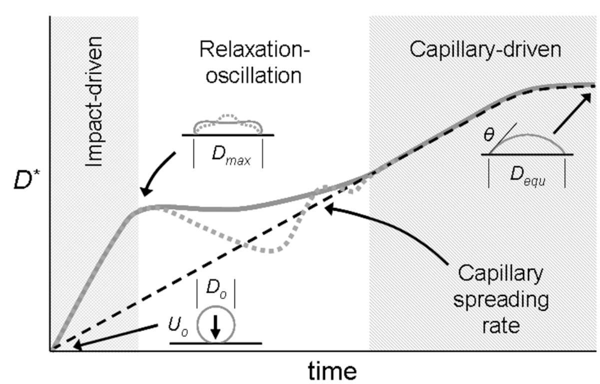

***Figure 2.** Examples of drop spreading behavior (after [3]).*

Capillary spreading, or spontaneous spreading, describes the tendency for a drop to spread to its equilibrium state under negligible inertial influences. The final equilibrium state may be derived by assuming that the sessile drop forms a spherical cap with a dimensionless spreading diameter D^*_{equ} given by:

$$D^*_{equ} = \frac{2}{\left(\tan^3\theta + 3\tan\theta\right)^{0.33}} \qquad (2)$$

where θ is the equilibrium contact angle. Capillary spreading on a wetting surface typically follows a power law with time [7]. When a drop is deposited with significant impact velocity, in contrast, its spreading immediately after impact is dominated by inertia and the spreading rate may be significantly greater. Driven by inertia, resisted by surface tension and with energy dissipated through viscous shear, the drop eventually reaches a quasi-static, maximum spreading state. The contact diameter at this point, D_{max}, has been estimated in many studies [8-11]. Dong et al. [3] compared a range of model predictions with their empirical results and found good agreement with Asai's empirical model [11]:

$$D^*_{\max} = \frac{D_{\max}}{D_o} = 1 + 0.48\mathrm{We}^{0.5}\exp\left(-1.48\mathrm{We}^{0.22}\mathrm{Re}^{-0.021}\right) \qquad (3)$$

despite the fact that it ignored liquid-surface interaction, i.e. wetting. This is perhaps not surprising, since impact inertia dominates the initial stages of spreading prior to D^*_{max}. After any inertial 'overshoot' in diameter, the drop tends towards the capillary spreading state, either with or without oscillation depending on the degree of viscous damping in the system. For a drop deposited on a wetting surface, D^*_{max} is typically less than D^*_{equ} and the spreading continues until D^*_{equ} is reached.

Observations of the spreading of drops from the point of impact to final equilibrium provide valuable information for the prediction and control of printed track width. Both flash photography and high-speed video imaging were used in the present work to study the impact and spreading behavior of ink drops on PCB substrates. Both UV-curable and phase-change inks were jetted from a commercial drop-on-demand (DoD) print head on to Cu-clad laminated boards with different surface finishes in order to study the influence of wettability (with UV-curable inks) and substrate temperature (with phase-change inks) on drop spreading.

Apparatus and Materials

Printing was performed with a Xaar XJ126 print head with 126, 50 µm-diameter nozzles jetting 80-picoliter ink drops at 5 m/s, in the system shown schematically in Figure 3. The head mounting had five-degree freedom of motion (traverse and vertical plus tilting about X-Y-Z) and incorporated a zoned heating system with built-in ink reservoir to allow printing of phase-change (hot melt) inks with melting temperatures up to 100°C. Two inks were used: a UV-curable ink (UV) and a developmental phase-change resist (PCR). Samples of copper-clad FR4 laminates used in PCB fabrication were used as deposition targets, with two different surface treatments: passivated or heavily oxidized. The wetting characteristics of the substrates were measured in terms of the static ink-substrate contact angle θ_s for millimeter-sized sessile ink drops (the phase-change resist was measured in a fully molten state). The ink properties, contact angles and the dimensionless groups describing the jetting conditions are listed in Table 1.

The heated substrate support was attached to a motorized indexer capable of 5 µm indexing resolution with a maximum velocity of 2 m/s. Initial drop spreading was observed using short-duration (20 ns) flash photography as described previously [12-14], but with a sensitive monochrome CCD camera (Prosilica, EC1020) rather than a digital SLR camera. The optical system provided <0.5 µm/pixel spatial resolution. Operation of the camera, printhead trigger, flash and substrate indexer was synchronized with appropriate delays to give an overall uncertainty in image capture of ~5 µs; this includes the effects of substrate roughness.

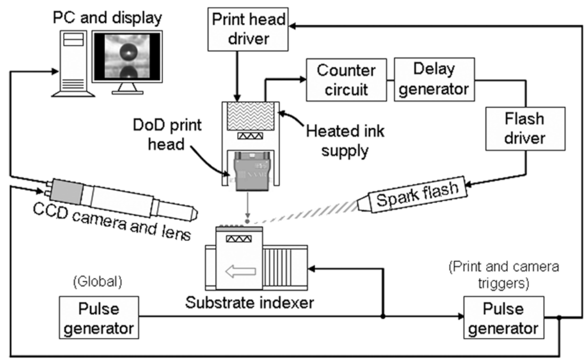

Figure 3. *Schematic diagram of imaging system.*

To monitor capillary spreading beyond ~1 ms after impact, the CCD camera was replaced by a CMOS high-speed camera (Photron 1024 PCI), and the substrate was continuously illuminated with a fiber-optic halogen lamp. In this way the spreading of a single ink drop could be recorded from ~150 µs to 100 ms after impact, at up to 27,000 fps. Single-frame images captured from the optical systems were analysed to determine contact diameter *D* as a function of time.

Table 1: Ink properties and experimental conditions

Ink	ρ (kg/m^3)	σ (N/m)	μ (Pa.s)	We	Oh	θ_s(°)
UV	1050	0.026	0.02	45	0.54	11[2]-25[3]
PCR	880	0.030	0.012[1]	24	0.33	8[2]

[1] Value at jetting temperature of 85°C
[2] On oxidized Cu surface
[3] On passivated Cu surface

Results and Discussion

Effect of wettability: UV-curable inks

The spreading of deposited UV-curable ink drops with attached ligaments on the oxidized and passivated Cu surfaces (with θ_s =11° and 25°, respectively) is shown in Figure 4. In both cases, the drops reached D^*_{max} approximately 20 µs after impact. The values of D^*_{max} were 1.33 and 1.37 for the oxidized and passivated Cu surfaces respectively, about 15 to 18% greater than the values estimated from (3). The time and values of D^*_{max} are consistent with previously reported results [3]. However in contrast to that work, subsequent oscillation and reduction in drop diameter were both absent, probably due to the effects of viscosity and surface tension. The oscillation of a spreading drop may be characterized by its oscillation time, t_{osc}, which can be approximated by the free oscillation period of a droplet [15]:

$$t_{osc} = \left(\frac{\rho D_o^3}{\sigma} \right)^{0.5} \quad (4)$$

The viscous damping time, t_{damp}, is approximated by [2]:

$$t_{damp} = \frac{\rho D_o^2}{\mu} \quad (5)$$

and the ratio $t_{damp} / t_{osc} = 1/\mathrm{Oh}$. For water, as used in [3], t_{damp} is an order of magnitude greater than t_{osc}, whereas for the UV-curable ink used here $t_{damp} \approx t_{osc}$ and any tendency for retraction and oscillation is effectively damped by the greater viscous dissipation.

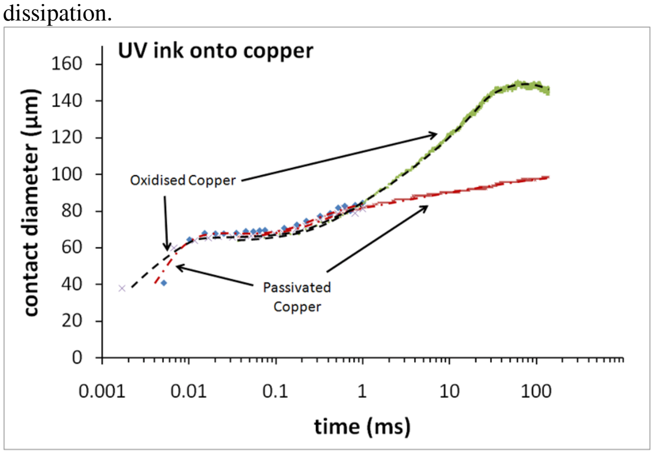

Figure 4. *Spreading of UV-curable ink on both passivated and oxidized copper.*

While Figure 4 suggests that the effects of wettability on impact-driven spreading were negligible, there were significant differences between the two substrates during the capillary spreading phase after ~1 ms. Spreading on the oxidized copper was significantly faster, following a power law with a time exponent of 0.14. A value of $D^*_{equ} \approx 2.94$ was reached after ~60 ms, about 19% greater than the value of 2.38 estimated from (2). Notable retraction then occurred, after ~70 ms. While it is possible that the retraction is related to surface texture and roughness variations, the actual cause is unclear and requires further investigation. Spreading on the passivated surface was notably slower, with a power law exponent of approximately 0.06. The drop reached the theoretical value of $D^*_{equ} = 1.74$ about 80 ms after impact, but continued to spread beyond the period of observation. These power law exponents differ significantly from those reported by Lavi and Marmur [16], who found exponents ranging from 0.31 to 0.48 for θ values between 30.5 and 61.5°.

Effect of surface temperature: phase-change inks

Figure 5 shows the impact and spreading of drops of phase-change resist on oxidized Cu surfaces with different surface temperatures, T_s. The deformation and spreading immediately after impact appears to be unaffected by the surface temperature, and D^*_{max} was reached in all case after ~20 µs. Minimal retraction and no significant oscillation were observed, although small oscillations of the dynamic contact angles (from advancing to receding) were apparent. Ligaments remained visible throughout initial spreading and only collapsed into the deposited drops after ~120 µs. The effect of substrate temperature became more apparent toward the end of initial spreading. As the temperature increased, the spreading diameter became notably larger.

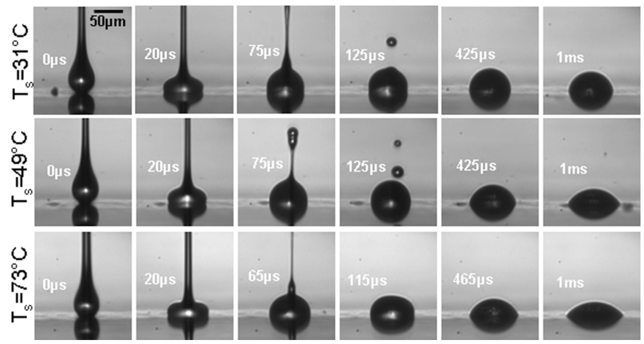

Figure 5. *Images of phase-change ink drops (including reflections) depositing on oxidized Cu surfaces with different surface temperatures; exposure time ~20 ns. The substrate was moving to the left, giving the observed displacement of the ligaments and satellite drops.*

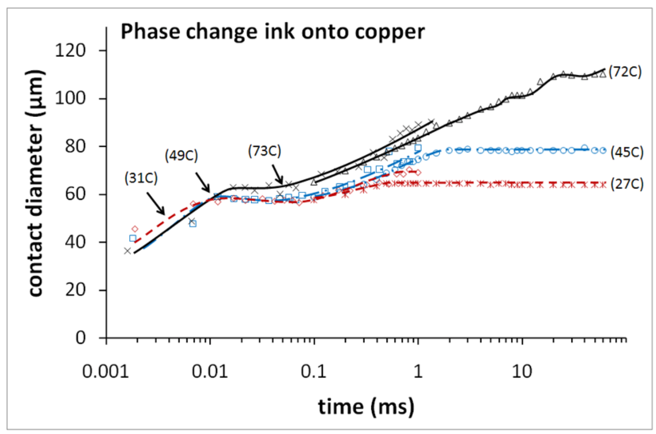

Figure 6. *Spreading of phase-change ink on oxidized copper at different substrate temperatures.*

Figure 6 shows the spreading of phase-change ink drops with substrate temperatures T_s of 31, 49 and 73 °C. While spreading immediately after impact appears unaffected by T_s, the value of D^*_{max} appears to be slightly temperature dependent, ranging from 1.13 to 1.23 as T_s increased from 31 to 73 °C. These values, however, are all within 10% of the estimated D^*_{max} of 1.4, confirming that the effect of T_s on impact-driven spreading is indeed negligible. For T_s = 31 and 49 °C the drops retracted significantly after this point. Capillary spreading rates for T_s = 45 and 72 °C were similar, with power law exponents of ~0.10. Spreading for T_s = 31 °C was slower with an exponent of 0.07. Drops deposited with T_s = 72 °C did not solidify and continued to spread even after 100 ms. With T_s = 27 and 45 °C capillary spreading was arrested after approximately 500 µs and 2 ms, respectively. The final normalized drop diameters, $D^*_f = D_f / D_o$ on the cooler surfaces were measured as 1.25 and 1.53 respectively.

An order-of-magnitude estimate of the effect of solidification can be made by determining the time needed for a molten droplet to lose all its latent heat and solidify completely. Assuming the thermal conductivity of the copper surface to be much greater than that of the molten drop, the solidification time, t_{sol}, may be estimated from

$$t_{sol} = \frac{D_o^2}{3\alpha_d} \frac{L_f}{C_p(T_m - T_s)} = \frac{D_o^2}{3\alpha_d} \mathrm{Ste}^{-1} \quad (6)$$

where α_d is the thermal diffusivity for the molten drop and Ste is the Stefan number, a dimensionless function of T_s [17]. Based on the thermal properties of the phase-change ink listed in Table 2, t_{sol} was estimated to have been at least three orders of magnitude greater than the impact-driven spreading time t_{spr} estimated from

$$t_{spr} = \frac{D_o}{U_o} \quad (7)$$

It is therefore clear that spreading immediately after impact was unaffected by solidification. However, this simple estimate of t_{sol} is still at least an order of magnitude greater than the spreading arrest times observed on the cooler surfaces, suggesting that complete solidification alone is insufficient to explain the effect of surface temperature on spreading. Studying the deposition of millimeter-sized wax drops on solids, Bhola and Chandra reached a similar conclusion and suggested that increases in viscosity and surface tension at lower melt temperatures may been responsible for the surface temperature effect [18]. Indeed, the damped impact-driven spreading and the lower capillary spreading rates observed with T_s = 31 °C are both consistent with an increase in viscous dissipation.

Table 2: Thermal properties of the phase-change ink

Ink	T_m (°C)	L_f (kJ/kg)	C_p (kJ/kg.K)	K (W/m.K)
PCR	68	158.4	2.0	0.18

Conclusions

Initial spreading of inkjet drops after impact on passivated and oxidized Cu surfaces was generally free of splashing and excessive oscillation, and this can be attributed to the effects of viscous damping. Values of D^*_{max} were consistently greater than those predicted by the empirical model of Asai et al. [11], possibly due to differences in the experimental conditions and materials used. While the effect of wettability on impact-driven spreading was negligible, it became significant during the capillary spreading phase. The spreading of UV-curable ink on the more wettable oxidized Cu surface followed Tanner's power law with an exponent of 0.14 [7]. However, the exponent for the less wettable passivated surface was much lower.

The effect of surface temperature on the spreading of phase-change ink was studied for the oxidized Cu surface. While lowering the substrate temperature appears to be effective in limiting drop spreading, the effect cannot be explained by solidification of the ink alone. The variations in drop spreading behavior were consistent with an increase in viscous dissipation during both the impact and capillary-driven phases of spreading.

Acknowledgement

This work was co-funded by the Technology Strategy Board's Collaborative Research and Development programme, following an open competition. The Technology Strategy Board is an executive body established by the UK Government to drive innovation.

References

[1] A.M. Worthington, On The Form Assumed by Drops of Liquids Falling Vertically on a Horizontal Plate, Proc Royal Soc London, 25, pg. 261. (1876).

[2] S. Schiaffino and A.A. Sonin, "Molten Droplet Deposition and Solidification at Low Weber Numbers," Phys Fluids, 9, 11 (1997).

[3] H. Dong et al., "Temporally-Resolved Inkjet Drop Impaction on Surfaces," AIChE J, 53, 10 (2007)

[4] A.P. Newbery and P.S. Grant, "Droplet Splashing during Arc Spray of Steel and The Effect on Deposition Microstructure," J Thermal Spray Techn, 9, 2 (1999)

[5] D.B. van Dam and C. Le Clerc, "Experimental Study of The Impact of An Ink-Jet Printed Droplet on A Solid Substrate," Phys Fluids, 16 (2004)

[6] D. Attinger et al., " An Experimental Study of Molten Microdroplet Surface Deposition and Solidification: Transient Behavior and Wetting Angle Dynamics," J Heat Transfer, 122 (2000)

[7] L.H. Tanner, "The Spreading of Silicone Oil Drops on Horizontal Surfaces," J Phys D: Appl. Phys., 12 (1979)

[8] S. Chandra and C.T. Avedisian, On the Collision of a Droplet with a Solid Surface, Proc Royal Soc London A, 432, pg. 13. (1991)

[9] M. Pasandideh-Fard et al., "Capillary Effects During Droplet Impact on a Solid Surface," Phys Fluids, 8 (1996)

[10] T. Mao et al., "Spread and Rebound of Liquid Droplets Upon Impact on Flat Surfaces," AIChE J, 43 (1997)

[11] A. Asai et al., "Impact of an Ink Drop on Paper," J Imaging Sci Techn, 37 (1993)

[12] I.M. Hutchings et al., "'High speed imaging and analysis of jet and drop formation", J. Imaging Science and Technology 51(5) 438-444 (2007)

[13] G.D. Martin et al., Jet Formation and Late-Stage Ligament Instability in Drop-on Demand Printing, NIP22, pg. 95. (2006)

[14] S.D. Hoath et al., Satellite Formation in Drop-on-Demand Printing of Polymer Solutions, NIP23, pg. 331. (2007)

[15] S.E. Bechtel et al., "Impact of a Liquid Drop Against a Flat Surface," IBM J Res Dev, 25, 6 (1981)

[16] B. Lavi and A. Marmur, "The Exponential Power Law: Partial wetting Kinetics and Dynamic Contact Angles," Colloids Surf A: Physicochem Eng Aspects, 250 (2004)

[17] R. Li et al., "Deposition of Molten Ink droplets on a Solid Surface," J Imaging Sci Techn, 52, 2 (2008)

[18] B. Bhola and S. Chandra, "Parameters Controlling Solidification of Molten Wax Droplets Falling on a Solid Surface," J Mater Sci, 34 (1999)

Author Biography

Wen-Kai Hsiao received his BS from the University of California, Santa Barbara and his MS and PhD from the Massachusetts Institute of Technology, all in Mechanical Engineering. He joined the Cambridge Inkjet Research Centre in 2007 with research interests in drop deposition behavior of both Newtonian and non-Newtonian fluids, continuous inkjet (CIJ) drop formation, and inkjet printing process development.