Study of Paper Deformation Mechanism in Color Inkjet Printing Process with Infrared Radiation Heater

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Abstract

In high speed inkjet printing system equipped with a drying system, IR type drying system is preferable considering recent needs for compact and light-weight design. However, the IR type drying system has a risk that a cockle height changes depending on colors of ink. Thus, the authors investigated the relationship between the cockle height and exposure energy of IR heater for different colors of ink (black and magenta) by setting up an off-line drying bench. As a result, the cockle height on the area printed with pigmented magenta ink became higher than that with pigmented black ink since the absorption ratio depends on colors. Furthermore, the number of peaks in cockle profile shifts from one peak to two peaks with increasing the exposure energy. Hence, we tried to clarify the mechanism about changing of cockle profile by simulation. Physical properties such as water swelling ratio and Young's modulus of ink soaked paper were measured using a newly developed instrument. Consequently, the changing of cockle profile was reproduced by considering shrink of the non-printed area.

Introduction

In recent years, high speed inkjet printing system has been introduced into digital publishing market. In this printing system, when printing full color images on a paper with water-based ink, paper deformation which is called "cockle" grows, because the amount of water swelling increases.

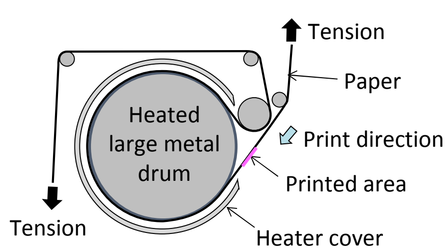
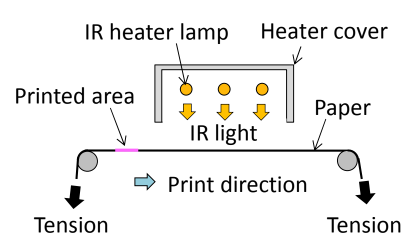
In case of the duplex printing, such a large cockle created by front side printing possibly causes misfiring of the print head when printing on back side, since the cockled paper contacts the print head. The misfiring causes image defects such as white streaks on a printed image. To avoid the undesirable contact, the distance between the paper and the print head (throw distance) needs to be set wide. However, the wide throw distance enhances the displacement of ink droplet landing position, which resulting in the deterioration of character quality. [1]

Reducing the cockle height requires much drying energy to evaporate moisture contents of ink from the paper. Table 1 shows typical drying systems applied in high speed inkjet printing system; metal drum type and infrared radiation (IR) type. The metal drum type heats the paper by contact with the metal drum from back side, which effectively suppressing the paper deformation. However, the metal drum usually features very heavy and large. On the contrary, the IR type is suitable for compact design as heating paper without contact, but there is a tendency of forming larger paper deformation than the metal drum type because of less constraining the paper in paper feeding.

Considering recent needs for compact and light-weight design, the IR type is preferable. However, addition to the deformable feature, the IR type has different absorption properties for energy of radiation depending on colors of pigment (black and other colors), that might provide differences in cockle height or shape.

In this report, the authors investigated the relationship between the cockle height and exposure energy of the IR heater for different colors of inks (black and magenta) by setting up an off-line drying bench. Furthermore, we tried to clarify the mechanism about changing of cockle profile with increasing the exposure energy by simulation. Physical properties such as water swelling ratio and Young's modulus of ink soaked paper were measured using a new instrument for the simulation.

Table 1. Comparison between metal drum type drying system and infrared radiation (IR) type drying system

Type of drying system	Metal drum type	Infrared radiation (IR) type
Configuration of drying system		
Heating method	Heated large drum and hot air	Radiant exposure
Compact and light-weight design	Less suitable	Suitable

Experimental Apparatus

Figure 1 describes the schematic diagram of the off-line drying bench. The print head is piezo type of 1200 dpi, and the drier has three IR heater lamps with near infrared wavelength. The temperature on the printed area and the non-printed area are measured by a radiation thermometer (Keyence FT-H20) located on next to the drier. Also, the cockle height is measured by a two-dimensional laser displacement meter (OMRON EZ700) also located on next to the thermometer.

Figure 2 indicates the top view of the measurement system using the two–dimensional laser displacement meter which scans the center of the printed area along the y-coordinate. The x and y coordinates in Figure 2 indicate Machine Direction (MD) and Cross Direction (CD) of paper, respectively.

Table 2 shows the experimental condition. Water-based pigmented black ink and pigmented magenta ink are used.

Figure 3 shows the absorption ratio spectra of the printed area, and the radiant intensity spectrum of the IR heater is also shown in the right axis. The absorption ratio of the printed area with pigmented magenta ink became lower than that of pigmented black ink ranging from 700 nm to 2500 nm.

Drop volume is 5.5pl and drying period is set to constant (2.1 sec). The energy density of the IR heater is controlled from 0.0 to 55.6 kW/m^2, which providing the printed area of pigmented black ink with the temperatures of 30 to 90 degC.

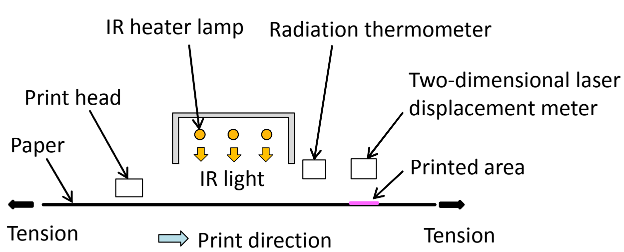


Figure 1. *Schematic diagram of the off-line drying bench*

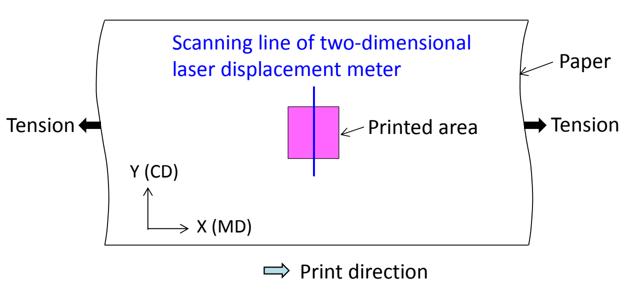


Figure 2. *Top view of the measurement system using the two-dimensional laser displacement meter which scans the center of the printed area along the y-coordinate*

Table 2. Experimental condition

Ink	Water-based pigmented ink (black , magenta)
Paper	Npi Form Next-IJ 81.4 gsm (manufactured by NIPPON PAPER INDUSTRIES CO., LTD.)
Nozzle density of print head	1200 dpi
Drop volume	5.5 pl
Print speed	2.6 m/min
Drying period	2.1 sec
Energy density of IR heater	0.0 , 19.2 , 37.7 , 55.6 kW/m^2
Printed area	1.5 inch x 1.5 inch
Environmental temperature	25 degC
Environmental humidity	30 %RH

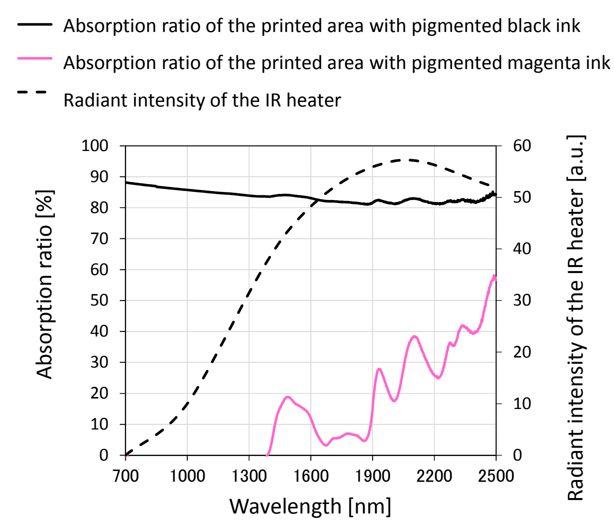


Figure 3. *Absorption ratio spectra of the printed area and radiant intensity spectrum of the IR heater*

Experimental results

Figure 4 shows the relationship between the cockle height and the exposure energy of the IR heater; (a) pigmented black ink and (b) pigmented magenta ink.

First, the authors focused on the cockle height. In both colors, the heights of cockle decrease as the exposure energy increases [2]. However, there exists dependence of colors in the cockle height, which is much higher in pigmented magenta ink case than in pigmented black ink case. The difference in height between black and magenta seems to be caused by the difference of temperature at the printed area because the absorption ratio depends on colors as mentioned before.

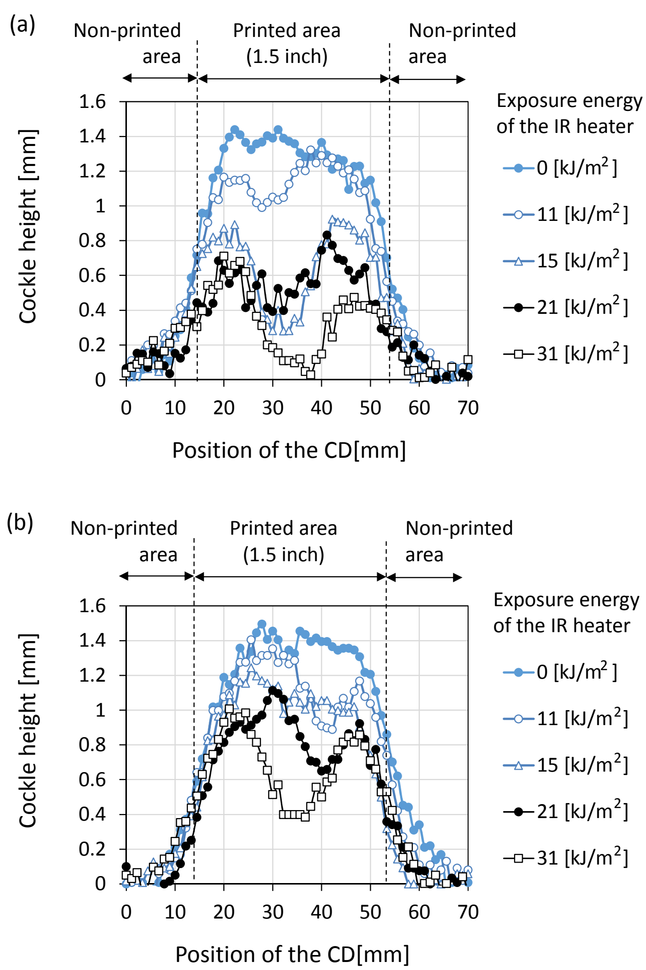


Figure 4. *Cockle profiles along the CD of the paper; (a) pigmented black ink (b) pigmented magenta ink*

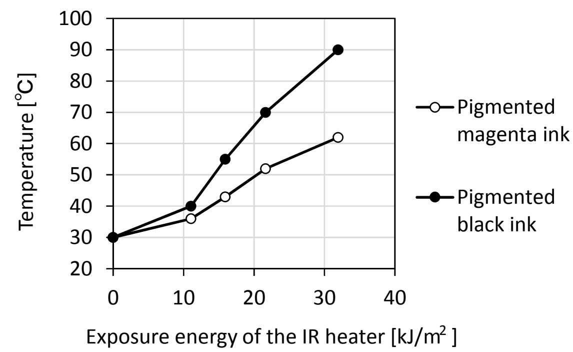


Figure 5. *Temperature on the printed area*

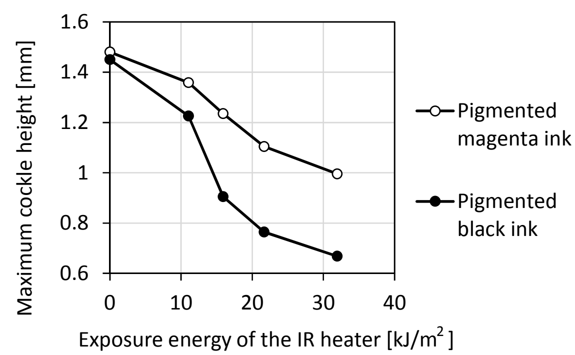


Figure 6. *Maximum cockle height*

Figure 5 shows the relationship between the exposure energy and temperature on the printed area for pigmented black ink and pigmented magenta ink. From Fig.5, we can see that pigmented black ink shows higher temperature than pigmented magenta ink. This result suggests that the moisture content of the paper printed in pigmented black ink is larger than that printed in magenta ink. Therefore, the difference in height with colors should be caused by the difference in moisture content of the paper with colors.

Figure 6 shows comparison of the maximum cockle height between pigmented black ink and pigmented magenta ink for the exposure energy. To reduce the cockle height to a same level, we can see that printed area with pigmented magenta ink requires more exposure energy than that with pigmented black ink. Furthermore, the difference of the height between both colors expands as the exposure energy increases.

Next, the authors focused on changing of cockle profile. In Figure 4 (a) and (b), it is observed that number of peaks in cockle profiles shifts from one to two with increasing the exposure energy.

In following chapter, the authors investigate the mechanism by simulation.

Simulation of Cockle Behavior

1) Simulation model

To clarify the mechanism about changing of cockle profile (increase in number of peak) when irradiating high exposure energy, the authors developed a simulation model which can consider swelling of the paper. This model applies the thermal expansion model to describe the water swelling, where the temperature corresponds to the moisture content.

Figure 7 shows the schematic diagram of simulation model. Colors indicate the moisture content of paper: red, blue and green represent the printed area, the non-printed area and the bleeding area respectively.

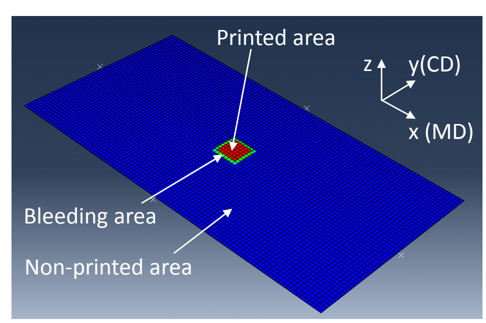


Figure 7. *Schematic diagram of simulation model*

2) *Measurement of water swelling ratio and the Young's modulus of ink soaked paper*

For the simulation, the authors should obtain both the water swelling ratio and the Young's modulus of ink soaked paper considering anisotropy of the paper.

Therefore the authors developed a new instrument shown in Figure 8. This instrument measures the displacement of swelling paper-by laser displacement meter, when ink is jetted to the paper through the spray mask. The water swelling ratio was estimated by the strain of paper at the saturation condition. The Young's modulus was obtained by the tensile test using ink soaked paper made by the instrument shown in Figure 8.

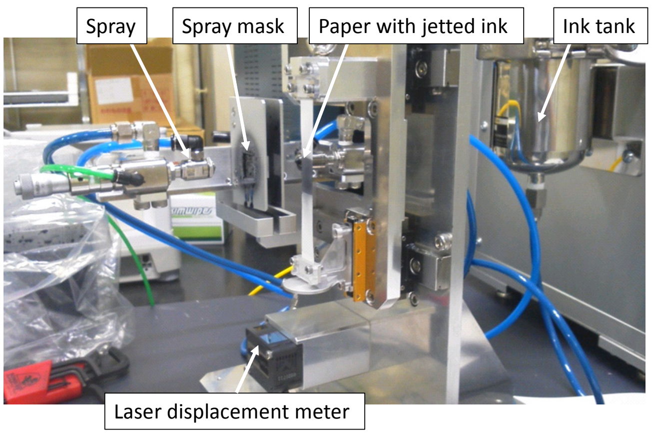


Figure 8. *Instrument for measuring the water swelling ratio*

3) *Simulation Condition*

The authors considered that the changing of cockle profile is caused by the balance of the expansion and the shrink of the paper. Thus, we investigated relationship between shape of cockle and the moisture balance of the printed area and the non-printed area after heating. Table 3 shows combinations of the moisture contents, where positive and negative values indicate expansion of the paper and shrink of the paper, respectively. Here, Case 1 means non-heating condition, where moisture content of printed area is adjusted that the cockle height by simulation fits to the experimental result at 0 kJ/m^2.

Case 2 and Case 3 exhibit the condition that applied exposure energy at 15kJ/m^2, where the moisture contents of printed area is set smaller than the Case 1 to express the effect of evaporation. Furthermore, Case 3 considers the effect of shrink at the non-printed area, where moisture content is set to negative value.

Table 4 shows simulation conditions. The measured Young's modulus of the CD (y-coordinate shown in Fig.7) is 2.55 times bigger than that of the MD (x-coordinate) as to the anisotropy, on the other hand, comparing the Young's modulus between printed (wetting) and non-printed (non-wetting) areas, the measured Young's modulus (x-coordinate) of the printed area is 3.75 times smaller than that of the non-printed area. Assume that the paper thickness is 100 micro meter, depth of ink penetration is 50 micro meter and tensions are loaded at both paper ends.

Simulations were carried out using the Abaqus CAE 6.12.

Table 3. Combinations of the moisture contents at the printed area and the non-printed area in simulation

	Moisture content of the printed area [a.u.]	Moisture content of the non-printed area [a.u.]
Case 1	0.011	0.0
Case 2	0.005	0.0
Case 3	0.005	−0.005

Table 4. Simulation condition

Physical property		Coordinate	Value
Young's modulus	Non-printed area	x	6.670 [Gpa]
		y	2.615 [Gpa]
		z	2.615 [Gpa]
	Printed area	x	1.780 [Gpa]
		y	0.690 [Gpa]
		z	0.690 [Gpa]
Water swelling ratio		x	0.045
		y	0.163
		z	0.163
Poisson's ratio		x	0.30
		y	0.15
		z	0.30
Paper thickness		z	100 [μm]
Depth of ink penetration		z	50 [μm]
Tension applied to the paper		x	1.32 [kgf]

4) *Results and Discussion*

Figure 9 shows the comparison between the simulation result and the experimental result of pigment black ink.

In Case 2, the cockle height shows good agreement between simulation and experiment at 15kJ/m^2, however its profile is different from the experimental result. On the contrary, Case 3 could reproduce the experimental result of two peaks in the cockle profile. Therefore, considering shrink of the non-printed area plays the essential role to reproduce the changing of cockle profile such as one peak to two peaks.

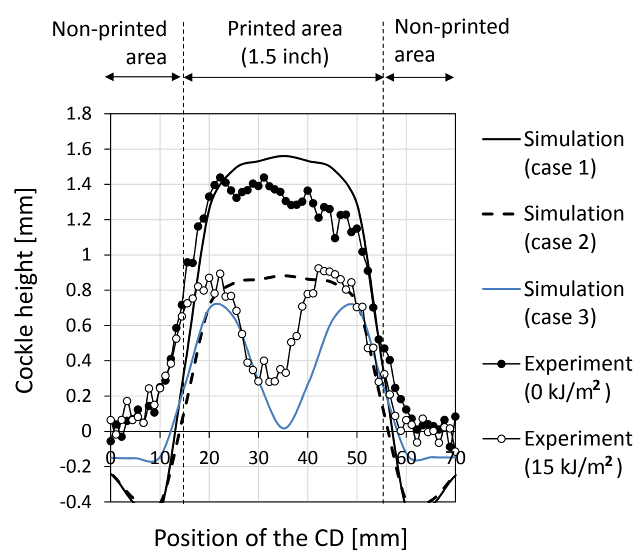


Figure 9. *Comparison of cockle profiles between simulation results and experimental results of pigmented black ink*

Thus, the changing of cockle profile is considered to be caused by the compressive stress forced to the printed area by shrink of the non-printed area.

These simulation results suggest that the cockle height is related to both the moisture content of the printed area and the cockle profile depending on the moisture balance between the printed area and the non-printed area addition to the Young's modulus.

Summary

In this study, the authors investigated the relationship between the cockle height and exposure energy of the IR heater for different colors of inks (black and magenta) by setting up an off-line drying bench. Additionally, the authors developed a simulation model which can consider swelling of the paper by the thermal expansion model, and tried to clarify the mechanism concerning the changing of cockle profile with increasing the exposure energy based on the moisture balance in the paper.

Consequently, following results were obtained;

- The cockle height on the area printed with pigmented magenta ink became higher than that with pigmented black ink, for example, in case of the exposure energy at 31 kJ/m^2, ratio in the cockle height between both colors becomes 1.5. This result was caused by the difference of temperature at the printed area because the absorption ratio of IR light depends on colors.
- As the exposure energy increases, the cockle height decreases in both colors, however, the number of peaks in cockle profile shifts from one peak to two peaks.
- The simulation result shows that shrink of the non-printed area plays the essential role to reproduce the above changing of cockle profile. Thus, the changing of cockle profile is considered to be caused by the compressive stress forced to the printed area by shrink of the non-printed area.

References

[1] Naoki Morita, Journal of the Imaging Society of Japan, Vol.52, No.5 (2013).

[2] Manabu Numata, Akira Sakamoto, Yasuhiro Ogasawara, Mami Hatanaka, Yukari Motosugi and Naoki Morita, Proc. of NIP29, 2013, 292

Author Biography

Motoharu Nakao obtained B.E. and M.E. degrees in electrical and electronic engineering and physical electronics at the Tokyo Institute of Technology in 2007 and 2009. He joined Fuji Xerox co., Ltd. in 2009 and has engaged in inkjet R & D group. He has been working on development of new image processing and clarifying the mechanism related to inkjet printing system.