2D Thermal Analysis to Predict a Fuser Performance

Jun O Kim*[1], *Youngdae Ko*[1], *Sokwon Paik*[2]; [1]*DMC R&D Center, SAMSUNG ELECTRONICS CO., LTD.*; [2]*IT Solutions, SAMSUNG ELECTRONICS CO., LTD.; Suwon, South Korea

Abstract

A simulation method to predict a fuser performance is presented. It is based on the 2D thermal analysis using Comsol software. The analysis model consists of a 2 roll-type IH fuser and paper with toner on it. A sequence of warm-up, print, ready, and warm-up again is simulated. The warm-up time to print, print power, ready temperature, ready power, and FCOT (first copy out time) are estimated. Based on the analysis results the TEC (typical electricity consumption) is estimated for the fuser. The estimated fuser performance is compared to the measured data from the fuser jig test.

Introduction

Numerical simulations are widely used to design the electrophotograhy process in laser printers[1]. The fixing process requires minimal energy consumption with high heating speed, which are represented by TEC and WUT (warm-up time), respectively. An effective simulation method is necessary.

In this paper a simple 2D analysis method is presented to simulate the fusing process which includes warm-up, print, ready and warm-up again. The print warm-up time and TEC by simulation are compared to the jig test results for the validity of the simulation.

Simulation Method

Analysis Fuser Model

A schematic cross-sectional structure of the analysis fuser model is shown in Figure 1. The inductor above the heat roller (HR) is not shown. The diameters of the heat roller and pressure roller (PR) are about 40 mm. The heat roller consists of solid Al shaft, sponge, Ni, silicone rubber, PFA layers. The pressure roller consists of steel pipe, silicone rubber, PFA layers. By the Joule heat due to the eddy current, the Ni layer area below the exciting coil is heated. The paper and toner thickness are taken as 0.1 mm and 20 µm, respectively. The thickness of Ni layer is 40 µm. The analysis fuser model parameters are shown in Table 1.

Numerical Analysis Model

Governing Equation

The fixing process is simulated by the conventional heat transfer analysis using Comsol 3.5a[2]. To take into account the velocity of the roller and paper/toner, the Eulerian form of governing equation is used, i.e., the heat conduction and convection through a fluid is formulated as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q. \quad (1)$$

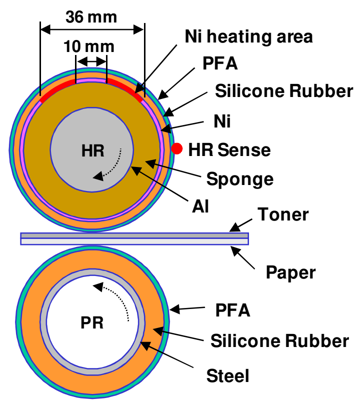

Figure 1. *Structure of the A3 color IH fuser model*

where T, ρ, C_p, $\mathbf{u}$, k, Q denote the temperature (K), density (kg/m^3), specific heat (J/kg·K), velocity field (m/s), thermal conductivity (W/m·K), heat source (W/m^3), respectively.

Table 1: Analysis model parameters

Item	Value
Printing speed (ppm)	45 (Letter landscape)
Paper length (mm)	215.9 (Letter)
Paper interval (mm)	78.96
Process speed (mm/s)	221.1
Power (W)	1300 max.
Print control temperature (°C)	170
HR length (mm)	330
Nip width (mm)	10.8

Material Property and Boundary Conditions

Comsol analysis model is shown in Figure 2. Since a thermal analysis is concerned, the shape deformation of rollers in the nip area is neglected. Instead a dummy area with nip width is introduced to consider the heat transfer from heat roller to pressure roller, as shown in Figure 2(b). The thermal conductivity of the dummy nip area is taken as anisotropic , i.e., $k_{xx} = k_{xy} = k_{yx} = 0$, k_{yy} = 10,000 W/m·K. Note that k_{yy} is very high to ensure the thermal contact effect between two rollers in the nip. The density and specific heat are taken as unities to take small values. When the paper is not fed, the toner and paper area in Figure 2(c) take the same material properties as the dummy area. When the paper is fed, the toner and paper area take their own material properties, and the process speed -V_p is applied to the domains. The inlet temperature and outlet convective flux boundary conditions are also applied in the toner and paper region.

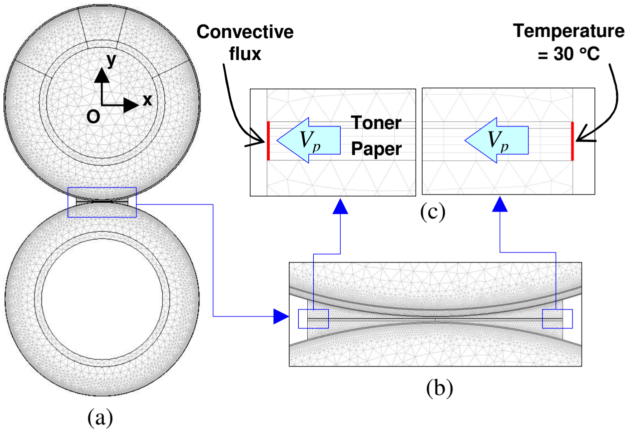

***Figure 2**. Comsol analysis model. (a) Mesh, (b) Mesh in the nip area (c) Boundary condition during paper feeding*

The initial temperature of the model is set as 30 °C. The convection heat transfer boundary condition is applied along the boundary surface:

$$q = h(T_{\mathrm{inf}} - T). \tag{2}$$

where q denotes the heat flux through the boundary, h and T_{inf} denote the convection heat transfer coefficient and the ambient temperature, respectively, and are taken as 10 W/m^2·K and 30 °C, respectively.

Velocity Field

Let $\mathbf{r} = [x, y]^{\mathrm{T}}$ be a position vector of a point P in a rotating body and $\mathbf{p} = [x_c, y_c]^{\mathrm{T}}$ be the origin of the rotation center O_c as shown in Figure 3. Then the velocity field $\mathbf{u}$ of the point P in the body can be represented as

$$\mathbf{u} = \boldsymbol{\omega} \times (\mathbf{r} - \mathbf{p}) \tag{3.1}$$
$$= [-\omega(y - y_c),\ \omega(x - x_c)]^{\mathrm{T}}. \tag{3.2}$$

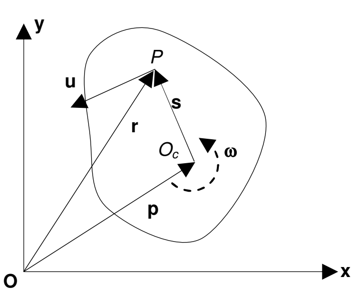

***Figure 3**. Velocity field of a rotating body*

where $\boldsymbol{\omega}$ denotes the angular velocity of the body. The velocity fields of the heat and pressure rollers can be calculated using eqn (3.2) from the printing speed and roller diameters.

Paper Interval Effect

Although changing the boundary condition for the paper and toner can account for the paper feeding, additional heat is released though the convective flux during the paper interval. To compensate for the paper interval, additional power is applied in the PFA region of the pressure roller as follows:

$$P_{\mathrm{PR}} = \alpha P \frac{L_{\mathrm{i}}}{L_{\mathrm{p}} + L_{\mathrm{i}}}. \tag{4}$$

where P_{PR}, P, L_{p}, L_{i} denote the power applied additionally to the pressure roller, the power supplied to heat roller during print, paper length, paper interval, respectively. α is a correlation factor, taken as 1/2.

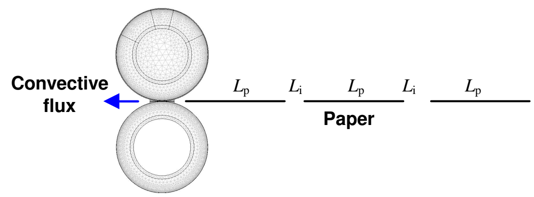

***Figure 4**. Paper interval effect*

Simulation Procedure

The overall analysis consists of the following steps. From Step 2, the previous end state is set to the current initial state.

Step 1: Perform a warm-up analysis with full power until the sense temperature reaches the print control temperature without paper feeding.

Step 2: Calculate the print power with paper feeding, while the sense temperature keeps the print control temperature. The paper and toner material properties should be changed to their own values and the boundary conditions should be changed as well as shown in Figure 2(c). The process speed should be applied also.

Step 3: Estimate the ready temperature corresponding the specified FCOT.

Step 4: Perform a cold-down analysis with power off and without paper feeding until the sense temperature reaches the ready temperature. Here the paper and toner material properties should be changed to the same as the nip dummy area. The velocity and boundary conditions should be changed to the same as Step 1 state.

Step 5: Calculate the ready power to hold the ready temperature.

Step 6: Perform a 2nd warm-up analysis with full power until the sense temperature reaches the control temperature without paper feeding. Check the 2nd warm-up time is acceptable compared to the specified FCOT. If not acceptable, go to Step 3

Step 7: Calculate the TEC according to the TEC measurement procedure.

Warm-up Analysis and Print Power Calculation

A warm-up analysis is performed to with full power for the HR sense temperature to reach the print temperature. Table 2 shows the analysis result.

Table 2: Warm-up analysis result

Item	Value
Print WUT (s)	24.4
Warm-up temperature (°C)	169.9
Warm-up speed(°C)	5.7

The paper is fed after print WUT, and the print power is calculated to keep the sense temperature after 15 s by changing the print power. The calculated power duty is 93.7% of full power, corresponding to 1218.1 W. Table 3 shows the analysis result and Figure 5 shows the temperature at the HR sense position for various power duties. Figure 6 shows the temperature distribution at WUT and at the end of print. Figure 7 shows the temperature change during warm-up with full power and paper feeding with power duty of 96.3%.

Table 3: Sense temperature according to the print power duty

Power duty	Sense temp. (°C) @WUT + 15 s
80.0%	155.5
90.0%	166.1
93.7%	170.0
100.0%	176.7

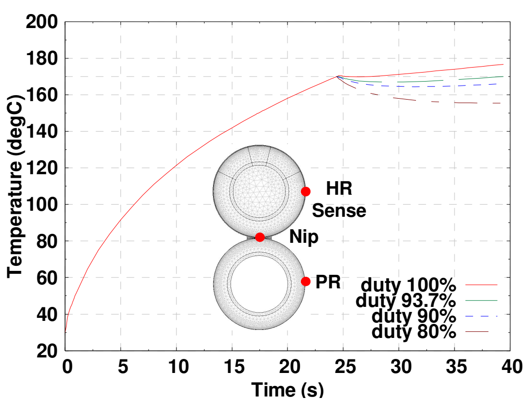

Figure 5. *Temperature change for different print power duties*

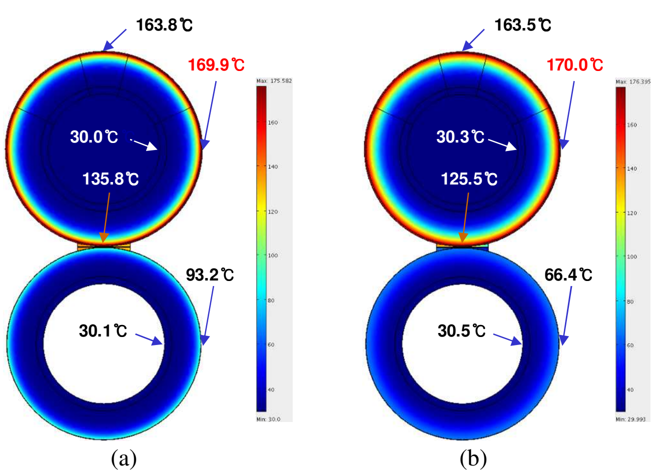

Figure 6. *Temperature distribution. (a) at print WUT, (b) at print WUT + 15 s with power duty 96.3%*

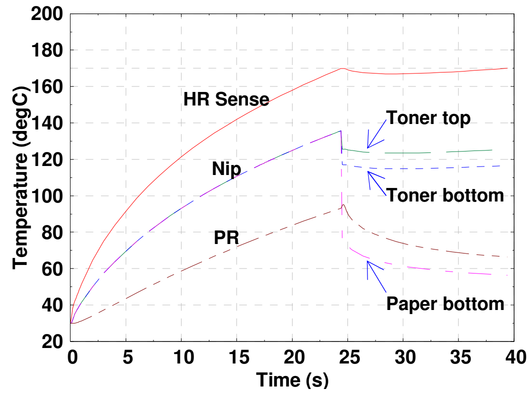

Figure 7. *Temperature change during warm-up and paper feeding*

Ready Temperature

At the end of print, the power is off to enter ready mode, as shown in Figure 8. The ready mode temperature and ready power duty should be determined so that the fuser should reach the print temperature from ready mode within the specified time, FCOT, say Δt = 5 s. Since the second warm-up speed is larger than the first one, the temperature change ΔT during Δt = 5 is estimated using the warm-up curve as shown in Figure 9. The temperature changes at the start and end of warm-up during Δt = 5 are ΔT_1= 61.6 °C and ΔT_2= 13.7 °C, respectively. The mean value is ΔT = 37.6 °C and the ready temperature is set to T_R = 170 °C - ΔT = 132.4 °C.

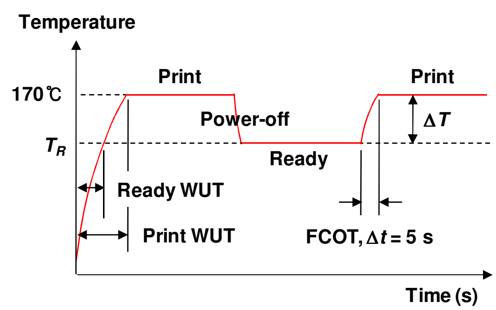

Figure 8. *Temperature change during warm-up and paper feeding*

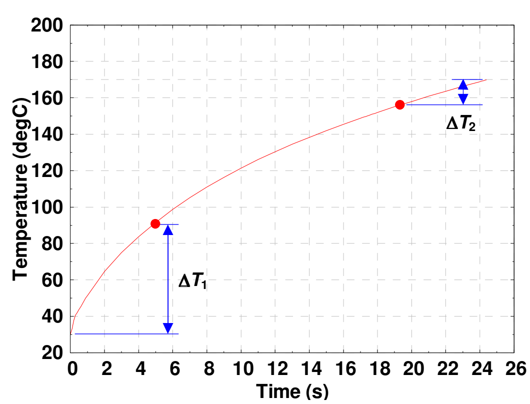

Figure 9. *Temperature changes at the start and end of warm-up during 5 s*

Cold-down Analysis and Ready Power Calculation

Since the ready temperature is determined, it is possible to calculate the ready power. A cold-down analysis is performed to reach the ready temperature, T_R = 132.4 °C. Note that the material properties, velocity and boundary conditions should be modified as stated previously. The analysis result is summarized in Table 4.

After entering the ready mode the ready power is calculated to keep the ready temperature after 15 s by changing the supply power. The calculated power duty is 37.5% of full power, corresponding to 487.5 W. Table 5 shows the analysis result and Figure 10 shows the temperature at the HR sense position for various power duties.

Table 4: Cold-down analysis result

Item	Value
Duration (s)	2.9
Cold-down temperature (°C)	132.7
Cold-down speed(°C)	-12.9

Table 5: Sense temperature according to the ready power duty

Power duty	Sense temp. (°C) @WUT + 15 s
30.0%	124.0
37.5%	132.4
40.0%	135.2
50.0%	146.3

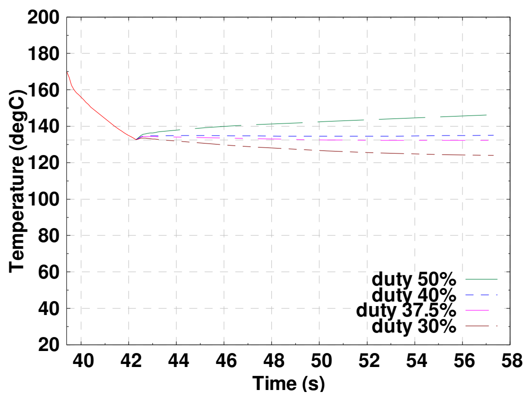

Figure 10. *Temperature change for different ready power duties*

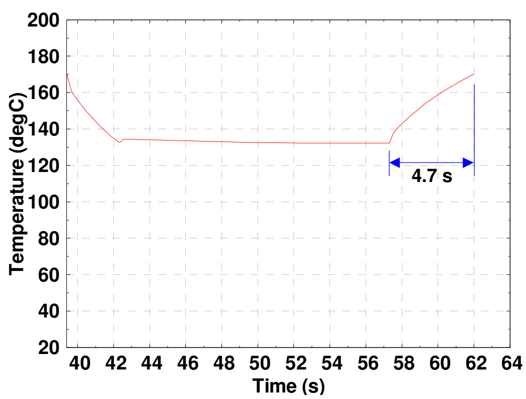

Figure 11. *Temperature change for different ready power duties*

2nd Warm-up Analysis

At the end of the ready mode a 2nd warm-up analysis is performed to with full power for the HR sense temperature to reach the print temperature. Figure 11 shows the temperature change, and the FCOT, the time to reach the print temperature from the ready mode, is 4.7 s, which is close to the specified FCOT 5 s. The estimated ready temperature T_R = 132.4 °C is justified. Now from Figure 5 we can see that the ready warm-up time, the time to reach the ready temperature from the initial temperature is 12.5 s.

Figure 12 shows the temperature change for the whole process. The whole analysis results can be summarized as follows:

- Initial temperature: 30 °C
- Print
  - Print temperature: 170.0 °C
  - Power duty: 93.7% (Power = 1218.1 W)
  - Print WUT: 24.4 s
- Ready
  - Ready temperature: 132.4 °C
  - Power duty: 37.5% (Power = 487.5 W)
  - Ready WUT: 12.5 s
  - FCOT = 4.7 s.

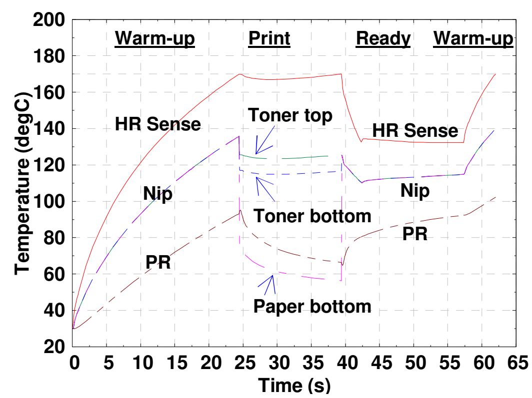

Figure 12. *Temperature change for the whole analysis process*

TEC Estimation

Based on the previous analysis results, TEC (Typical Electricity Consumption) can be calculated per eqns (5) and (6), as described in [3].

$$TEC = 5\times\left[E_{JOB\_DAILY} + (2\times E_{FINAL}) + [24-(N_{JOBS}\times 0.25) - (2\times t_{FINAL})]\times\frac{E_{SLEEP}}{t_{SLEEP}}\right] + 48\times\frac{E_{SLEEP}}{t_{SLEEP}}, \tag{5}$$

$$E_{JOB\_DAILY} = (2\times E_{JOB1}) + \left((N_{JOBS}-2)\times\frac{E_{JOB2}+E_{JOB3}+E_{JOB4}}{3}\right) \tag{6}$$

where

- E_{JOB_DAILY}: daily job energy,
- E_{FINAL}: final energy,

- N_{JOBS}: number of jobs per day,
- t_{FINAL}: final time to sleep,
- E_{SLEEP}: sleep energy,
- t_{SLEEP}: sleep time,
- E_{JOBi}: energy of the i^{th} job.

Table 6 shows the TEC estimation results. For simplicity E_{JOB2}, E_{JOB3}, E_{JOB4} are assumed to be 85.8%, 81.4%, 81.1% of E_{JOB1}, respectively. These values are based on TEC measurement of other IH printer. E_{FINAL} and E_{SLEEP} are not included in TEC calculation and the ready mode energy is not included either.

Table 6: TEC Estimation

Item	Value
ppm	45
Jobs/Day	32
Images/Job	31
E_{JOB1} (Wh)	22.8
E_{JOB2} (Wh)	19.6
E_{JOB3} (Wh)	18.6
E_{JOB4} (Wh)	18.5
(E_{JOB2} + E_{JOB3} + E_{JOB4})/3 (Wh)	18.9
E_{JOB_DAILY} (Wh)	611.6
TEC (kWh)	3.058

Comparison with Jig Test

The analysis results are compared to the measured data from the fuser jig test in Table 7. Figure 13 shows the fuser test jig. *TEC* value in the jig test is calculated with assumed energy for job 2, 3, and 4 as described before. Figure 15 and 16 show the power input to the fuser and the temperature at the HR sense position during warm-up and print. The temperature curves show different slopes during warm-up, however, the print warm-up time and TEC are almost the same.

Table 7: Cold-down analysis result

Item	Simulation	Jig Test
Print WUT (s)	24.4	23.36
E_{Job1} (Wh)	22.797	22.025
TEC (kWh)	3.058	2.955

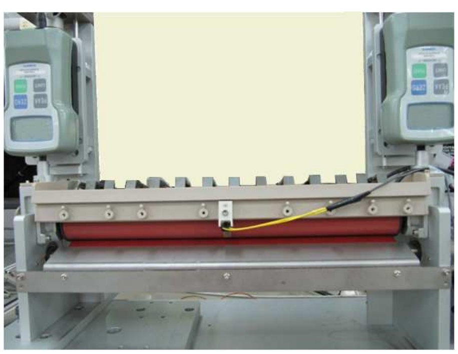

***Figure 13**. IH fuser test jig*

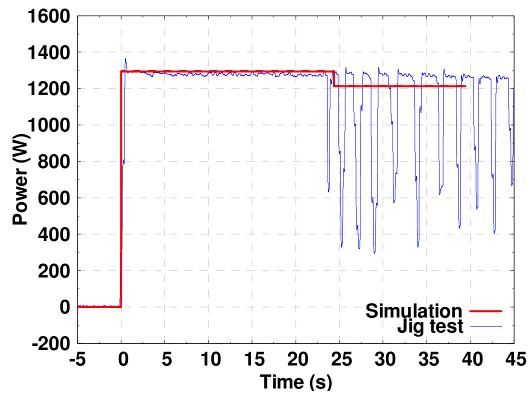

***Figure 14**. Power input to the fuser during warm-up and print*

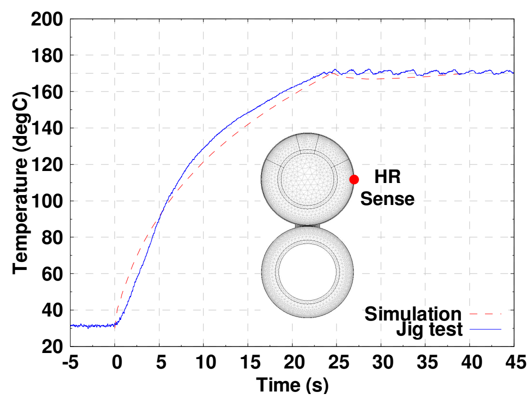

***Figure 15**. Temperature during warm-up and print*

Conclusion

A simple 2D simulation method is proposed to estimate the fuser performance based on the conventional heat transfer analysis. A sequence of warm-up, print, ready, and warm-up again is simulated and the warm-up time to print, print power, ready temperature, ready power, and FCOT are estimated. The estimated warm-up time and TEC are compared to the measured data from the fuser jig test, showing that the proposed method is reasonable.

References

[1] Hiroyuki Kawamoto, Numerical Simulations of Electrophotography Processes, IS&T's NIP24: Int. Conf. on Digital Printing Technologies, Pittsburgh, pg.10-13 (2008).

[2] Comsol Multiphysics Modeling Guide: Heat Transfer Fundamentals (2008)

[3] Imaging Equipment Program Requirements Version 1.2, http://www.energystar.gov/ia/partners/product_specs/program_reqs/ Imaging_Equipment_Program_Requirements.pdf.

Author Biography

Jun O Kim received the BS degree from Seoul National University, Korea in 1985, and MS and PhD degrees from the Korea Advanced Institute of Science and Technology (KAIST), Korea in 1987 and 1996, respectively, all in mechanical engineering. Between 1987 and 1990 he was a researcher at the Hyundai Maritime Research Institute (HMRI), *Korea. He joined Samsung Advanced Institute of Technology (SAIT), Korea in 1996. Since 2008 he has been with the DMC R&D Center at Samsung Electronics Co., Ltd. He has been working on the analysis and design of mechanical structures based on finite element analysis. His recent research is focused on the fusing technology in LBP.*

Young Dae Ko received the BS and MS degrees from Chung-Ang University, Korea in 1998 and 2000, respectively, all in mechanical design engineering. From 2000 to now, he has worked as a mechanical engineer at Samsung Electronics Co., Ltd. He has been working on design, test and analysis of mechanical equipments and set elements. His recent research is focused on the fusing technology in LBP

Sokwon Paik received the BS and MS degrees in astronomy from Yonsei University, Korea in 1994 and 1996, respectively, and PhD degree from Texas A&M University, USA in 2005, in mechanical engineering. Between 2005 and 2008 he was a postdoctoral research associate at Oak Ridge National Laboratory, USA. In 2008, he joined Samsung Electronics Co., Ltd. He has been working on fusing technology in LBP with the analysis and design of mechanical structures based on finite element analysis.