Analysis of Droplet Train/Moving Substrate Interactions in Ink-Jetting Processes

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Abstract

Ink-jetting technology has been applied to several processes in solid free-form fabrication (SFF) wherein droplets impinge onto a substrate to deposit the build material. Droplet impact behaviour on a surface has been the interest of many researchers; however, few studies have been undertaken to investigate the interaction of droplets with the moving substrate. This paper reports the impact behaviour of the droplets jetted at different frequencies onto a substrate moving over a range of velocities. The phenomena associated with the interaction were classified into three main regimes.

1 Introduction

Several processes have been developed in the area of solid free-form fabrication (SFF) using the concept of material deposition [1]. Jetting is gaining more interest these days as a result of latest developments in the jetting heads. The technique is capable of depositing pico-litre sized droplets onto a substrate. This can provide of a high resolution and good final surface quality with a completely dense structure. These advantages can be applied in a layer-wise process where a functional part is made for actual use instead of a prototype. The authors are investigating such a possibility at Loughborough University by jetting two mixtures of caprolactam with initiator and catalyst to polymerise nylon on the substrate under appropriate conditions (e.g. temperature and inert gas). The concept of the process is similar to cast nylon but has lots of challenging issues with jetting, droplet placement, spreading and mixing the droplets of the two mixtures jetted separately by a drop on demand (DoD) mode jetting head. In addition, a rapid polymerisation of each layer is required which can be achieved by precise selection of mixture composition, droplet deposition and mixing method. Droplet formation characterisation and its impact behaviour on a moving substrate will be two of the main challenges in the research work. A good understanding and control of these two phenomena is required as prerequisites of the research work. Initial work studied continuous ink-jetting (CIJ) a diluted solution of a biodegradable UV (ultra-violet) sensitive resin onto a moving substrate. The achievements of this study are reported in this paper.

The impact of a droplet onto a substrate accompanies a number of issues such as mechanical deformation which depends on the droplet's physical properties and the surface conditions [2]. The droplet may stick to the surface, bounce off or splash and split into smaller droplets [3]. In the case of a stationary substrate, a droplet will spread radially to form a liquid layer [4]. In addition, depending on droplet kinetics and the impinging surface, a crown may be formed [4, 5]. However, in the case of a moving substrate, the droplet spreading seems to be biased by the substrate motion.

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There are several references reviewed in the literature describing droplet impact behaviour on a stationary surface [4-7]. A lack of literature was found in droplet impact behaviour on a moving surface, especially in SFF area. Where droplets impinge onto a stationary liquid surface, it was shown that the impact behaviour is directly dependent on the physical properties of the liquid and the frequency of the droplet train [7]. However, this paper reports the impact behaviour on a moving substrate. By varying the substrate velocity and the droplet train frequency, it was planned to investigate the droplet impact behaviour quantitatively.

2 Experiments

A solution of isopropanol (Propanol-2 PUR from Acros Organics) and a bio-degradable resin developed for TNO Science and Industry was applied in this study. All the experiments were undertaken at a controlled room temperature of 20°C. Table 1 shows the physical properties of the solution. A contact angle measuring instrument (OCR20 from DataPhysics Instruments GmbH) was used to measure surface tension of the solution applying the pendent drop method and contact angle on a simple microscope glass slide (Lames Porte Object from Menzel Glaser GmbH) applying the sessile drop method. The dynamic viscosity of the materials was measured using a standard rotational viscometer (VT500 from Haake). Figure 1 shows the result.

Property	***Value***	***Unit***
Density	0.98 ± 0.01	g/cm^3
Surface Tension	26.4 ± 0.2	mN.m^{-1}
Contact Angle	22.8 ± 2	Degree

Table 1. Physical properties of the jetting material

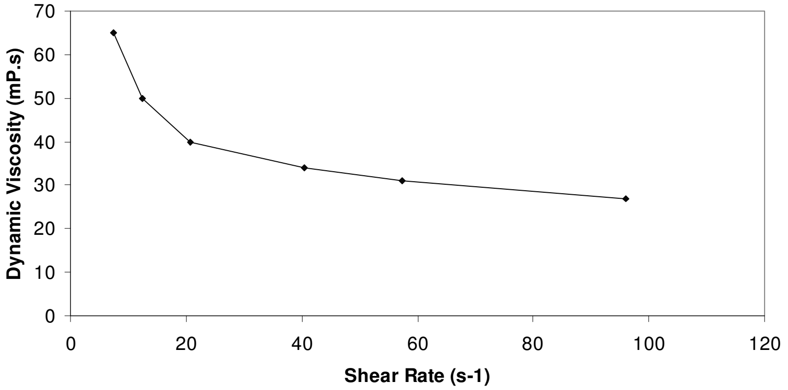


FIG 1. Dynamic viscosity of the jetting solution at 20 °C

Figure 2 shows a schematic of the applied setup in the current work. Two pumps were used to feed the jetting head. The prismatic pump (S/L Easy-load II from MasterFlex) supplied the jetting material through a beaker to a dosing pump (HLPC K-120 from Knauer) known as micro-pump in this paper. A damper was used to smooth the flow rate which was set at 0.55 ml/min and pressure generated by the pumps. The fluid was consequently deposited in the form of droplets through the jetting head designed and manufactured by TNO Science and Technology. The piezoelement of the jetting head was vibrated by an amplifier (LVPZT E-501-00 from Physik Instrumente Ltd. (PI)) which received sinewave signals from a function generator (TG330 from Thurlby Thandar Instruments Ltd. (TTi)).

The imaging system consisted of a high speed camera (FASTCAM APX-RS from Photron Inc.) and a light source (VIT from Everest Inc.). The light source was positioned in order to capture a shadow of the droplets and impact phenomena. A lens was used to magnify the impact location of the droplets impact. Positioning of the droplets was achieved by a 3D motion system manufactured by Aerotech Inc., where a high speed slide provided a variable speed. The jetting head was set at a height of 45 mm above a 1 mm thick glass slide (OCR20 from DataPhysics Instruments GmbH) fixed to the high speed slide. Imaging of the droplet impact was achieved on 35 mm of the length of the glass substrate.

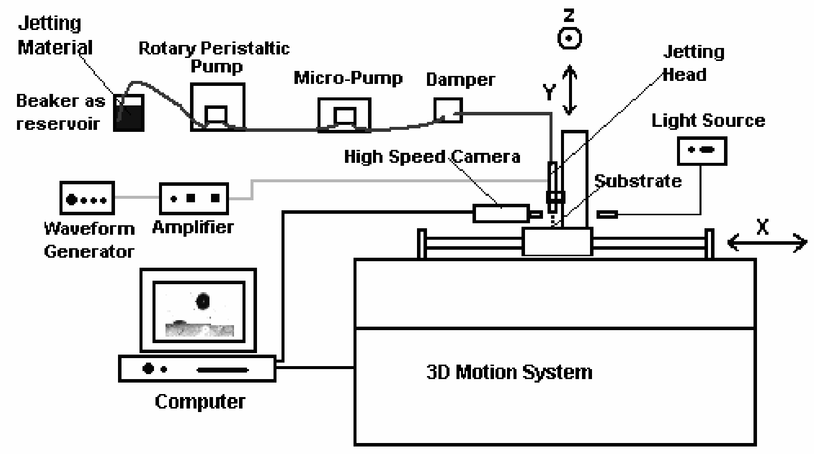


FIG 2. A schematic of the setup

Different frequencies (from 5 to 20 kHz) with fixed amplitude of 0.65 v were applied to study the effect of droplet formation on impact phenomena. The appropriate frequency for the study was found to be between 9 to 18 kHz and gave a consistent droplet formation. Two frequencies of 12 and 18 kHz were typically selected as the relatively low and high frequencies in the droplet impact study. The imaging system was set to capture impact phenomena with a rate of 45,000 frames per second (fps). Substrate velocities in the range of 0.1 to 9 m/s were applied. The camera was triggered by remote control and impact of the droplets on the moving substrate was captured. The images were then analysed to quantify droplet formation characteristics and the impact behaviour. Droplet formation characteristics such as droplet size, velocity and generation rate, and impact behaviour such as spread layer thickness were quantified using the glass slide’s thickness as a reference.

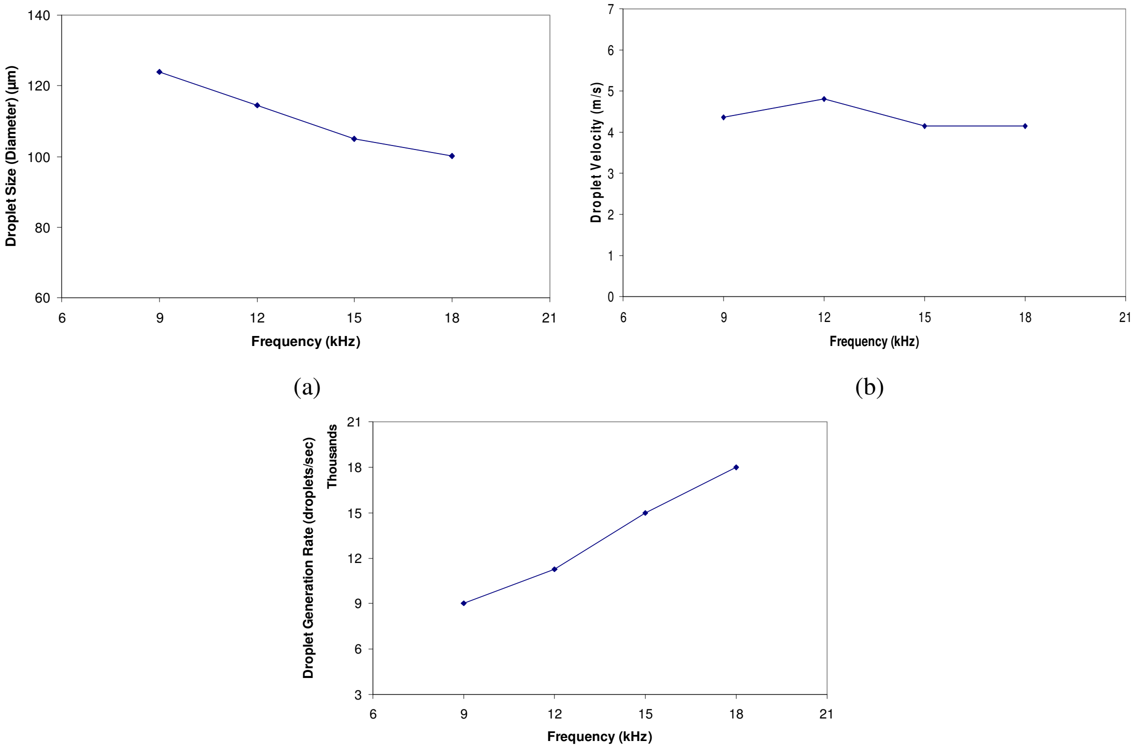
3 Results and Discussions

3.1 Droplet Formation Characterisation

Figure 3 shows the effect of frequency on droplet size (diameter), velocity and generation rate. By increasing the frequency, the droplet size was decreased while in contrast, the droplet generation rate increased. There was a slight variation in droplet velocity.

3.2 Droplets Impact on a Moving Substrate

The droplet impact rate should be taken into account in case of a train of droplets. Table 2 shows the impact energy and its rate at different frequencies. It was interesting to find that the impact energy rate of a droplet train at 12 kHz was much higher than 18 kHz even with taking the droplet impingement frequency into account.



(a) (b)

(c)

FIG 3. Variation of (a) droplet size, (b) velocity and (c) generation rate

Frequency (kHz)	*Impact Energy (nJ)*	*Impact Energy Rate (mJ/µs)*
9	9.7	89
12	9.4	105
15	5.7	81
18	4.7	84

Table 2. Impact energy rate at different frequencies

Figure 4 shows a sequence (nine consequent frames) of droplets impinging on the moving substrate. The camera captured at least three images for each droplet. The sequence in Figure 4 shows impingement behaviour of the three consequent droplets to illustrate the similarity and repeatability of the impact behaviour at the chosen conditions. As can be seen in the figure, spreading droplets made a liquid layer (film) with a specific thickness. The advancing liquid layer front was a result of both the deposition process and substrate travel. A wave formed on the liquid layer shown as W1 (Wave 1) caused by impact of droplet 1 and W2 made by droplet 2 as shown in Figure 4. It is seen that the waves shape and motion are repeatable. At a high substrate velocity, some un-wetted (un-covered) sections of the substrate were caused as Figure 5 shows.

Figure 6 shows formation of a wave in front of the advancing liquid layer formed with a low substrate velocity. This kind of wave had a crown-like shape which could be a result of the interface at the wet/dry surface boundary (shown in the figure) of the advancing liquid layer onto the dry surface. The existence of such interface as the source of the waves is in accordance with the theory of Yarin and Weiss [6]. However, there was a periodic behaviour in wave formation in front of the advancing liquid layer as shown in Figure 6.

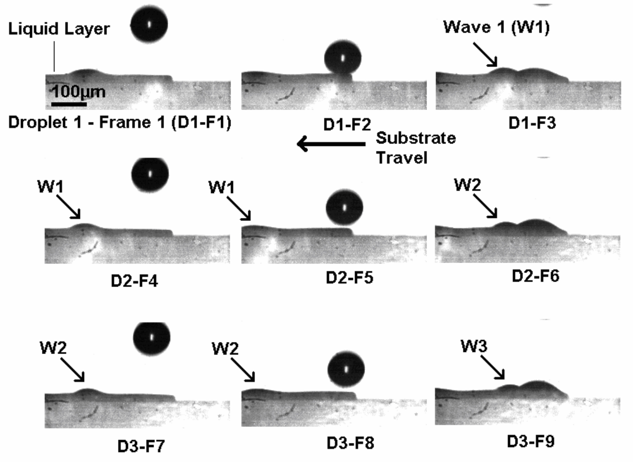


FIG 4. The solution's droplets impinging on the substrate with 8 m/s velocity (Frequency 15 kHz)

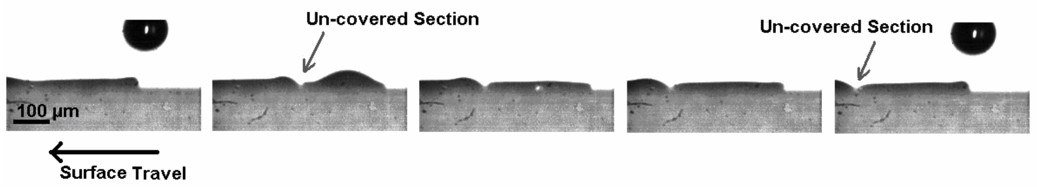


FIG 5. Uncovered sections in the droplet spreading at too fast substrate (9 m/s) (Frequency 9 kHz)

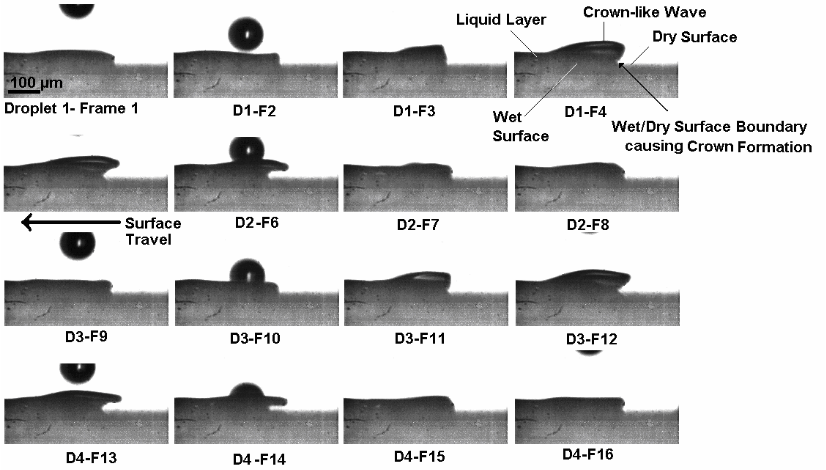


FIG 6. The droplets impinging on the substrate with a high speed (1 m/s) (Frequency 12 kHz)

Figure 7 shows the formation, growth and advancement of a wave and finally its separation from the advancing liquid layer. This phenomenon seems to be a result of material build-up in the advancing liquid layer front. As shown in the sequence in Figure 7, the wave separated from the advancing front of the liquid layer after reaching a certain volume. This phenomenon which will be discussed further was only seen at higher substrate velocities and jetting frequencies where the impingement frequency was high (Figure 3(c)). The separation of the built-up liquid from the advancing layer front was typically repeated three times along the monitored length of the substrate (35 mm).

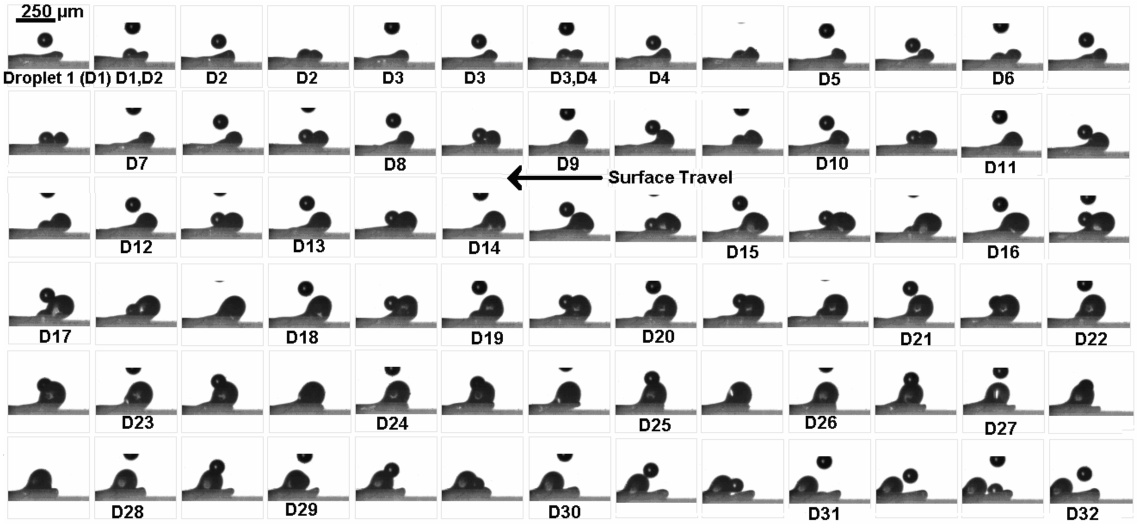


FIG 7. Solution liquid build-up wave in front of the advancing liquid layer at a high impingement frequency (Substrate velocity 7 m/s, Frequency 18 kHz)

Figure 8 and 9 show the variation of the spread layer thickness and the height of the waves formed at the front of the advancing liquid layer with varying substrate velocity at two typical jetting frequencies. Dots in the figures indicate the spread layer thickness while the height of the waves is shown by vertical lines on top of the dots to show the rising and falling nature of the waves made above the spread layer thickness. An image inside Figure 8 and 9 indicate how the maximum height of the waves was measured in relation to the layer thickness.

The spread thickness with a substrate velocity greater than 3 m/s for the two studied jetting frequencies was constant but a thicker layer was achieved at 18 kHz frequency. As Table 2 reveals, the impact energy of the droplets and the impact energy rate at 12 kHz frequency was higher than 18 kHz which helped the deposition process. This made a thinner liquid layer of 25 µm for 12 kHz compared with the 30 µm layer thickness of 18 kHz. This was mostly affected by the higher droplet size generated at lower frequency (Figure 3(a)).

The maximum height of the waves had different trends in different process conditions as Figure 8 and 9 reveal. High values of maximum wave height (seen in Figure 9) at the higher frequency (18 kHz) with higher substrate velocity (>3 m/s) corresponds with the situation shown in Figure 7. The droplets impinged onto the wet substrate and made a wave at the front of liquid layer. Growth of the wave was seen up to a certain volume until it separated from the advancing front of the liquid layer. On the other hand, lower values of maximum wave height seen in Figure 8 and 9 (lower substrate velocities), corresponds with the situation shown in Figure 6 where droplets impinged onto the wet surface and made a wave without any build-up which fell quickly before impingement of the following droplets. In addition, situations shown in Figure 4 and 5, where no wave was formed in the advancing front of the liquid layer with higher substrate velocities, were demonstrated in Figure 8.

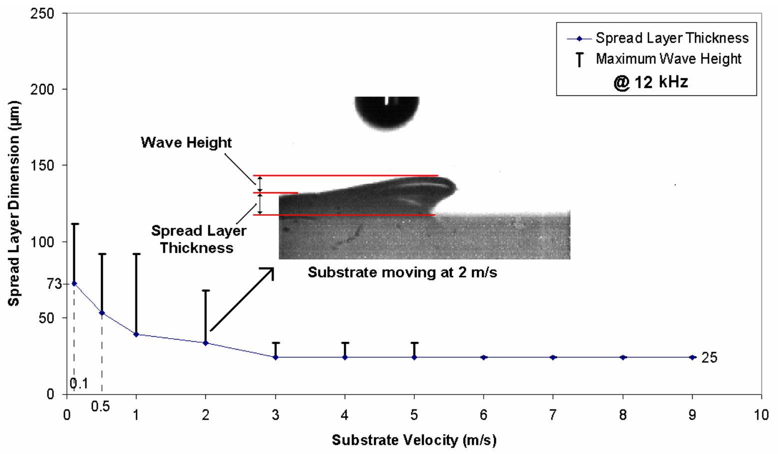


FIG 8. Variation of the spread layer dimensions (spread layer thickness and maximum wave height) formed by the droplets jetted at 12 kHz impinging onto the substrate with varying velocity

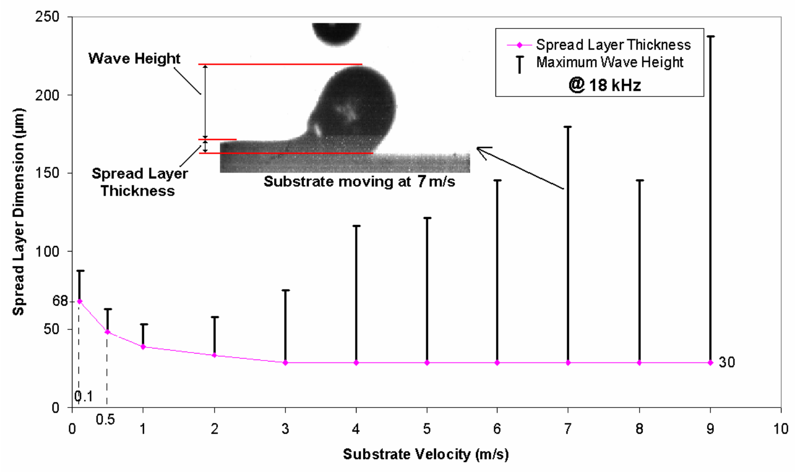


FIG 9. Variation of the spread layer dimensions (spread layer thickness and maximum wave height) formed by the droplets jetted at 18 kHz impinging onto the substrate with varying velocity

3.3 Droplet/Moving Substrate Interaction Regimes

In spreading a droplet, the deformation process is driven by the droplet physical properties, its impact energy and the surface physical properties [5, 6]. In the case of a moving substrate, the deposition of the droplets depends also on the substrate motion. Three main droplet/moving substrate interaction regimes were found. Figure 10 classifies the three regimes as 1, 2, and 3.

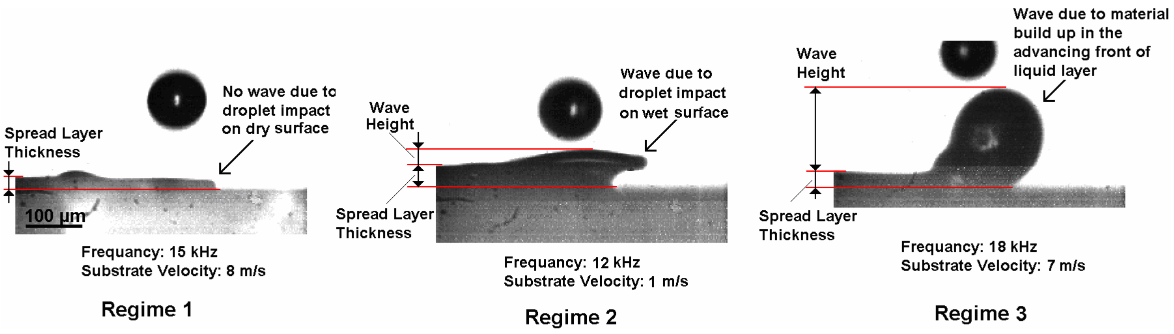


FIG 10. Spreading regimes in droplet impact on a moving substrate in different process parameters

Regime 1

In Regime 1, no wave is formed at the front of the liquid layer as can be seen in Figure 4 and 10. However, a capillary wave behind the front of the liquid layer was formed as Figure 4 shows. This was generally due to a high substrate velocity typically higher than 5 m/s. Figure 8 clearly shows the zone of this regime. Generally, this regime was seen with lower frequencies and higher substrate velocity and is preferred in terms of a smooth spread layer.

Regime 2

Regime 2, as shown in Figure 10, exhibits a crown-like wave at the advancing front of the liquid layer. Generally, this wave was formed with every droplet impingement or every other impingement (Figure 6). Therefore, the periodic behaviour of formation and damping of the wave is characteristic of Regime 2. This periodic behaviour could be due to the impingement frequency and the liquid layer thickness.

As shown in Figure 6, the source of the crown-like wave was the wet/dry surface boundary. This was due to the difference in surface energy between the spreading solution and the dry (glass) surface. Therefore, in an impact of a droplet on a wet surface, a kinematic discontinuity is made resulting in a crown-like wave. This is similar to the splashing droplets in impingement onto a stationary liquid surface investigated by Yarin and Weiss [6]. The crown-like wave had a height almost equal to the spread layer thickness. Regime 2 occurred during impingement of the droplets onto the substrate with lower velocity (typically less than 3 m/s) where the substrate was made wet by previously spread droplets. Although having waves in front of the liquid layer in this regime, the waves diminished just after spreading. This regime does not affect the layer surface uniformity.

Regime 3

Regime 3 was the generation of large waves (as shown in Figure 10) at the front of the advancing liquid layer. As the sequence in Figure 7 shows, the characteristic of this wave was formation, growth, travel with the advancing liquid layer onto the dry substrate and finally separation from the front after reaching a certain volume (shown in Figure 9 as maximum height). This kind of wave also had a periodic behaviour and occurred typically three times along the substrate.

The height of the wave of the Regime 3 was much higher than the wave in Regime 2. Comparing Figures 8 and 9, this regime was seen with higher jetting frequency (18 kHz) and higher substrate velocities. The flow rate for the two frequencies (12 kHz and 18 kHz) was the same. Thus the main difference between Regime 3 in Figure 9 (substrate velocities higher than 3 m/s) and Regime 1 in Figure 8 (substrate velocities higher than 5 m/s) is the size of the droplets and their kinetic energy. In Regime 3 the droplets are smaller and have lower kinetic energy. In Regime 1 the larger droplets that have higher kinetic energy promote greater spreading of the material. The growth process continued to a certain volume until the inertia of the built-up wave separated it from the advancing front and it merged into the spread liquid layer. The separation volume inferred from the wave's height increased with substrate velocity as shown in Figure 9 showing the effect of the substrate velocity in Regime 3.

Although the wave eventually merged with the spread layer, it may not be flattened completely before any phase change. This could lead to a bump in the surface of the fabricated layer. Therefore the surface finish of a fabricated part could suffer from this regime.

4 Conclusions

The deposition phenomenon of a train of droplets in different process conditions is discussed in the current work. More specifically, the effects of the droplet formation characteristics and the substrate motion were correlated with the impact behaviour by studying the droplet spreading behaviour. It has been shown that three different regimes occur during the impact of droplets onto a moving substrate. The most dominant factor was the substrate velocity where waves can occur at higher values by choosing an incorrect jetting parameter. When a high substrate velocity is required, lower frequencies having higher impact energy can avoid formation of large waves which are harmful for achieving a smooth spread layer surface. By careful selection of jetting conditions and substrate velocity, it is possible to obtain a uniform layer before any phase change process. The high speed movement of the substrate helps to spread the material but this needs to be controlled carefully otherwise positional resolution and surface uniformity will suffer.

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