# The Dawn of Ink-Jet Fabrication in Reel-to-Reel System

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## Abstract

*Flexible substrates are becoming more important in the printed circuit board and display industry. The flexible circuit boards can be thinner and lighter than rigid board, and can be flexibly and easily assembled into high level electronic product. The era of ink-jet fabrication is coming due to its low cost, high throughput and the feasibility of manufacturing on flexible substrate. The innate of ink-jet printing in non-contact characteristic and digitalization of patterning make it become a bright star in future manufacturing. In this paper, an evaluation of the possibility of ink-jet fabrication in reel-to-reel system was prepared for (a) the comprehensive stability occurred in jetting behavior, it included the stability of electrical firing control, ink back pressure control and ink temperature control. (b) The need of surface property and uniformity prior to ink-jet printing, especially for polyimide substrate and its treatment. (c) The image compensation of extension due to the reel-to-reel process. (d) The quality deterioration by the acoustic disturbing while high-speed flying of substrate relative to print head. (e) The integrated line flow design and compromise of speed and performance. Specially, the working surface of the substrate is kept out of contact with each transmitting roller to avoid the pollution in this continuous roll-to-roll circuit fabrication system by ink-jet printing. This design is important for modular process flow.*

## Introduction

Plastic electronics are big business these days. They are still sparse on the sales floor, but electronics giants in Japan, Europe, and North America are all pushing hard on the technology to make ultra-cheap printable electronics for everything from smart cards and product ID tags to the electronic drive circuitry for large-screen displays. Researchers have shown that they can make many of these devices with materials that already exist. But among the deviling details, most of today's plastic electronic materials that can be printed from liquids—the cheapest manufacturing method—are unstable in air and quickly degrade [1].

## Evaluation a Reel to Reel IJP System

### *(a) Ink-Jet Printing Stability*

#### *Environmental Condition*

As a liquid drop approaches a solid surface, the liquid can either displace or compress the air. The landing profile dominated by the drop kinetic energy and the surface properties between the liquid-solid interfaces [15]. Based on the rapid initial spreading of the liquid on the surface (the radius of the spreading disk increases as the square root of time), the liquid front will compress the air. At a standard pressure, the gas resists compression, forcing the liquid edge to lift, and making free liquid sheet to be broken. The corresponding force (per unit area) is proportional to the gas density, speed of sound (resulting from air compression) and liquid velocity. Surface tension, which maintains the liquid cohesion, opposes this destabilizing force [10]. Splashing occurs when the two forces are equal, and so is reduced as the gas density vanishes. Xu et al. [11] observed that splashing occurs more easily with a heavier gas (krypton or sulphur hexafluoride), it implies that the air can be used to modulate the behavior of a drop landing, by lower pressure condition or lighter molecular weight. Or alternative, a vibration induced force to balance this air resistance. Chen [12] found a vibration force will smearing the ring formation of drop landing and, Couder [13] found vibrating force against with gravity at a sufficiently high frequency can prevent coalescence and help the drop simply bounces on the surface. This environmental condition and vibration induced is a key consideration for reel-to-reel process.

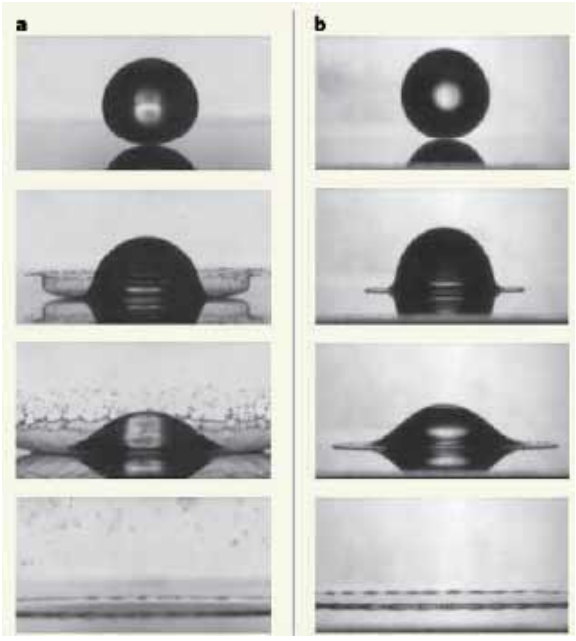


***Figure 1.*** *Impact zone as shown in these high-speed photographs taken by Xu* et al.*[11], air pressure determines the outcome of the impact of an ethanol drop on dry glass. a, At ambient pressure there's a splash. b, In a rarefied atmosphere — 0.3 atm, equivalent to that found at the summit of Everest — a corona fails to form and there is no subsequent splash.*

## *Back Pressure Control*

Undoubtedly, a back pressure dominates the stability during drop-to-drop jetting. In our design, the pressure can be keep within ±0.1 mbar in tuning range of 3-20 mbar. However, when operated at high speed printing, the print head moved related to flexible substrate, the pressure condition will deteriorate down to ±1.4 mbar due to the air flow circulation occurrence. The trend is proportional varying with the relative motion speed. In this design, now we are trying to equip a blunt surface to guide the air streaming, avoid of the air circulation near nozzles, as shown in Fig.2. The guide plate will keep smoothing stream flow beneath print head and lag the occurrence of vortex, makes the less pressure disturbing into nozzle.

| | Sampling A | Sampling B | Sampling C |
|---|---|---|---|
| Setting | 7.971 | 7.979 | 7.978 |
| Max. | 8.208 | 8.296 | 8.235 |
| Min | 7.728 | 7.735 | 7.671 |
| Std. | 0.099914 | 0.104642 | 0.103005 |

(a)

| | Sampling A | Sampling B | Sampling C |
|---|---|---|---|
| Setting | 8.133 | 7.973 | 7.880 |
| Max. | 14.232 | 13.755 | 13.969 |
| Min | 2.006 | 1.590 | 1.269 |
| Std. | 1.502388 | 1.304801 | 1.394658 |

(b)

***Table.1*** *Back pressure stability in jetting (a) Stationary, no relative moving between head and substrate). (b) Head is moving related to substrate at high speed. Unit: mbar.*

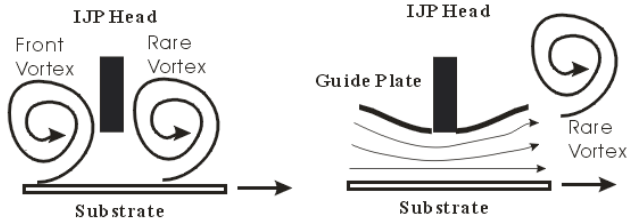



***Figure.2*** *Guide plate equipped at the print head to avoid the vortex disturbing back pressure.*

## *(b) Uniformity*

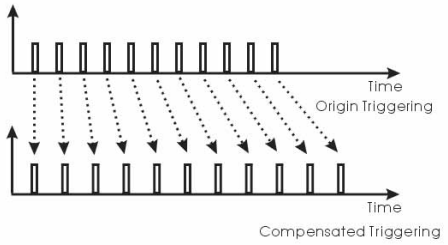
The need of surface property and uniformity prior to ink-jet printing is especially for polyimide substrate and its treatment. Generally, softer substrate like PI, its extension during delivery will deteriorate the uniformity and need to carefully compensate the deviation. Below tabulated some flexible substrates for their $T_{g,}$ extension, and peel strength property.

| Material | Tg (℃) | Z-Axis Expansion (%) | Density ($g/cm^3$) | Dielectric Constant ($D_K$@1MHz) | Peel Strength (N/cm) |
|---|---|---|---|---|---|
| FR-4 Epoxy | 140 | 4.5 | 1.79 | 4.3-4.7 | 15.8 |
| High $T_g$ FR-4 Epoxy | 150 | 3.7 | 1.97 | N/A | 12.3 |
| BT Epoxy Blend | 185 | 3.75 | 1.77 | 3.5-4.3 | 15.6 |
| Polyimide | 250 | 1.75 | 1.68 | 4.0-4.3 | 13.1 |

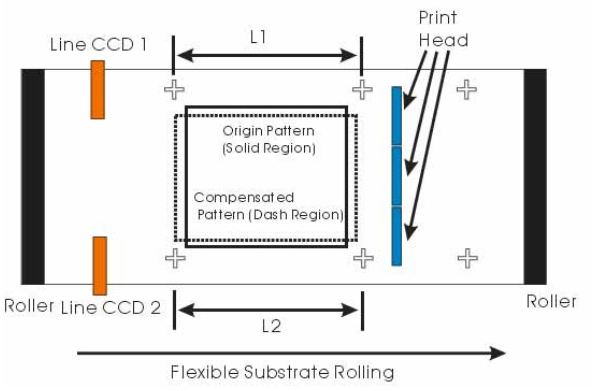
***Table.2*** *The property of flexible substrate.*

## *(c) Pattern Compensation*

The image need to compensate during the substrate continuously delivery process. Differ from the sheet manufacturing process, the reel-to-reel image compensation is real-time feedback treatment. The system calculate the image variation according to real-time detecting the substrate delivery detecting information, then communicate the compensating data to the firing system. By the compensating data, the firing system controls the frequency timing delay (as shown in the Fig.3(A)) and drop on demand (as shown in the Fig.3(B)) for origin pattern modification.




(A)




(B)

***Figure3.*** *(A) The frequency firing delay control. (B) The drop on demand control.*

## *(d) Acoustic Disturbing*

Liquid jets of macroscopic dimensions and their breakup into drops have been of great scientific interest [2]. Perturbations at the nozzle opening and surface tension help drive capillary instabilities in jets. Through the application of linear stability analysis to inviscid incompressible fluid columns, Rayleigh concluded that out of all disturbances the fastest growing one has a wavelength of about nine times the column's radius [3]. The Rayleigh instability behavior, drop enlarges surface to afford driving energy (moving bulk molecules to surface), and release driving energy by shrinking drop surface [4]. The accepted mechanism of jet breakup involves flow from regions of the liquid column with smaller radii (necks where the Laplace pressure is larger) to crest regions where the pressure is lower, until pinch-off occurs; extensions of Rayleigh's original work have shown that the effect of viscosity can reduce the breakup rate and increase the drop size [5-9].

Two factors dominate from drop jetting to landing on the substrate, the Reynolds number and Weber number, defined as Re=(Inertia / Viscosity) $=\rho v l/\eta$, We = (Inertia / Surface Tension) $=\rho v^2 l/\gamma$, where $\rho$ is density, $\eta$ is viscosity, $\gamma$ is surface tension, $v$ is velocity, and $l$ is characteristic length.

In Fig.4, some observations for jetting quality were concluded. If the jetting behavior presented along A-A straight line, the jetting was in stable. However, if A-A shown in curve, most of the condition was caused by the air disturbing due to the relative velocity variation during printing, or for flexible substrate, the vertical vibration induced this disturbing. For the curve A-C, the evaporation made smaller size at same dynamic momentum, , where the drag force~velocity$^2$*A. In ideal case, we hope A-A // B-B, in a Near Newton's fluid, if the A-A coupled with B-D, it implies the Rheology fluid, with higher surface tension or lower viscosity (High Re/We), and on the contrary, the A-A coupled with B-E, it implies the Rheology fluid, with lower surface tension or higher viscosity (low Re/We).

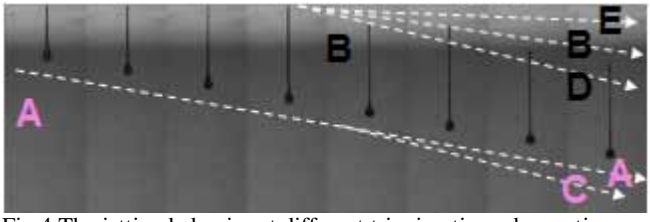



Fig.4 The jetting behavior at different trigging time observation

To get the ideal quality AA//BB, in system design, avoid the occurrence of air disturbing should be carefully consideration, especially for flexible delivery and printing at high speed. As shown in Fig.5(a), a traditional reel-to reel process passing a working, no any supporting or assistance to stabilize the substrate vibration, which causes the air disturbing. In our design, a floating vacuum bed is controlled with certain gap to stabilize the substrate vibration, and a ideal ink-jet printing quality of AA//BB can be reached, as shown in Fig.5 (b).

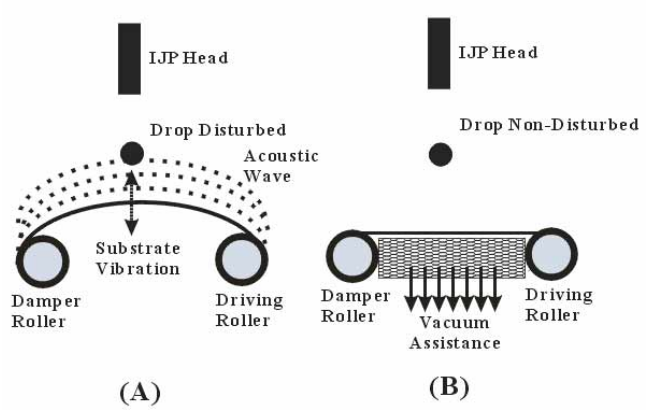



***Figure 5(A)-(B)*** *An assistance apparatus to stabilize the substrate vibration to reduce air disturbing.*

## *(e) Flow Integration*

### *Maintain Requirement*

Flexible substrates are new and important applications in circuited board and display industry. The flexible substrates are produced by "roll" type, and these are long, thin and flexible material. Employing the roll-to-roll manufacturing method in flexible circuit board or flexible display process can save the men power, material cost and apparatus cost. There are economic advantages to making a product long because it can be manufacturing continuously instead of in batches.

But there are specialties for the ink jet printing roll-to-roll manufacturing process. These are different from the traditional roll-to-roll manufacturing process. One example is the maintain station. For a continuous rolling procedure, the ink-jet printing is hard to design a maintain

service likes purging, vacuum, wiping, and it obstacles the possibility to lead to real production.

### *Module Design*

As Chiu mentioned [14], to avoid working surface pollution during ink-jet printing, it needs to keep out of contact with each transmitting roller. . Prior study developed a new flexible substrate delivery design for the metal film ink jet printing process. The substrate on the delivery path always keeps one side surface contact with all transmitting roller. The design is modularized and flexible. Besides, consideration of the time lag for each step, in this design, a buffer mechanism was design to matching each process in this continuous system. By add more modules or just the distance between the rollers, one can tune the needed processing time.

## Conclusion

IJP reel-to-reel process is beginning to make significant inroads into the commercial world, and if the field continues to progress at its current. Yet the future holds even greater promise for this technology, with an entirely new generation of ultra low-cost, lightweight and even flexible electronic devices in the offing. However, their practical implementation in electronic applications will ultimately be decided by the ability to produce devices and circuits at a cost that is significantly below that needed to manufacture conventional electronic circuits based on, for example, silicon. If successful, these low-cost fabrication processes will ultimately result in the "all printing world" of large-area devices and electronic circuits using roll-to-roll or web based methods. Before the day, much work must be done before such an ambitious goal can be realized. This paper describes more concepts and considerations we ever done in our IJP reel-to-reel prototype. It included the care of ink-jet stability, the ink-jet uniformity, the acoustic effects on drop landing, pattern compensation, and the flow integration issues. We can expect this technology whose functions are only now being envisioned will one day revolutionize the world in which we live.

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