Drawback During Deposition of Overlapping Molten Wax Droplets

Two overlapping droplets impacting on a solid surface coalesce and recoil so that the edges of the droplets are drawn back, a phenomenon called drawback. A series of experiments were conducted on the merging of two overlapping wax droplets deposited on an aluminum drum to characterize the drawback process between the two droplets. Drum temperature, droplet overlap ratio, and the time interval between impacts of droplets were varied. Wax bumps, formed by coalescence of two droplets on the drum surface, were photographed and their length and width measured. An aspect ratio and dimensionless drawback index, quantifying the extent of drawback, were calculated from these measurements. When drum temperature is increased, or the time interval between impacts of the two droplets is reduced, there is more drawback and the ink bumps become round, since the cooling rate of droplets is slower and droplets have a longer time to change shape due to surface tension. A simple heat transfer model was developed to predict changes in droplet-cooling rate with changes in droplet overlap, substrate temperature, or time interval (deposition frequency). Experiments were also conducted on the formation of lines by depositing 20 droplets. Measurements on the drawback of two droplets were used to predict conditions under which broken lines are obtained.

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1 Introduction

The deposition of molten droplets on cold solid surfaces is an essential step in a number of industrial applications. In solid-inkjet (SIJ) printing [1], the printhead deposits molten droplets of solid, wax-based ink on a rotating drum where they solidify, forming high quality color images that are transferred onto paper. In microfabrication [2,3] and rapid prototyping [4–6], three-dimensional parts are built by depositing molten wax, polymer, or metal droplets. In electronic packaging [7,8], microdroplets of molten solder are dispensed on printed circuit boards to form bumps on which electronic chips are attached, or to lay down electrically conductive lines. Light-emitting polymer displays are electrically conductive lines. Light-emitting polymer displays are manufactured by polymer droplet deposition [9]. All these processes require small droplets (tens of microns in diameter) to be placed with high precision on a substrate. Movement of droplets after deposition can severely degrade dimensional tolerances in the part being made. Therefore, in addition to the impact of single droplets [10,11], it is also important to understand fluid interactions between droplets placed sequentially on a surface, since these may displace droplets.

Figure 1 shows two droplets with initial diameter \(D_0\) dispensed with frequency \(f\). A droplet on a substrate at temperature \(T_0\). The second droplet impacts at time interval \(A\) after the first. Coalescence occurs if the center-to-center distance \(L\) is less than \(D_0\), which is the maximum diameter after impact and spread of a single droplet. The final diameter is determined by fluid flow during impact and, if \(T_0\) is less than the melting temperature of droplets \(T_m\), by the droplet solidification rate.

The equilibrium shape of the coalesced droplets is the one that minimizes surface energy, which on a flat surface is a spherical cap. During the transition to this final shape, the edges of the droplets are drawn back along the axis joining the centers of the two drops. This process is referred to as “drawback.” Figure 2 schematically shows the drawback process of two droplets, which are deposited sequentially and eventually coalesce on the substrate surface. After the second droplet reaches the maximum spread as shown by Fig. 2(a), the edges retract to form the final shape shown in Fig. 2(b). The retraction processes of the two edges are not identical due to the sequential depositions of the two droplets. This asymmetry becomes more pronounced if droplets cool and freeze after impact: The droplet deposited first, that solidifies the most, will withdraw less.

Drawback can create problems in droplet based manufacturing processes that require accurate placement of droplets on a surface. Unpredictable movements of droplets may make lines break or vary in thickness. SIJ printers create the entire spectrum of colors by superimposing droplets of primary color inks on each other or placing them in close proximity. Movement of droplets may cause poor color reproduction or undesired lines across the image. Drawback of droplets touching one another is one of the principal causes of defective images [12,13].

Only a few studies have been done on the deposition of multiple droplets. Gao and Sonin [2] experimentally studied sweep deposition of droplets of molten candelilla wax on Plexiglas, where droplets were dispensed at a constant frequency to form straight lines on a moving substrate. A geometric model was developed to determine if neighboring droplet could touch during deposition at varied frequencies and substrate speeds. They avoided, however, experiments under conditions for which drawback was significant. Ghafoori-Azar et al. [14] investigated, both experimentally and numerically the interaction of millimeter-sized molten droplets impacting on a steel surface. For large droplets, surface tension forces were much less important, and drawback was not significant. Haferl and Poulikakos [15,16], investigated the pileup of two molten metal droplets on a substrate surface, where the first deposited droplet had already solidified upon the head-on impact of the second droplet. Duineveld [17] used experiments and analysis to study the stability of liquid lines formed by depositing a row of droplets on a substrate under isothermal conditions. It was observed that the lines become unstable by forming a series of liquid bulges connected by a ridge of liquid.
The aim of our study is to experimentally investigate the deposition of two overlapping molten wax droplets on a cold substrate. Droplet spacing, time interval between droplet depositions, and substrate temperature were varied in experiments. We photographed solidified, coalesced droplets and quantified the extent of drawback using a dimensionless parameter based on measurements of the final length and width. Experiments were also conducted on the formation of lines by depositing 20 droplets. The results of two droplets’ deposition were used to predict line breakup. A simple heat transfer model is presented to explain trends in how drawback varies with experimental parameters.

2 Experimental Method

Experiments were carried out using components of a commercially available SIJ printer (Phaser 8400 printer, Xerox Corporation, Rochester, NY). The piezo-electrically-driven, drop-on-demand printhead generated droplets, and a rotating aluminum drum, 120 mm in diameter, served as a moving substrate. The drum had internal heaters, regulated by a temperature controller, which could be used to adjust its temperature with an accuracy of ±0.1°C. Using this apparatus, drum temperature, drum speed, and jetting frequency of the printhead could be controlled to vary the parameters $T_s$, $L$, and $\Delta t$ shown in Fig. 1. Droplets were formed of a wax-based ink (Solid Ink 8400, Xerox Corporation, Rochester, NY), with an effective melting temperature of 90°C. The drum surface was wiped with a thin layer of silicone oil before droplets landed on it, so that ink droplets did not adhere strongly to it.

In each test, a nozzle in the printhead fired two droplets consecutively onto the rotating drum, as shown in Fig. 3(a). Droplets spread and overlapped to form a wax bump (Fig. 3(b)). As drawn in Fig. 3(a), the lower droplet was the first one deposited: The first droplet is shown at the bottom of all images in this paper. The drum was then removed from the printer and photographs of wax bumps taken at room temperature under an optical microscope. The lengths of the vertical ($D_y$) and horizontal ($D_x$) axes of the bumps were measured from each photograph, as shown in Fig. 3(b), using an image analysis software. The curvature of the drum surface was neglected when measuring the photographs, since the drum diameter (∼120 mm) was much larger than the droplet size (∼40 μm). For each test condition, more than 50 samples were measured: Mean values are given in all figures in this paper, with standard deviations indicated by error bars.

Three parameters can be changed to vary deposition conditions: drum speed $u$, droplet ejection frequency $f$ (Hz), and drum temperature $T_s$. Initial droplet diameter ($D_0$ ~ 40 μm), impact velocity ($U$ ~ 5 m/s), droplet temperature at impact ($T_i$ ~ 135°C), and

\[
\begin{align*}
\Delta t & : \text{time interval between droplet depositions} \\
L & : \text{droplet spacing} \\
D_s & : \text{droplet diameter} \\
T_s & : \text{substrate temperature} \\
T_i & : \text{droplet temperature at impact} \\
u & : \text{drum speed} \\
f & : \text{droplet ejection frequency}
\end{align*}
\]
drum-to-printhead distance (\(\sim 1\) mm) were kept constant. The wave form used to drive the printer nozzles was not varied during experiments.

Droplet center-to-center distance \(L\) (\(\mu\)m) was calculated from the drum speed and droplet ejection frequency \((L=ul/f)\). The time interval between consecutive droplet impacts was \(\Delta t=1/f\). The diameter \((D_d)\) of an individual droplet after impact and solidification on the drum was a function of substrate temperature and was measured from photographs. The extent of overlap between two droplets deposited on the drum surface was described by the overlap ratio

\[
\lambda = 1 - \frac{L}{D_d}
\]

For complete overlap, when the centers of the droplets coincide, \(\lambda = 1\), while there is no overlap when \(\lambda < 0\).

The extent of drawback for two overlapping droplets can be quantified by defining a dimensionless drawback index. Ideally, if there is no interaction between two overlapping droplets, their combined length should equal \(D_d+L\). The ratio of the actual length \(D_s\) to this ideal length gives the drawback index

\[
\theta = \frac{D_s}{D_d+L}
\]

When there is no interaction between overlapping droplets, \(\theta=1\). If there is retraction of the contact line, \(\theta<1\). For \(\theta>1\), interactions have made the droplets spread further than they would have individually. If the overlapping droplets can eventually reach equilibrium state same as the first droplet, the equilibrium shape is a spherical cap with the same equilibrium contact angle. The base diameter of the spherical cap is \(2^{1/3}D_s\), and its drawback index, referred to as equilibrium drawback index \(\theta_e\), is given by

\[
\theta_e = \frac{\sqrt[3]{2}}{\lambda - \lambda}
\]

In Eq. (3), the definition of overlap ratio \(\lambda\) (Eq. (1)) has been used.

The circularity of the ink bump can be described by an aspect ratio

\[
\beta = \frac{D_s}{D_d}
\]

For \(\beta \rightarrow 1\), the periphery of ink bump resembles a circle. As the amount of overlap decreases, and \(D_s\) becomes narrower, \(\beta\) becomes larger until finally, when the edges of the droplets are just touching, \(\beta\) goes to infinity.

3 Deposition of Two Droplets

Figure 4 shows photographs of wax bumps formed by the merging and solidification of two sequentially deposited droplets. In this series of tests, the drum speed was kept constant, while changing the droplet ejection frequency. Consequently, the spacing, \(L\), between the droplet centers was varied from 7 \(\mu\)m to 63 \(\mu\)m. The time between deposition of the two droplets increased with spacing, from \(\Delta t=42\ \mu s\) to 375 \(\mu s\). Tests were done at three drum temperatures, 50°C, 60°C, and 75°C, though only the results for 60°C and 75°C are shown in Fig. 4. The spread diameter of a single droplet \((D_d)\) was measured to be 58 \(\mu\)m for \(T_s=50\)\(°\)C, 59 \(\mu\)m for \(T_s=60\)\(°\)C, and 64 \(\mu\)m for \(T_s=75\)\(°\)C. The corresponding overlap ratios, \(\lambda\), are shown in Fig. 4, along with two samples of ink bumps at each condition. The bumps become more elongated as the spacing increases. At \(L=63\ \mu\)m, the droplets did not touch on the surface at 60°C, since \(D_s=59\ \mu\)m. On the 75°C surface, \(D_s=64\ \mu\)m, just enough for the droplets to touch and to be drawn together.

The variation of drawback index, \(\theta\), with overlap ratio \(\lambda\) is shown in Fig. 5(a) for the three drum temperatures. \(\theta<1\) shows that drawback occurred, as was most evident on a surface at 75°C. When overlap was minimal (\(\lambda<0\)), there was not much drawback since there was little interaction between droplets. Increasing \(\lambda\) to 0.1 produced much more drawback, reducing \(\theta\) below 0.8. Further increasing the amount of overlap reduced the drawback index. Finally, when overlap became large (\(\lambda \sim 0.7\)), \(\theta\) became greater than 1. In this case, the second droplet landed on top of the first and flowed over it, spreading more than it would have had it landed on the bare substrate. Drawback was less when drum temperature was lowered, since droplets solidified sooner, giving less time for movement. The equilibrium drawback index, \(\theta_e\), is also plotted as a function of \(\lambda\) in Fig. 5(a). If two droplets come to equilibrium, drawback occurs for \(\lambda<0.74\), since \(\theta_e>1\), and there is no drawback for \(\lambda>0.74\), since \(\theta_e<1\). The measured drawback indices are larger than \(\theta_e\) for \(\lambda<0.7\) and close to \(\theta_e\) for \(\lambda \sim 0.7\). Figure 5(a) shows that, for relatively small overlap \(\lambda<0.7\), drawback occurs when two overlapping droplets recoil toward the equilibrium shape.

Figure 5(b) shows the variation of aspect ratio for varying overlap ratio. At low overlap, the droplets were elongated, giving large values of \(\beta\). As overlap increased, wax bumps became almost perfectly round. The bumps on a surface at 50°C and 60°C were much more elongated than those on a surface at 75°C, showing that at the higher temperature droplets remained liquid for a longer time and surface tension forces had more time to pull the ink bumps towards their equilibrium shape.

The test results shown in Fig. 5 confirm that the drum temperature and droplet generation frequency (and hence time interval) both affect droplet drawback. Further tests were carried out to examine the effect of both these factors \((T_s\) and \(\Delta t)\). Drum temperature was raised from 50°C to 80°C in increments of 5°C, while keeping droplet center-to-center distance \(L=42\ \mu\)m and the time interval between deposition \(\Delta t=250\ \mu s\). As drum temperature increased, the spread factor of a single droplet \(D_s\) increased from 58 \(\mu\)m to 77 \(\mu\)m so that the overlap ratio was not constant but varied from 0.28 to 0.45. As a result, the equilibrium drawback index was not constant. Figure 6(a) shows the drawback index \(\theta\) as a function of drum temperature \(T_s\). The drawback index
is less than unity for all the tested drum temperatures, and \( \theta \) decreases toward \( \theta_0 \) as drum temperature increases, indicating that rising substrate temperature enhances drawback. At the same time, \( \beta \) decreases and approaches 1 (see Fig. 6(b)) as ink bumps become more circular.

Reducing droplet generation frequency \( f \) from 4800 Hz to 400 Hz increased the time interval between impacts of two droplets \( (\Delta t) \) from 0.21 ms to 2.5 ms. Overlap ratio \( (\lambda =0.45) \) and drum temperature \( (T_s=60^\circ C) \) were constant. Figure 7(a) shows that \( \theta \) decreases toward \( \theta_0 \), as time interval decreases, indicating that reducing time interval enhances drawback. When the time interval between droplet impacts is brief \( (\Delta t =0.2–0.6 \text{ ms}) \), there is a significant drawback: The first droplet does not have time to solidify before the second lands on it, and the two liquid masses coalesce. When \( \Delta t=2.5 \text{ ms} \), drawback is negligible. In this case, the first droplet has more time to freeze and is less mobile when the second droplet lands on it, reducing drawback. Increasing the time interval made wax bumps more elongated (see Fig. 7(b)): For \( \Delta t=2.5 \text{ ms} \), the aspect ratio \( \beta =1.7 \), corresponding to an elliptical bump formed by the merging of two droplets, the first of which had enough time to solidify before the second landed on it. At lower values of \( \Delta t \), wax bumps were much more circular and \( \beta \) approached 1.

An additional test was conducted to further examine the effect of \( \Delta t \). Large values of \( \Delta t \) can be achieved if two droplets are generated from different nozzles. Figure 8(a) shows wax bumps formed by yellow and cyan droplets, of which the cyan droplet landed \( \Delta t \approx 100 \text{ ms} \) after the yellow droplet. This time interval is much larger than the thermal diffusion time of the droplet \( D_\lambda^2/\alpha \approx 20 \text{ ms} \), where \( \alpha =9.76\times 10^{-8} \text{ m}^2/\text{s} \) is the thermal diffusivity of the wax. This implies that the yellow droplet had completely solidified when the cyan droplet impacted, resulting in incomplete merging (Fig. 8(a)). This test provided a striking contrast to Fig. 8(b) (already shown in Fig. 4(a)), which shows complete coalescence due to much shorter time intervals.

4 Heat Transfer Model

A molten wax droplet impacting a solid surface flattens and spreads out until it reaches its maximum diameter. Then, surface tension forces make it recoil so that the liquid-solid contact line retracts. The extent of spreading and recoil are controlled by the viscosity and surface tension of the liquid, properties that are sensitive to temperature \([10]\). Also, the droplet may freeze, partially or wholly during impact; if the contact line freezes, its motion will be arrested. The cooling rate of two sequentially deposited droplets will depend on the substrate temperature, the time interval between impact of the droplets, and the extent of overlap. Our experiments (see Figs. 5–8) show that all of these parameters affect drawback and consequently the shapes of wax bumps.

To estimate the time required for a molten droplet to cool, we developed a simple heat transfer model. A droplet with tempera-

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Fig. 5 Measurements of wax bumps formed by deposition of two overlapped wax droplets as shown in Fig. 5. (a) Drawback index \( \theta =D_y/(D_x+L) \); (b) aspect ratio \( \beta =D_y/D_x \).

Fig. 6 Measurements of wax bumps formed by two wax droplets deposited on drum surface with varied drum temperatures \((0.28<\lambda<0.45; \Delta t=250 \mu \text{s})\). (a) Drawback index \( \theta =D_y/(D_x+L) \); (b) aspect ratio \( \beta =D_y/D_x \).
Energy in the droplet is removed by heat conduction to the substrate. Convection losses to the ambient air are negligible, since the Biot number is less than 0.1. Assuming that the droplet can be modeled as a semi-infinite body with constant surface temperature (at the droplet-substrate interface), the heat flux at the boundary is [18]

\[ q^* = \frac{k(T_i - T_s)}{\sqrt{\pi \alpha^* t}} \]  

where \( \alpha^* \) is thermal diffusivity of ink droplets given by

\[ \alpha^* = \frac{k}{\rho C_p^*} \]

\( k \) is thermal conductivity. For a droplet generation frequency, \( f = \Delta t^{-1} \), when the second droplet arrives, the remaining thermal energy of the first droplet, \( H_1 \), is

\[ H_1 = H_0 + \frac{\pi D_s^2}{4} \int_0^{\Delta t} q^* dt \]  

Here, we neglect the spreading process and assume the contact area constant, which is valid when the droplet spreading time \( \sim \left( \frac{D_s}{U} \right) \) is much less than the droplet-coolinging time. Integrating Eq. (8) gives

\[ H_1 = H_0 - \frac{\sqrt{\pi k(T_i - T_s) D_s^2 \Delta t}}{2 \sqrt{\alpha^*}} \]  

If we set \( H_1 \) equal to zero, solving Eq. (9) gives a critical time interval \( \Delta t_c \) (and hence a critical droplet generation frequency \( f_c = 1/\Delta t_c \)), at which energy of the first droplet is lost and its contact line is arrested when the second one arrives,

\[ \Delta t_c^* = \frac{\pi}{9B^2(1 + S^{1/2})^2} \]  

The three nondimensional parameters used in Eq. (10), referred to as dimensionless time (equivalent to Fourier number), spread factor, and superheat parameter, are defined as

\[ \Delta t_c^* = \frac{\alpha^* \Delta t_c}{D_0^4}, \quad B = \frac{D_s}{D_0}, \quad S = \frac{T_i - T_m}{T_m - T_s} \]

The spread factor \( B \) is the ratio of the final spread diameter of a single droplet to its initial diameter, which ranged from 1.5 to 2 in our experiments. The cooling time for one single droplet is \( \Delta t_i = \Delta t_f = 1/f_c \). In Fig. 9, \( \Delta t_i \) and \( f_c \) are plotted as a function of drum temperature \( T_i \) for several values of \( B \). The ink properties used are \( L_f = 183 \) kJ/kg, \( \alpha^* = 3.475 \times 10^{-8} \) m²/s, and \( T_m = 90^\circ C \), and the initial droplet temperature \( T_i = 135^\circ C \). If either drum temperature increases, or spread factor decreases, droplet-cooling rate diminishes and therefore the critical frequency becomes lower.

For typical conditions in our experiments, \( B = 1.5 \) and \( T_i = 60^\circ C \) (see Fig. 4(a)), \( f_c \) is approximately 1.2 kHz. Droplet generator frequencies in our tests were almost always much higher than this, implying that the first droplet had not fully cooled down before the second arrived. Figure 7(a) shows how the effect of drawback diminishes as the time interval increases (decreasing droplet generation frequency). For \( \Delta t = 2.5 \) ms, there is almost no drawback (\( \theta \sim 1 \)), while for \( \Delta t > 0.6 \) ms drawback becomes more pronounced. This lends support to the heat transfer model developed in Eqs. (5)–(8) and (9)–(10).

In the case that \( \Delta t < \Delta t_c \) (and \( f > f_c \)), the second droplet lands on a droplet that is still cooling down. The energy of the second droplet is assumed to incorporate the residual energy in the portion of the first droplet it overlaps, and is given by

\[ C_p = C_p + \frac{L_f}{T_i - T_m} \]

\[ q^* = \frac{k(T_i - T_s)}{\sqrt{\pi \alpha^* t}} \]
Both droplets are assumed to have the same shape, that of a spherical cap (see Fig. 10). $V_O$ is the volume of the portion of the first droplet overlapped by the second droplet, and $V'$ is the ratio of $V_O$ to the volume of the whole droplet,

$$V' = \frac{V_O}{\pi D_0^3/6} \tag{12}$$

$V_O$ can be calculated from

$$V_O = \int_{0}^{D_{s,1/(1-k)}} A_O \, dx \tag{13}$$

where $A_O$ is the cross-sectional area of the spherical cap given by

$$A_O = \frac{\pi (k(T_s - T_m)) D_x^2}{2\sqrt{1-k}} \tag{11}$$

The initial shape of the second droplet is modeled as a spherical cap to merge with the overlapped part of the first droplet. A side-view scanning electron microscopic (SEM) picture of a single droplet deposited on drum surface shows a final shape of a spherical cap.

![Fig. 9 Critical time interval $\Delta t_o$ (and hence a critical droplet generation frequency $f_o=1/\Delta t_o$), as a function of drum temperature $T_s$ for varied spread factors $B$. Here, Eq. (10) is plotted in its dimensional form.](image)

![Fig. 10 The initial shape of the second droplet is modeled as a spherical cap to merge with the overlapped part of the first droplet. A side-view scanning electron microscopic (SEM) picture of a single droplet deposited on drum surface shows a final shape of a spherical cap.](image)

![Fig. 11 Equation (19) is plotted in a dimensional form, $t_c$ as a function of drum temperature $T_s$. The embedded pictures and the line $(\lambda=0.4, \Delta t=0.25\text{ ms})$ correspond to the experimental test shown in Fig. 7.](image)
spread factor $B=1.6$. The ink properties and temperatures are the same as used for plotting Eq. (10) in Fig. 9, and all the values of $T_s$, $\lambda$, and $\Delta t$ are in the ranges of our experimental tests. It should be noticed that $t_s$ is in the order of milliseconds, which is much larger that the spreading time scale $D_0/\mu=10 \mu s$ and the viscous/capillary time scale $D_0\mu/\sigma\sim 15 \mu s$. Here, $\mu (=0.011 Pa \ s)$ and $\sigma (=0.029 \ N/m)$ are the viscosity and surface tension of droplets, respectively. This indicates that the droplet has ample time to spread and recoil after reaching maximum spread.

Figure 11 shows that the cooling time of the second droplet increases with drum temperature, indicating that the contact line of the second droplet has more time to draw back on a hotter surface. The line with $\lambda=0.4$ and $\Delta t=0.25$ ms corresponds to the experimental data shown in Fig. 6, and the pictures taken in that test have been added in Fig. 11. In this case, as $T_s$ increases from 50°C to 80°C, $t_s$ increases from $\sim 1$ ms to $\sim 2.8$ ms (Fig. 11). As a result, the contact line of the second droplet has a relatively long time to retract, thereby increasing drawback. This agrees with our experimental observations (see the pictures in Fig. 11). This is also confirmed by Fig. 6, which shows that $\theta$ decreases from 0.94 to 0.83 and $\beta$ decreases from 1.48 to 1.1.

Increasing the time interval between droplets allows the first droplet to cool down before the second one is deposited on it and decreases the time taken for the second droplet to cool. In Fig. 12(a), the cooling time of the second droplet ($t_s$) is calculated as a function of time interval between droplets ($\Delta t$). The line with $T_s=60°C$ and $\lambda=0.45$ corresponds to the experimental results shown in Fig. 7. The calculated cooling time decreases as the time interval increases (Fig. 12(a)). Correspondingly, drawback becomes less (Fig. 7(a)), showing that the droplet remained liquid for a shorter period.

Figure 12(b) shows the variation of droplet-cooling time as a function of overlap, and shows that $t_s$ increases with increasing $\lambda$. The droplet has more time to move after impact, and the fluid mechanics of interaction may be quite complex as the two liquid droplets merge, spread, and retract. As seen in Fig. 5(a), drawback may increase or decrease, depending on the substrate temperature and amount of overlap. The simple heat transfer model proposed here cannot predict the motion of the droplets following their coalescence.

5 Formation of Lines

The lines of solid material are formed on a flat surface by depositing overlapping droplets in a row. Ideally, to form lines of uniform thickness, the spacing between droplets should be constant, but due to drawback, droplets may move from the place they land. To observe this effect, lines were made by depositing 20 droplets in a line. The spacing between droplets, substrate temperature, and droplet frequency were varied. Three drum temperatures, 60°C, 75°C, and 80°C, were tested.

Figure 13 shows lines formed on a surface at 75°C with two overlap ratios of (a) $\lambda=0.80$ and (b) $\lambda=0.63$. The widths of the lines at various points, normalized by maximum spread diameter of a single drop ($D_s$), are shown in Fig. 13. The two lines significantly differ in shape with overlap ratio, ellipsoidal for $\lambda=0.80$ and dumbbell-shaped for $\lambda=0.63$. Similar shapes were seen at other drum temperatures for the same overlap ratios. Drawback of droplets, which was controlled by the amount of overlap and local thermal conditions, produced these variations in line thickness.

Decreasing the overlap ratio reduces the overlap effect and allows production of lines with much more uniform thickness. If, however, overlap is too small, the lines begin to break up. Figure 14 shows lines formed with relatively low overlap for three drum temperatures: (a) 60°C, (b) 75°C, and (c) 80°C. At each temperature, the lines produced at least two values of $\lambda$: The larger value gave lines of reasonably uniform thickness, and the lower value was near the threshold where lines started to show discontinuities. In Fig. 14(a), for $\lambda=0.34$, uniform lines were obtained. At $\lambda=0.12$, two lines are seen, produced under the same conditions; one is continuous and the other is broken. The difference appeared to be due to variations in local substrate conditions. Breakup is clearly caused by drawback: The second droplet was pulled back by the first so that it no longer overlapped the third
droplets, producing a break. This pattern was repeated with the next set of droplets, resulting in a sequence of droplet pairs (Fig. 14(a)).

Raising substrate temperature promotes drawback (see Fig. 6(a)) and therefore breakup of lines takes place at larger values of \( \lambda \). On a surface at \( T_s=75°C \), \( \lambda =0.21 \) produced discontinuous lines (Fig. 14(b)). At \( T_s=80°C \) (Fig. 14(c)), lines were discontinuous at \( \lambda =0.26 \). The location of the breaks was random, as it was with lines made with a very low overlap \( \lambda =0.8 \).

The lengths of lines were measured, and the drawback index \( \theta \) calculated by dividing the ideal length assuming no interaction between droplets

\[
D_s = D_s + (m - 1)L
\]

where \( m=20 \) is the number of deposited droplets. The values of \( \theta \) are presented in Fig. 15 for cases where continuous lines were obtained, and show that drawback is more pronounced at high drum temperatures, as was seen with two droplet depositions (see Figs. 5(a) and 6(a)). Whereas we measured \( \theta >1 \) when \( \lambda >0.6 \) for two droplets (see Fig. 5(a)), \( \theta \) was always less than 1 for lines of droplets. Increasing overlap appears to make the lines wider (see Fig. 13(a)) rather than much longer.

We can use the observations made with two droplets to predict conditions when a line of droplets will no longer be continuous, but will break up due to drawback. When two overlapping droplets are deposited on a surface, the far edge of the second drop is located (see Fig. 16) at \( x=(D_s + L)\theta \), where \( \theta \) is the drawback index measured for two droplets and \( x=0 \) corresponds to the left edge of the first droplet. If there was no interaction with the first two droplets, the left edge of the third droplet would be located at \( x=2L \), overlapping the first two by

\[
\Delta X = (D_s + L)\theta - 2L
\]  

(21)

If \( \Delta X <0 \), the third droplet will not touch the first two and there will be a break in the line. Dividing Eq. (21) by \( D_s \) and using the definition \( \lambda \) (Eq. (1)), we get

\[
\frac{\Delta X}{D_s} = (2 - \lambda)\theta - 2(1 - \lambda)
\]  

(22)

Using the values of \( \theta \) from Fig. 5(a), Eq. (22) is plotted in Fig. 17 for two substrate temperatures, 60°C and 75°C. Photographs of lines formed at several different values of \( \lambda \) are also shown as insets to Fig. 17. For the cases that \( \Delta X/D_s <0 \), the lines are discontinuous.

The critical condition to form continuous lines is \( \Delta X/D_s =0 \). Setting the left hand side of Eq. (22) to zero, we obtain a relationship between \( \theta \) and \( \lambda \) as follows:

\[
\Delta X = (D_s + L)\theta - 2L
\]  

(21)

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Using the values of \( \theta \) from Fig. 5(a), Eq. (22) is plotted in Fig. 17 for two substrate temperatures, 60°C and 75°C. Photographs of lines formed at several different values of \( \lambda \) are also shown as insets to Fig. 17. For the cases that \( \Delta X/D_s <0 \), the lines are discontinuous.

The critical condition to form continuous lines is \( \Delta X/D_s =0 \). Setting the left hand side of Eq. (22) to zero, we obtain a relationship between \( \theta \) and \( \lambda \) as follows:
The locus of Eq. (23) is plotted in Fig. 18. Conditions under the curve will lead to breakup of lines, while those above it will produce continuous lines. As drawback effect rises, i.e., $\theta$ decreases, discontinuous lines are expected to occur for a large range of $\lambda$. The results of two droplets' deposition presented in Fig. 5(a) are shown in Fig. 18, using empty and solid symbols to represent discontinuous and continuous conditions. The effect of drum temperature on the formation of lines can be found by comparing the discontinuous conditions (empty symbols) for the three drum temperatures in Fig. 18. It shows that, when the drum temperature is high, the line breakup occurs for a larger range of overlap ratio. This agrees with the experimental observation that lines broke up easily for high drum temperature (see Fig. 14).

6 Conclusions

The merging of two overlapping molten wax droplets deposited on a cold, rotating aluminum drum was studied. Drum temperature, droplet overlap ratio, and the time interval between depositions of droplets were varied in experiments. The dimensions of a wax bump, formed when droplets coalesce on the drum surface, were measured. To give a quantitative measure of droplet drawback and the shape of the coalesced wax bump, a dimensionless drawback index and aspect ratio were defined. Experimental measurements showed that when drum temperature is increased, or the time interval between impacts of the two droplets is reduced, there is more drawback and the wax bumps become round, since the cooling rate of droplets is slower and droplets have a longer time to change shape due to surface tension. The effect of changing droplet overlap becomes more pronounced when droplet-cooling time is longer. A simple heat transfer model was developed to predict changes in droplet-cooling rate with changes in droplet overlap, substrate temperature, or deposition frequency. The formation of lines by deposition of 20 droplets was studied. If drawback was sufficient to pull back a droplet before the next one landed on it, lines were not continuous but had gaps. Data from the drawback of two droplets could be used to predict conditions under which lines broke up.

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