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ORIGINAL ARTICLE

A study on the enhancement of printing location accuracy in a roll-to-roll gravure offset printing system

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Abstract This paper presents how to make a design of a roll-to-roll gravure offset printing system and how to control the printing process for the enhancement of printing location accuracy. Factors that cause printing errors include imprecision due to printing components, measurement and control, and printing environment. The suggested concept of design adapts the stop-and-go web feeding mechanism, which is able to avoid lag measurement control and coupled control of speed, tension, and register control. Regarding the control of the printing process, the effect of a synchronization error between the stage and blanket rollers on printing precision was investigated analytically and experimentally. The change of synchronization during the printing process was observed and the measure to compensate the synchronization error automatically was also examined.

Keywords Gravure offset · Gravure · Printing · Printed electronics · Roll-to-roll · Overlay printing

Nomenclature

R_r	Representative radius
R_t	True radius
θ	Rolling angle
L	Rolling circumference length
L	Stage moving distance
E	Synchronization error

1 Introduction

Academies and industries recently performed diverse research efforts on the production of electronic or display elements using printing processes. This is because the printing process has a price competitiveness superior to the patterning process that relies on the existing technologies of light exposure or chemical etching. Turning to the ubiquitous or high-energy era, in particular, this printing process can be applied to production of thin film transistors [1–5], flexible displays [6, 7], radio frequency identification (RFID) tags [8], touch screen devices [9], and so forth. Attention is concentrated on the research of printing technologies using roll-to-roll processes, as these kinds of products require flexibility and mass production method.

Printed electronic elements using roll-to-roll printing processes are produced using a roll-to-roll transfer that continuously feeds flexible plastic film as substrates and conductive, semi-conductive, or insulating materials using direct patterning processes, including those printing processes like gravure [10], gravure offset [11–13], flexo, inkjet [14, 15], screen [16], pad printing [17], etc. The gravure, gravure offset, and flexo printing processes, which are the most extensively used for roll-to-roll printing, have differences, as indicated in Table 1.

The gravure printing has merits such as giving the smallest line width of 30–40 μm, realized at a fast printing speed, but also has limitations such as requiring a high printing pressure and a 1–5-μm printing thickness, which is restricted to flexible substrates and is impossible to use on glass or other hard materials. The flexo printing may produce a smaller line width of 40 μm and has micron-thick printing but it also has limitations such as that it can hardly control the printing thickness and it can use ink material with polarity. Nano imprint lithography can make fine lines

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Table 1 Roll-to-roll compatible printing processes

	Gravure offset	Gravure	Flexo	Nano imprint lithography
Minimum feature size	> 10 μm	> 30 μm	~40 μm	< 100 nm
Printing pressure	Medium	High	Medium	Low
Printability on glass	O	X	O	O
Ink viscosity (cPs)	~10,000	Several hundreds	Several hundreds	~10
Thickness	1–15 μm	1–5 μm	~4 μm	< several hundred nm

of less than 100 nm. However, it still requires the lithographic step and its process time is very slow. The gravure offset printing is applied to diverse products like liquid crystal displays, plasma display panels, organic light-emitting diodes, RFID, solar batteries, and so forth, since it is advantageous to overlay printing with fine line widths of 10 μm or so on diverse types of substrates at a relatively lower printing pressure.

In order to precisely fabricate printed electronic devices, one of the most critical issues is the enhancement of overlay printing accuracy. Overlay printing accuracy refers to the degree of how accurately the second pattern can be printed on a desired location over the first pattern in two-layer printing. Therefore, if the printing location accuracy is high, the printing overlay precision can be also high. Printing location accuracy refers to the degree of how accurately patterns can be printing on a desired location. Printing location accuracy may be regarded as being easily attainable by using precise vision and an actuating system. However, if the distance between the printed register markers, which is supposed to be fixed at the same distance of the master register markers, varies according to the printing process parameters, then the printing location accuracy also varies at every point of the printed patterns. More than several tens of micron accuracy variations may take place due to the imprecision and change of printing components during the process, complicated printing machine control, and environmental issues. In this paper, research has been performed on the concept design and fabrication of the printing equipment that enables printed patterns to meet precise overlay and on the enhancement of printing location accuracy by analyzing synchronization of the gravure offset printing roller and stage.

2 Design and fabrication of equipment for precise overlay printing

Table 2 shows causes for errors that may take place in overlay printing. The table can be classified into errors caused by imprecision and a change of printing machine components during the printing process, by limitation of measurement and control, and by environmental effect.

Among printing components, the precision of engraved gravure master is one of the most influential factors. Since every machine has inherent errors and the engraved gravure master is made using a machine with inherent errors, imprecision is inevitable. For the quality enhancement of the engraved gravure master, it is more advantageous to adapt a flat type than a roll type since various pattern sizes and types of the engraved gravure master making can be precisely obtained.

During the gravure offset printing process, the printing components with soft or flexible properties, such as an offset blanket, a flexible substrate, and ink, can alter or deform, changing into materials with slightly different properties, which can affect overlay printing accuracy. These soft or flexible materials should be maintained within a tolerable range. As the printing process is being repeated, the amount of absorbed solvent continuously increases and overlay

Table 2 Error factors of overlay printing

Error factors		Design concept
Imprecision due to printing components	Engraving error of gravure master	Flat gravure plate
	Deformation of flexible substrate	Reduction of tension
	Property change of offset blanket	Absorption control and compensation
	Rheological change of ink	Encapsulation of ink
Measurement and control	Limit of vision measurement	CCD camera with high resolution
	Lagged measurement location	Direct measurement
	Coupled speed/tension/register controls	Decouple by adaption of stop-and-go control
	Synchronization of rollers and stage	Precise synchronization control by analysis
Environment	Temperature and humidity control	Constant temperature and humidity facility

printing accuracy worsens. This will be discussed in detail in another chapter. Since flexible substrates can be stretched by pulling it and creating tension, and it is advantageous to find a means to reduce or remove tension during the process. In many cases, significant variations in the usual printing quality are attributable to changes in ink conditions. The change of ink is due to the evaporation of ink solvent during the process. Ink must also be maintained in consistent conditions by encapsulation. For this, an ink cup style blade is used to maintain a consistent ink condition.

Regarding measurement and control, there are several critical issues that affect overlay printing accuracy. The precision of measurement restricts the precision of control. If a charge-coupled devices (CCD) camera with several micron pixel sizes, which is used for obtaining the location of a typical register marker, is equipped with a printing system, the worse precision of the pixel size is achieved through its control process. In roll-to-roll printing on continuously supplied substrates, the measurement location of the register marker is placed apart from the printing location, requiring complicated lag control. This means that the past-printed overlay data are used for the current register control. If the measuring location coincides with the printing location, it makes the register control use the current data and results in more precision. In addition, there are several control systems that are coupled together: speed control, tension control, and register control. These controls affect each other all at once in a combined manner. For example, if the speed changes, it affects the tension and register. Therefore, instead of the continuous web feeding mechanism, we adapted stop-and-go web feeding mechanism that is suitable for avoiding lag measurement control and the coupled controls of speed, tension, and the register control. The stop-and-go mechanism is one of the roll-to-roll web feeding mechanisms. The stop-and-go web control method provides a flexible substrate onto a printing stage by the roll-to-roll web feeding apparatus and then stops moving the web until the printing is over. During the printing step, the CCD camera detects the register markers and the printing stage moves for a more precise alignment by using current overlay data. After the printing step, the flexible web goes by again. In this stop-and-go mechanism, the tension and speed of web area zeros and the register control can be carried out more accurately and easily, since it uses current overlay data and is independent from other controls.

In contact ink transfer printing methods in which the gravure offset printing is included, the two parts in which ink is engaged should have relative movement only in the departing direction. For example, if ink is transferred from a stage to a roll, the moving velocity of the stage and the line velocity of the roll should have same value. This synchronization has an effect on the overlay printing accuracy. If the synchronization error is 1 %, then overlay printing error is 1 %, theoretically. Precise synchronization can be achieved by precise motor-stage actuation, precise parts fabrication, and a synchronization process control.

In addition, plates and substrates are deformed by changes in ambient temperature. Ambient humidity changes cause changes in printing conditions, including variations in the ink viscosity. Therefore, a constant temperature and humidity facility is required for the manufacture of the printed electric devices.

Figure 1 shows a working principle of the equipment designed considering the above design method. Figure 1a is a schematic diagram that shows stop-and-go web feeding. At stage b, an ink cup filled with ink before the printing process is shown. At stage c, the ink cup performs ink doctoring by moving to the engraved pattern part. At stage d, the blanket roller moves to the pickup start position to pick up the ink and the blanket roller lowers vertically. At stage e, the ink filled inside the pattern is picked off while the blanket roller and *X*-axis move under the condition of the synchronization actuation. At stage f, the blanket roller with picked off ink rises vertically. At stage g, the blanket

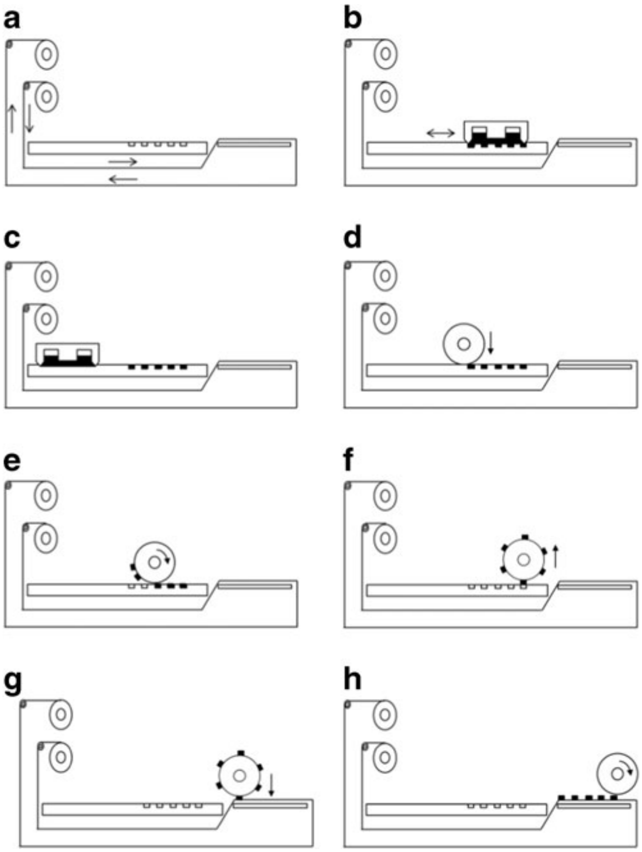

Fig. 1 Working principle of the plate-to-plate gravure offset printing system: **a** stop-and-go web releasing process; **b** doctoring process; **c** finishing the doctoring process; **d** starting the off-process; **e** off-process; **f** finishing the off-process; **g** starting the set-process; **h** finishing the set-process

roller with picked off ink lowers vertically to set the ink on the substrate media that is being printed on. At this time, the substrate alignment is complete by recognizing register markers. At stage h, the blanket roller rises after finishing setting the ink.

Figure 2 shows the schematic diagram and picture of the roll-to-roll gravure offset printing equipment that is designed to carry out the working principle delineated in this chapter. By using this roll-to-roll gravure offset printing system, experiments on how precisely it can print where it was intended were carried out. Table 3 shows the printing process conditions. A silver paste ink with 20,000-cPs viscosity was used and the blanket material was an 85-mm-wide polydimethylsiloxane (PDMS) whose specific characteristics are described under the reference literature [12]. The roller has a 50-mm radius. It is wound with a 1.30-mm-thick under-blanket and a 0.65-mm PDMS blanket on top of the under-blanket. The same register markers were printed over 20 times. The locations of the printed register markers, which have a cross shape, were measured by two CCD cameras. The first one was fixed on the blanket roller for capturing patterns that were transferred to the blanket roller after the off-process and the other was fixed on the stage for capturing patterns, which were finally printed on the substrate after the set-process. The printing location accuracy can be stated by the moving degree of locations of the printed register markers.

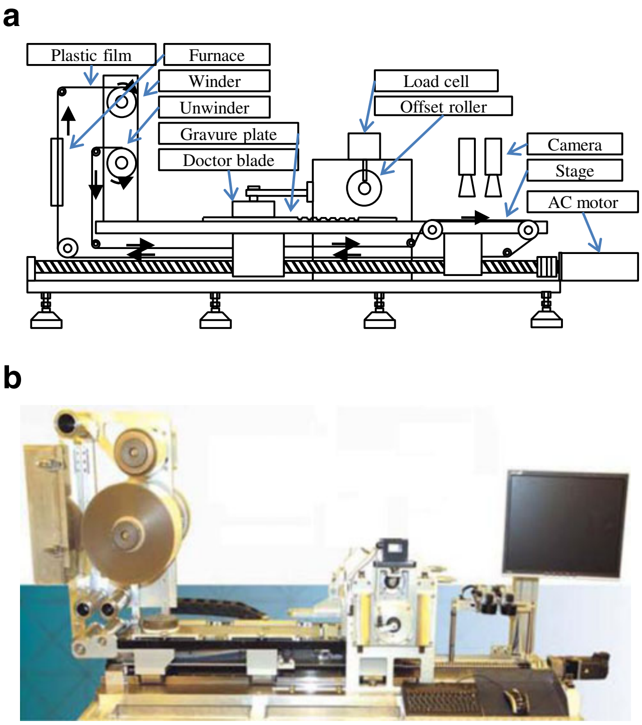

Fig. 2 Roll-to-plate gravure offset printing equipment: **a** schematic diagram; **b** picture

Table 3 Conditions of the printing process

Off speed	50 mm/s
Set speed	50 mm/s
Off pressure force	16 kgf
Set pressure force	16 kgf
Printing number	10th
Blanket width	85 mm

According to the experiments by using this machine, the printing location accuracy of this roll-to-roll printing system was measured at two directions: machine direction (MD) which is same with printing direction; and cross direction (CD) which is vertical with printing direction. Table 4 shows the experimental results. The error measured after the set-process can be regarded as the final printing location accuracy of this machine. This roll-to-roll gravure offset printing system has average printing location errors of 4.2 μm in the machine direction and 2.3 μm in the cross direction, respectively. The maximum printing location errors were 9.0 μm in the machine direction and 5.9 μm in the cross direction, respectively.

3 Synchronization for enhancement of printing location accuracy

Figure 3 shows a schematic diagram of the driving synchronization between a flat gravure plate and a blanket roller. In this figure, synchronization means that the rotational linear velocity of the blanket roller at the contact point has the same value with the moving speed of the flat gravure plate. Ideally, if the radius of the blanket roller is fixed, the angular speed of the blanket roller can be calculated to have the same speed with the flat gravure plate. If synchronization is done precisely, when the flat gravure plate is driven by a distance, L, and the blanket roller with the representative radius, R_r, rotates by the angle of the circumference length, then l should be same with the distance L.

In a practical perspective, R_r and θ are entered for the blanket roller and the distance L is entered for the stage. If the blanket roller is made from a rigid material into a perfect circle shape, its R_r and θ values can be obtained through measurements and calculations. However, when the blanket roller is made of an elastic material, it is very difficult to measure the true radius, R_t, as it will vary depending on process conditions such as printing force. Besides, the blanket roller does not have a perfect circular shape. The radius is different at every point of the blanket roller. Therefore, the true radius, R_r, means the average radius at the given process condition, which is difficult to exactly know. The radius value entered for rotating the blanket roller would be the representative

Table 4 Printing location accuracy of the roll-to-roll gravure offset printing system in the MD and CD

(μm)	Average error (MD)	Average error (CD)	Maximum error (MD)	Maximum error (CD)	Std. dev. (MD)	Std. dev. (CD)	Sample number
After off-process	3.5	2.0	6.3	3.8	3.2	2.1	20
After set-process	4.2	2.3	9.0	5.9	5.6	3.0	20

radius, R_r, which is different from the true radius, R_t, causing a synchronization error E.

$$\begin{aligned} E &= l - L = (R_r - R_t)\theta \\ &= (R_r - R_t)\frac{L}{R_t} = \left(\frac{R_r}{R_t} - 1\right)L \end{aligned} \tag{1}$$

For example, if R_r=50.05 mm is entered for a blanket roller with the true radius of R_t=50.00 mm and it is driven by L=100 mm, then a synchronization error of 100 μm is caused. It is because the radius error is 0.1 %. This tells us that this equipment can cause a substantial printing location even though the stage has a repetition precision under 5 μm and the roller has an actuating precision of 5 μm or less.

4 Experiments and discussions

4.1 Synchronization experiments

Synchronization error can be measured by comparing the distance between two patterns on a flat gravure plate with the distance between the two patterns on a substrate that is printed by the flat gravure plate and the blanket roller. If synchronization error is zero, then the distance on a flat gravure plate and printed pattern distance should be same.

In our experiments, the distance between two patterns on a flat gravure plate was L=42 mm. The R_r was set from 50.50 to 51.10 mm. Figure 4 shows the synchronization error of the printed patterns. The experimental data shows that the error is linear to R_r. This result fits the Eq. (1) well. By using the first-order interpolation, the representative radius R_r, which results in minimal synchronization errors, can be found out. In this experiment, it was finally set to 51.00 mm.

Even though representative radius R_r was finally set precisely through synchronization experiments, the synchronization precision changes depending on the varying values of the printing process variables, such as the printing force and repeated printing numbers. This is because the radius of the blanket roller changes when the printing force changes. Repeated printing makes the blanket swell due to the solvent absorption [11, 12] and this results in the radius changes in the blanket roller. The effects of the printing force and repeated printing on synchronization errors will be discussed based on the experimental data.

4.2 Synchronization error due to printing force variation

If a roll-to-roll printing system uses an elastic roller just like the system discussed in Chapter 2, the synchronization error attributable to variations in printing force derives from the deformation of the blanket roller, which results in a change in its radius. Even though the radius change can be predicted through a numerical method [18], it is not easy to find out the deformation of the blanket roller due to so many varieties of blanket rollers, such as materials, radius, thickness, and force. It is advantageous to explore the correlation between the blanket roller deformation and the printing force to identify the requirements for a printing system through experiments and simple analysis based on a practical perspective rather than numerical interpretation.

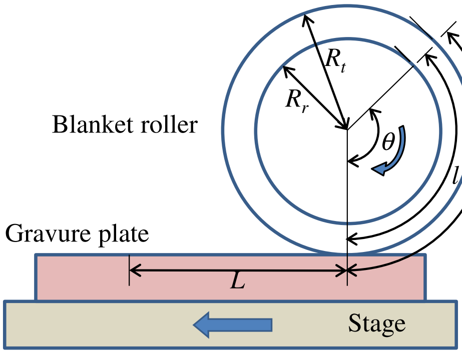

Fig. 3 Schematic diagram of gravure offset printing to explain the synchronization error

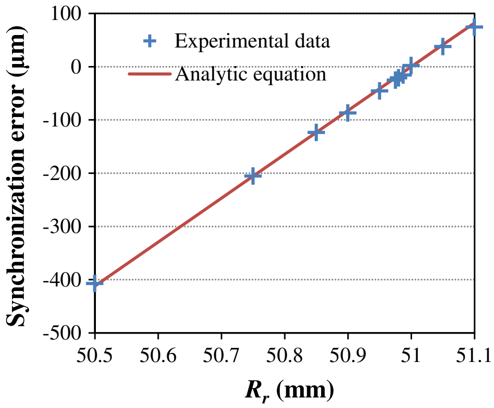

Fig. 4 Synchronization error depending on representative radius, R_r

Table 5 Synchronization errors depending on printing forces before and after compensation

Printing force (kgf)	12	16	20
Average of synchronization error before compensation (μm)	5.7	6.0	20.3
St. dev. of synchronization error before compensation (μm)	4.9	3.8	12.0
Radius compensation (μm)	10	0	−100
Average of synchronization error after compensation (μm)	2.0	6.0	3.8
Std. dev. of synchronization error after compensation (μm)	4.4	3.8	4.9

Table 5 shows the synchronization errors based on diverse printing forces, 12, 16, and 20 kgf. It is the mean values and standard deviations of nine times printing when the synchronization is set based on 16 kgf and the synchronization radius of the blanket roller is not changed for the printing forces of 12 and 20 kgf. The results of synchronization errors due to printing forces of 12, 16, and 20 kgf were 5.7, 6.0, and 20.3 μm, respectively. The errors around 5–6 μm were acceptable since it was around the precision of the printing machine. However, the error of 20.3 μm was unusual printing location inaccuracy. The compensation of the representative radius for synchronization was needed. Table 5 also shows the averages and standard deviations of printing location accuracy after the compensation of the representative radius. Only a 0.01-mm radius variation had to be compensated when the printing force was 12 kgf as compared with that of 16 kgf. On the contrary, when the printing force was 20 kgf, the printing location accuracy greatly improved by compensating the radius variation by decreasing it by 0.1 mm. After such compensation, the averages of printing location accuracy were 2.0 and 3.8 μm for the printing forces of 12 and 20 kgf, respectively. According to F verification, it corresponds to a heteroscedasticity hypothesis. This means that the printing location accuracy has improved at both or at a single end by a significant degree of 1 % or less.

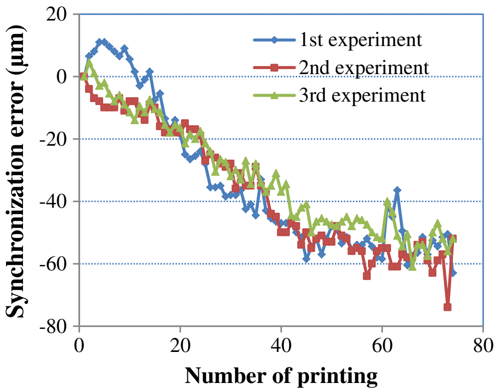

Fig. 5 Synchronization error depending on number of repeated printing

4.3 Synchronization error due to repeated printing

Figure 5 shows the synchronization error depending on the number of repeated printing. The experiment was carried out three times. At the very beginning of the experiment, the printing location error was almost within machine precision. However, as the printing experiments were repeated without any rest between the printings, the printing location errors were larger. After the 70 continuous usages, the error was as much as around 60 μm. In the gravure offset printing, the blanket roller, which is usually made of PDMS rubber, absorbed the solvent of ink gradually [11, 12]. It caused the blanket roller to swell and enlarged the true radius of the blanket roller. Therefore, if the representative radius is fixed, the synchronization error becomes bigger in the minus direction in the Eq. (1). The error of 60 μm corresponds to the radius change of 73 μm, which can be calculated from the Eq. (1).

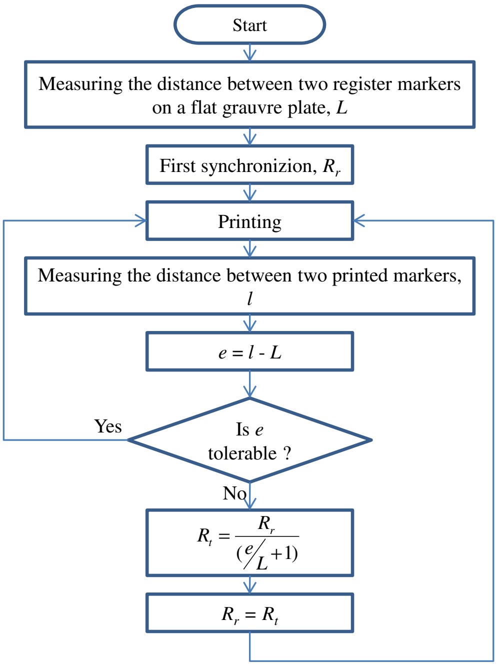

Fig. 6 Block diagram for automatic compensation of synchronization

Although the best way is to prevent the blanket swelling, in a roll-to-roll printing process, devices are required to be printed in short periods of time, so swelling is inevitable. Therefore, the synchronization radius of the blanket roller should be compensated. Figure 6 shows the automatic compensation algorithm. The synchronization for blanket change, printing force variation, repeated printing, and so on, can be compensated by periodically measuring the distance between two printed register markers and keeping it same as the original distance on a flat gravure plate by using the Eq. (1).

5 Conclusion

The overlay printing is crucial in gravure offset printing for printed electronics while printing location accuracy is essential for overlay printing. The error factors arising in roll-to-roll gravure offset printing include imprecision due to printing components, measurement and control, and the printing environment. For the purpose of this paper, research was performed on equipment design and fabrication to remove or minimize such error elements. In order to avoid lag measurement control and coupled control of speed, tension, and register control, the stop-and-go web feeding mechanism was adapted. Finally, the average printing location errors of 4.2 μm in the machine direction and 2.3 μm in the cross direction, respectively, were obtained. Our research was performed on the effects of the synchronization between the stage and blanket roller, which was formulated into a simple equation and was supported by the experiments. We also paid attention to the change of synchronization during the printing process. The synchronization should be compensated surely or frequently after blanket change, printing force variation, and repeated printing. It is due to the radius change of the blanket roller. The automatic compensation algorithm, which periodically measures the distance between two printed register markers and keeps it the same width as the original distance on a flat gravure plate, was suggested. Consequently, it may be concluded that the suggested design and process control of roll-to-roll gravure offset printing could enhance printing location accuracy and overlay printing accuracy, and it could help to fabricate printed electronic devices more precisely and accurately.

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References

1. Klauk H (2006) Organic electronics materials, manufacturing, and applications. Wiley, Weinheim
2. Kats AE, Huang J (2009) Thin-film organic electronic devices. Annu Rev Mater Res 39:71–92
3. Li Y, Wu Y, Ong BS (2007) A simple and efficient approach to a printable silver conductor for printed electronics. J Am Chem Soc 129:1862–1863
4. Perelaer J, Hendriks CE, de Laat WM, Schubert US (2009) One-step inkjet printing of conductive silver tracks on polymer substrates. Nanotechnology 20:165303
5. Sekitani T, Yokota T, Zschieschang U, Klauk H, Bauer S, Takeuchi K, Takamiya M, Someya T (2009) Organic nonvolatile memory transistors for flexible sensor arrays. Science 326:1516–1519
6. Gaudiana R, Brabec C (2008) Organic materials—fantastic plastic. Nat Photonics 2:287–289
7. Weber J, Potze-Kamloss K, Hasse F, Detemple P, Voeklein F, Doll T (2006) Coin-size coiled-up polymer foil thermoelectric power generator for wearable electronics. Sens Actuators A 132:325–330
8. Sangoi R, Smith CG, Seymour MD, Venkataraman JN, Clark DM, Kleper ML, Kahn BE (2005) Printing radio frequency identification (RFID) tag antennas using ink containing silver dispersions. J Dispers Sci Technol 25:513–521
9. Frey MH, Zu L, Hagermoser ES (2009) Touch screen sensor. US Patent Application 0219257
10. Jiang W, Liu H, Ding Y, Tang Y, Shi Y, Yin L, Lu B (2009) Investigation of ink transfer in a roller-reversal imprint process. J Micromech Microeng 19:015033
11. Pudas M, (2004) Gravure-offset printing in the manufacture of ultra-fine-Line thick-films for electronics. Ph.D, The Oulu University, Oulu
12. Lee T-M, Noh J-H, Kim I, Kim DS, Chun S (2010) Reliability of gravure offset printing under various printing conditions. J Appli Phys 108:102802
13. Chun S, Grudinin D, Kim S, Lee D, Kim S-H, Yi GR, Hwang I (2009) Roll-to-roll printing of silver oxide pastes and low temperature conversion to silver patterns. Chem Mater 21:343–350
14. Wallace DB, Hayes DJ (1998) Solder jet technology update. IJ Microcircuits Electron Packag 21:73–77
15. Lee T-M, Kang TG, Yang JS, Jo J, Kim KY, Choi BO, Kim DS (2008) Drop-on-demand solder droplet jetting system for fabricating micro structure. IEEE Trans Electron Packag Manuf 31:202–210
16. Lee T-M, Choi YJ, Nam SY, You CW, Na DY, Choi HC, Shin DY, Kim KY, Jung KI (2008) Color filter patterned by screen printing. Thin Solid Films 516:7875–7880
17. Lee T-M, Hur S, Kim JH, Choi HC (2010) EL device pad-printed on curved surface. J Micromech Microeng 20:015016
18. Kim KS, Kim CH, Kim H-Y, Kim DS (2010) Effects of blanket roller deformation on printing qualities in gravure-offset printing method. Jpn J Appl Phys 49:05EC04