The Effects of Corona Treatment on Impact and Spreading of Ink-jet Drops on a Polymeric Film Substrate

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Abstract

The effects of varying corona surface treatment on ink drop impact and spreading on a polymer substrate have been investigated. The surface energy of substrates treated with different levels of corona was determined from static contact angle measurement by the Owens and Wendt method. A drop-on-demand print-head was used to eject 38 μm diameter drops of UV-curable graphics ink travelling at 2.7 m/s on to a flat polymer substrate. The kinematic impact phase was imaged with a high speed camera at 500k frames per second, while the spreading phase was imaged at 20k frames per second. The resultant images were analyzed to track the changes in the drop diameter during the different phases of drop spreading. Further experiments were carried out with white-light interferometry to accurately measure the final diameter of drops which had been printed on different corona treated substrates and UV cured. The results are correlated to characterize the effects of corona treatment on drop impact behavior and final print quality.

Introduction

In recent years ink-jet printing has become an increasingly flexible tool for manufacturing. Not only can traditional graphics be printed with extremely high quality, but now also at a much greater scale and speed than previously imagined. Other techniques using ink-jet printheads are developing rapidly with good results across electronic, manufacturing and biological engineering. Understanding the fundamentals of drop impact on to a solid surface is essential for controlling the shape and position of the deposited material. In a graphics context this would determine the quality of an image, but in other applications it can influence whether a pixel in a display screen operates correctly, a living cell is in the right place or if a circuit will conduct electricity.

Many applications require fluids to be deposited on to a poorly-wettable surface, such as a polymer film, coated glass or silicon. In order to achieve good adhesion the ink must wet the surface adequately. In order to achieve this, substrates often have their surface modified by corona discharge treatment (CDT), which increases the surface energy, and therefore enhances the wettability of the surface.

The various phenomena involved in liquid drop impact and spreading have been widely investigated for many different substrates and impact conditions. Four stages of impact have been identified by Rioboo et al. [1] as the kinematic, spreading, relaxation and wetting phases. The timescale and rate of change of diameter in each phase together determine the final drop diameter. Several approaches to predicting this from the initial conditions have been made over the last twenty years with considerable success. However there is little literature on the behavior of sub-millimeter drops, and currently none which examines the effects of CDT on drop impact and spreading behavior.

Corona treatment is used widely across the printing industry to increase the surface energy of polymeric films and metal foils. The corona discharge is produced by electrodes connected to a high-voltage generator which ionize the air between them and the surface of the film, which is backed by a grounded base roll. The ions produced are believed to oxidize the surface of the substrate, increasing its surface energy and thus reducing the contact angle between the printed fluid and the substrate (e.g. Kannangara et al. [2]).

Investigations by Meiron and Saguy [3] into the effect of corona treatment on high surface energy polymers showed that the increase in surface energy came from the polar component of free surface energy. This is supported by chemical analysis of corona-treated surfaces by Briggs et al. [4] who found a 3.5 % increase in oxygen-based functional groups for a low level of corona treatment (final surface energy 44 mJ m^{-2}) and a 4.7 % increase for higher treatment (surface energy 59 mJ m^{-2}). Investigation of the surface topography of corona-treated polypropylene has been carried out by Strobel et al. [5] and O'Hare et al. [6]. Using atomic force microscopy (AFM) they imaged the surface before and after treatment and suggested that the surface energy was affected by the formation of low molecular weight oxidized materials.

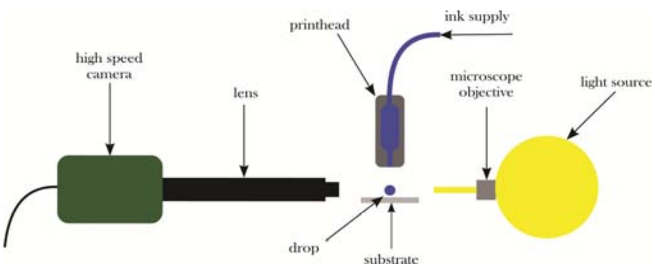
The objective of the present work was to determine the effects of different intensities of CDT on ink drop spreading on a polypropylene-based film substrate. The change in surface energy was investigated and its influence on the behavior of 38 μm diameter droplets impacting at 2.7 m/s, during both the kinematic and spreading phases, is discussed. Methods of calculating the maximum drop diameter were compared and the dependence of final drop diameter on the level of CDT was studied for drops printed under industrial conditions.

Experimental methods and materials

The substrate used in these experiments was a top-coated polypropylene-based film manufactured by UPM (UPM, Helsinki, Finland). Printing and drop impact experiments were performed with a commercial UV-curable graphics ink (SunJet, UK). All corona treatment was carried out with a commercial machine (CP-LAB, Vetaphone A/S, Denmark) and printing experiments and measurements were carried out within one hour of treatment.

Contact angles were measured by the sessile drop method using millimeter-sized drops of the UV-curing ink, triple-distilled water and ethylene glycol, as described by Marmur [7]. Ten measurements of angle were taken and averaged for each combination of fluid and surface, with an error of $\pm 1.8^{o}$.

Figure 1 shows the optical setup used to image the impact and spreading of the ink drops. A Xaar 126/80 drop-on-demand printhead was used to produce individual 38.5 ± 0.2 µm diameter drops traveling at 2.7 ± 0.1 m/s. These conditions correspond to a Reynolds number for jet formation of approximately 11.2 and a Weber number of approximately 8.9. Drop spreading was recorded for the first 300 ms after impact. This cut off was used because in industrial applications UV-curable inks are pinned within this timescale with a low dose of UV light to preventing further spreading. The early stages of drop impact were captured with a Shimadzu ultra-high speed video camera (Hypervision HPV-1). Illumination for these experiments was provided for a period of 2 ms by a high intensity flash system (Adapt Electronics Specialized



Imaging AD500). Images were captured at 500,000 frames per second for 100 frames, with a resolution of 0.66 µm per pixel. The later stages of drop spreading were studied with a Phantom V7.3 high speed video camera with a Navitar 12× lens at 20,000 frames per second, with a resolution of 0.88 µm per pixel; in these experiments the drop was illuminated with a Flexilux 150 W halogen light via a Microtec light guide, focused through a microscope objective to achieve a local high light intensity.

Figure 1. *Experimental setup used to study drop impact and spreading for 38 mm drops travelling at 2.7 m/s. The types of cameras and light sources used are described in the text.*

Individual drops which had been printed on to the substrate at 1 to 6 dpd (droplets per drop) from a Xaar 1001 grayscale drop-on-demand printhead and cured within 100 ms of printing with a 275 nm UV light were measured by white-light interferometry with a Wyco NT3300 instrument, which is capable of measuring features between 0.1 nm to 2 mm in height, with a vertical resolution of 0.1 nm. The heights and widths of the cured drops were measured from 2-D optical sections in both the *x* and *y* directions (in the plane of the substrate), and were repeated for several drops for each sample.

Results and discussion

Quasi-static behavior

Contact angle analysis is a simple yet useful technique for calculating the surface energy of a substrate. The contact angle values determined for millimeter-sized drops of water, ethylene glycol and UV ink on polymer substrates after corona treatment to

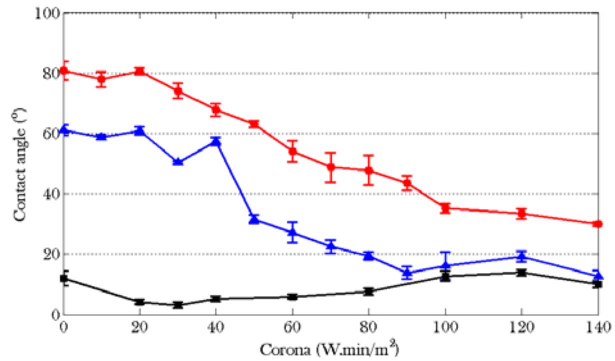


Figure 2. *Static contact angle results for water (circles), ethylene glycol (triangles) and graphics ink (squares) on substrates with different levels of CDT*

levels between 0 and 140 W.min/m^2 are plotted in Figure 2. It is clear that increasing the level of CDT decreased the contact angle for both water and ethylene glycol. However for the UV ink the contact angle decreased slightly for low levels of CDT and then increased at higher levels.

The polar (γ^p) and dispersive (γ^d) components of surface energy and the total surface energy were calculated from the Owens and Wendt equation: see equations (1) and (2) [8]. The results are shown in Figure 3. The total free surface energy (γ) increased with increasing treatment level, due to an increase in the polar component, while there was little change in the dispersive component. This would be consistent with an increasing level of surface oxidation with a higher level of CDT.

$$(1-\cos\theta)\,\gamma_l = 2\sqrt{\gamma_s^d\,\gamma_l^d} + 2\sqrt{\gamma_s^p\,\gamma_l^p} \qquad (1)$$

$$\gamma_l = \gamma_l^d + \gamma_l^p \qquad (2)$$

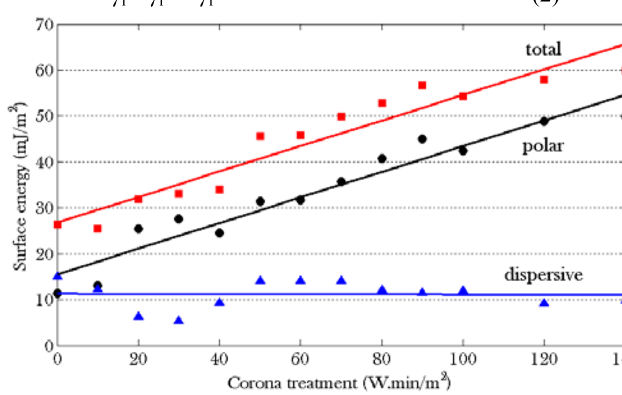


Figure 3. *Surface energy calculated from the Owens and Wendt equation: polar component (circles), dispersive component (triangles) and free surface energy (squares) for substrates with different levels of CDT*

The contact angles measured in these quasi-static tests were used to compute wetting envelopes for the different levels of corona treatment. The contours corresponding to a 0° contact angle for each level of CDT are shown in Figure 4. This shows how increasing the level of CDT increases the wettability of the substrate. The point corresponding to the UV ink lies between the

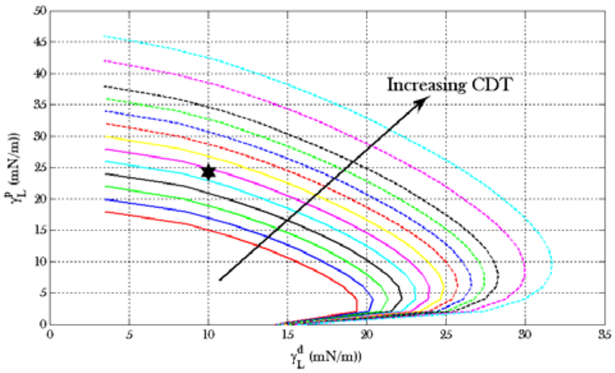


Figure 4. *Wetting envelopes derived from quasi-static measurements of contact angle for different levels of corona treatment from 0 to 140 W.min/m^2. The star shows the values for the UV ink.*

40 and 50 W.min/m^2 contours which suggests that the film requires treatment beyond 40 W.min/m^2 for the ink to wet the substrate completely.

Dynamic analysis

In order to study the effects of corona treatment on the deposition of drops under printing conditions (i.e. with very small drops deposited dynamically), the spreading behavior of printed drops of UV ink was imaged continuously during the kinematic, spreading and relaxation phases. In all these dynamic experiments the drops had a diameter D_o of 38 µm and a velocity at impact, U_o of 2.7 m/s. The results have been analyzed in terms of spread factor and non-dimensional time. The non-dimensional time, t^*, is defined by $t^* = t^*U_o/D_o$. The spread factor, β is the instantaneous deposit diameter D divided by the initial diameter, D/D_o.

In order to examine the effects of CDT on the kinematic phase of impact the first few hundred microseconds were also imaged as described above. Figure 5 shows the results for the first 100 µs of impact. The transition between the kinematic and spreading phases can be seen after ~4 µs.

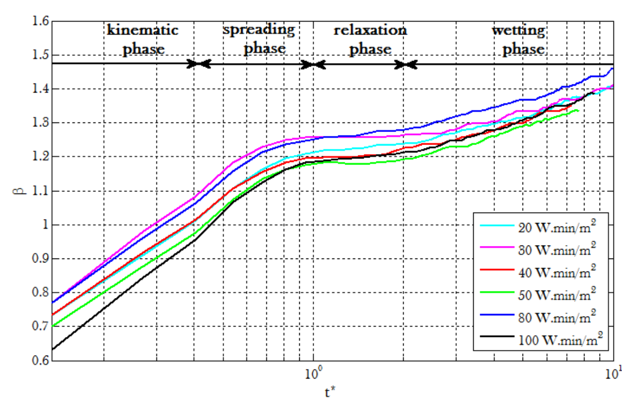


Figure 5. *Spread factor plotted against non-dimensional time for impact of 38.5 µm drops of UV ink at 2.7 m/s on polymer substrates with different levels of corona treatment during the earliest stages of spreading. The different phases of spreading are marked.*

Different levels of CDT do not change the diameter or duration for the kinematic phase. Similarly, the early stages of the spreading phase remain unchanged by different levels of CDT. This is not unexpected as the earliest impact stages are controlled purely by inertia and the effects of substrate surface energy have not yet come into play.

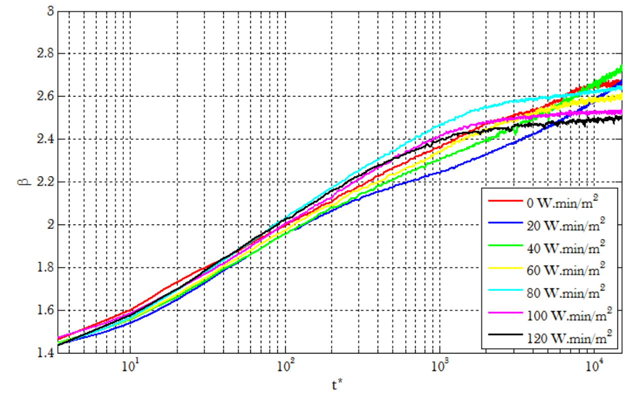


Figure 6. *Spread factor plotted against non-dimensional time for impact of 38.5 µm drops of UV ink at 2.7 m/s on polymer substrates with different levels of corona treatment.*

Figure 6 shows the spread factor for the first 300 ms after impact on polymer substrates treated with different intensities of CDT. At low levels of corona treatment the time taken to reach the relaxation phase appear to be longer, whereas for 80 - 120 W.min/m^2 the transition between the wetting phase and reaching equilibrium clearly occurs between 20 and 40 ms after impact. This is consistent with the static contact angle results for UV ink, as the drop will spread further before reaching its equilibrium contact angle.

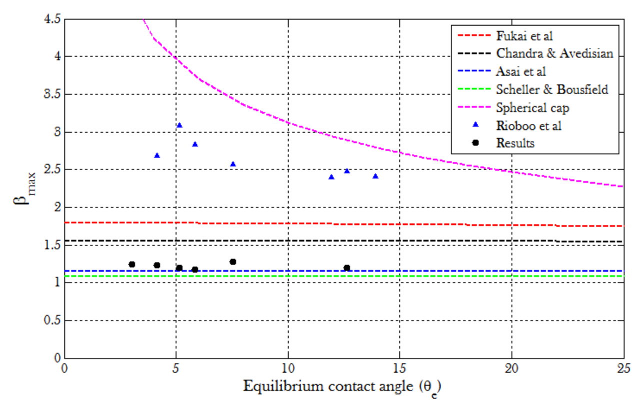


Figure 7. *Maximum spread factor for drops of UV curing ink printed on substrates with different levels of CDT. Spread factors are plotted against the quasi-static contact angles for the ink on the same substrates.*

The maximum spread diameter, D_{max}, and associated maximum spread factor $\beta_{max}= D_{max} /D_o$, were measured for ink drops printed on substrates after different levels of CDT. The values are plotted in Figure 7 against the contact angle values measured for large drops in the quasi-static experiments. Many methods have been reported for predicting β_{max}. The models of Asai et al. [9] and Scheller & Bousfield [10] are based on the We and Re numbers, and do not require a contact angle measurement. Both are empirical, with the model of Asai et al. being based on micrometre-sized drops. The model of Chandra & Avesidian [11] is based on energy conservation with a cylindrical shape at β_{max}. Fukai et al. [12] developed a semi-empirical model based on Chandra & Avesidian's work. In a further model a spherical cap shape can be assumed, based on volume conservation and the value of static contact angle. This approach gives a similar result to the value of β_{max} proposed by Rioboo et al [1] which is based on volume conservation but uses the advancing contact angle, θ_{adv}, instead of the static contact angle.

The predictions from each of these models are also plotted in Figure 7. The models of Asai et al. [9] and Scheller & Bousfield [10] are in best agreement with the results. The model based on a spherical cap and the value of quasi-static contact angle overestimate the final diameter. Use of the advancing contact angle together with volume conservation [1] also overestimates β_{max}. These results suggest that previous models derived for large (millimeter-sized) drops are applicable to the much smaller drop sizes encountered in ink-jet printing, and that a simple model based on We and Re numbers is a good predictor for β_{max} under the conditions studied here.

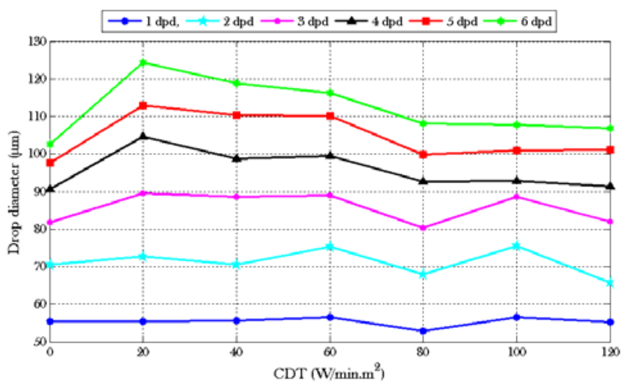


Figure 8. *Final drop diameter for printed and cured drops on polymer substrates with different levels of corona treatment, for six different drop sizes (gray-scale levels)*

Final print quality

In order to validate these experimental results obtained with individual drops in laboratory conditions, printed samples generated in a full-scale industrial web printing system were analysed. Drops of UV ink were printed from a Xaar 1001 head on to the same polymer substrate which had been corona treated (with an in-line system) and were UV-cured ~100 ms after printing. White-light interferometry was used to measure the final deposit diameter for the solidified drops. The sizes of the drops were varied by varying the gray-scale level, from 1 to 6 drops per dot (dpd). For this head, each step in the gray-scale level corresponds to a change of 6 pl in total drop volume. The results are shown in Figure 8.

The maximum printed drop diameter occurred for treatments between 20 and 40 W.min/m^2. This is consistent with the low contact angle results measured at these levels of treatment and the relatively prolonged spreading phase before drop relaxation. It can therefore be concluded that the results found experimentally under laboratory conditions are applicable to practical industrial printing conditions.

Conclusions

The changes in surface energy for a coated polypropylene-based film substrate have been investigated for different intensities of corona discharge treatment. The total surface energy of the film increased with the level of CDT, and was associated with an increase in the polar component. This resulted in an increase in wettability for both ethylene glycol and water. A UV-curing graphics ink was found to wet the surface best for treatment levels between 20 and 40 W.min/m^2.

The impact and spreading of 38 μm drops of graphics ink with an initial velocity of 2.7 m/s were studied in detail during the kinematic, spreading and relaxation phases. The spread factor (instantaneous deposit diameter divided by the original drop diameter) was recorded during drop impact for substrates with different levels of corona treatment. The main influence of CDT on spreading behavior was to extend the spreading phase and increase the time before the relaxation phase was reached at low levels of corona treatment. This behavior correlates with the quasi-static contact angle results and is also consistent with measurements by white-light interferometry of final deposit diameter for printed and cured drops produced with a gray-scale print-head in an industrial system.

Several approaches to predicting the maximum spread factor have been compared with experimental measurements. It was found that the models using both Weber and Reynolds numbers, proposed by Asai et al. [9], gave the most accurate prediction for this experimental setup.

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Author biography

Eleanor Betton received her MEng in mechanical engineering from the University of Bristol, UK (2007). Her masters work focused on fluidized granular flows and separation. She is currently completing her PhD at Cambridge University in which she has investigated corona treatment, drop impact and coalescence of ink-jet droplets.