A Coupled Thermal-Structural Nip Analysis of Thermal Dye Transfer Printing

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Abstract

A coupled two-dimensional thermal-structural nip analysis using a commercially available finite element package, i.e., ABAQUS, has been developed to simulate the thermal dye transfer (TDT) printing process. Incorporating all key components in the thermal printing process, this simulation model includes a simplified printhead, the layered structure of a thermal media pair, i.e., dye donor ribbon and receiver, and the elastomer-covered platen roller. The unique feature in this simulation is its capability of simultaneously solving the structural and contact mechanism of the approaching surfaces during thermal printing and calculating the heat transfer through these interfacial contacts.

During the simulation, the model mimics the movement of the dye donor ribbon and receiver, which are brought into intimate contact between the printhead and the platen roller. Thermal energy or heat generated by pulsing the heating elements in the printhead flows through the media and across interfacial contact pairs, e.g., printhead and dye donor ribbon, and dye donor ribbon and receiver (where the dye diffusion occurs). The contact area and contact pressure at the interfaces, temperature distribution, thermal history, and stress-strain state are all calculated for each component. The model has been successfully implemented to investigate the effects of platen rollers, to study the media and equipment interactions, and to help identify essential material properties for media design.

Introduction

Thermal dye transfer printing is often referred as dye diffusion thermal transfer (D2T2) or dye-sublimation printing. This printing system provides high quality and an environmentally safe method of transferring images to print and transparency materials. Resistive-head thermal dye transfer printing uses thousands of tiny heating elements that come in contact with the dye donor ribbon. Each dye donor ribbon releases a color dye when heated. The amount of heat from each element and the corresponding temperature distribution across the entire donor and receiver, especially the area directly underneath the printhead, controls the amount of dye being transferred to the receiver. This dye diffusion mechanism blends the dyes and creates a continuous-tone image that distinguishes thermal dye transfer printing from other digital printing technology.

Figure 1 shows a typical thermal printing configuration. In a thermal printing process, the dye donor ribbon and the receiver are brought into intimate contact between the printhead and the elastomer-covered platen roller. Heating elements inside the printhead are pulsed with an electrical current (voltage) to generate heat that transfers across the interfaces of the printhead and the dye donor ribbon and through the donor-receiver assembly. To achieve high dye transfer efficiency, it requires an intimate and sufficient contact between the printhead and the dye donor ribbon, and between the dye donor ribbon and the receiver, to ensure efficient heat transfer across the interfaces and high activity of dye diffusion from the dye donor layer of the dye donor ribbon to the dye-receiving layer of the receiver.

As described above, thermal dye transfer printing, even in a very simplified form, involves multiple aspects of physics, such as electrical resistive heat generation, contact area and nip mechanics, heat transfer across interfaces concerning contact discontinuity, and heat-stimulated and -assisted dye diffusion. While working on a holistic understating of the dye diffusion mechanism and optimization of the thermal-resistor pulsing scheme, we focus on the coupled thermal-structural nip analysis in this study, which simulates the thermal and mechanical interactions between the thermal media and the printing system [1–3].

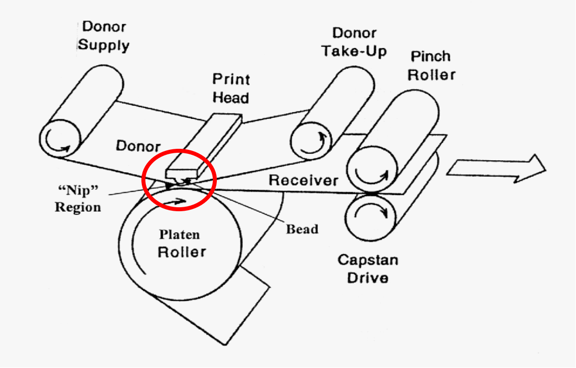

Figure 1. A typical thermal printing scheme

Coupled Thermal-Structural Nip Analysis

In the past, a number of two-dimensional (2-D) finite difference models and 2-D and 3-D finite element methods had been used to solve heat transfer problems related to thermal dye transfer printing [4,5]. However, most of the previous work has focused on the thermal media without taking into account the interactions between media and thermal printer. The contact area and nip pressure profile are affected by the loading conditions from the printhead, the thermal and mechanical properties of the platen roller and the thermal media characteristics. It is apparent that a coupled thermal-structural nip analysis can more accurately capture the physics involved in thermal printing and be more flexible in terms of studying the impacts of various system parameters. In theory, a fully coupled thermal-structural analysis is not required for thermal printing because the mechanical and thermal solutions do not affect each other strongly. However, when the associated contact mechanics in thermal printing is considered, we choose a fully coupled thermal-stress analysis readily available in ABAQUS/Standard to calculate the mechanical and thermal solutions simultaneously. Furthermore, in addition to providing a fairly stable contact algorithm, ABAQUS/Standard also accounts for contact conductance across the interface between contact pairs.

A coupled thermal-structural analysis of the present model comprises a thermal printhead with heating element, a dye donor ribbon, a receiver, and the elastomer-covered platen roller base cushion as shown in Figure 2. It is noted that the separation of the dye donor ribbon and the receiver at the peeling bar is not in the scope of the present model. All components are modeled as separate deformable regions that allow relative motions when necessary. Surface-to-surface contacts are subscribed for all contact pairs and temperature-dependent thermal and mechanical properties are used for all materials. Figure 3 shows the cross-section of the thermal media and finite element meshing used in the simulation. Meshing density in the contact area is essential for a converging solution.

To simulate a thermal dye transfer printing process, either a fixed engagement or a fixed nip load is applied at the top surface of the printhead. When the printhead is engaged, the load will transport through the printhead to form an intimate contact between the interfaces, i.e., printhead and dye donor ribbon, dye donor ribbon and receiver, and receiver and platen roller. Then the thermal media and platen roller assembly move forward (to the right in Figure 3) to mimic motion of printing.

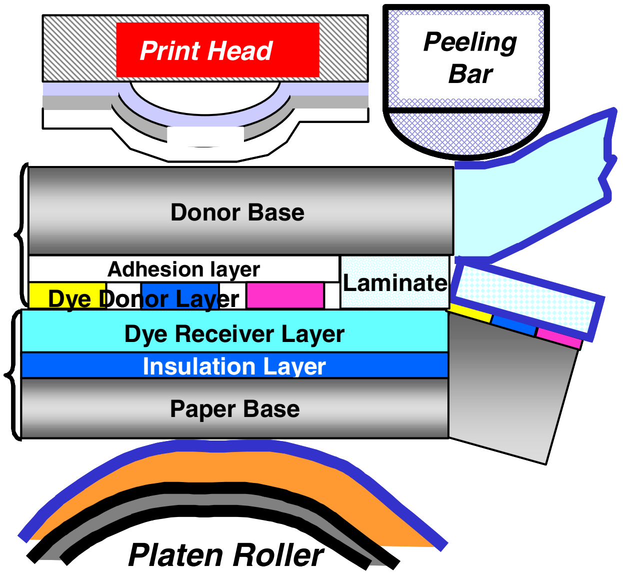

Figure 2. *A close-up cross-sectional scheme of a thermal printing system*

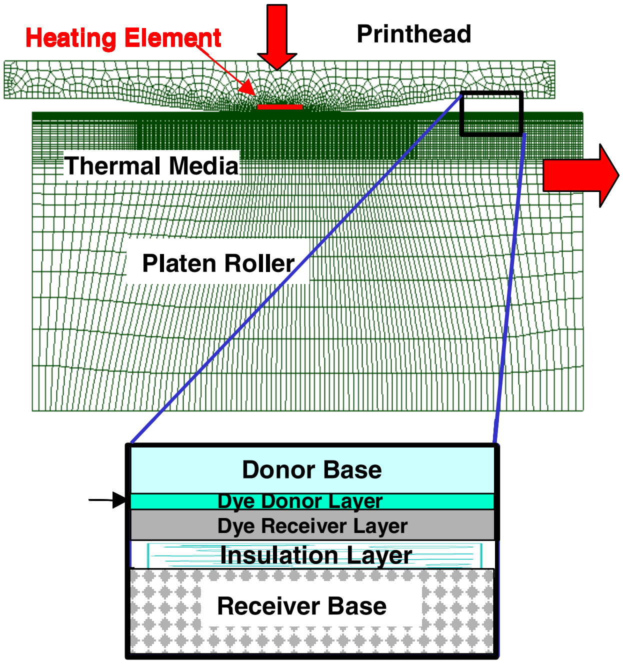

Figure 3. *Finite element meshing used in the simulation.*

Thermal Joint Resistance of Contact Area

To capture the heat transfer across the interfaces of all the contact pairs requires not only the knowledge of contact mechanics, such as the distribution of contact pressure, loading condition-dependent contact area, and thermal and mechanical properties of all components in thermal printing assembly, but also the thermal joint resistance of the contact area [6]. Because of the smoothness of both surfaces of the dye donor ribbon and receiver, it is reasonable to assume that an intimate contact (in both the microscopic and macroscopic sense) can be achieved when sufficient pressure is applied onto the contact pairs and their interfacial gaps are closed. Gap conductance that can be temperature or pressure dependent available in ABAQUS/Standard enables one to account for heat flow across an interface in the normal direction. Heat radiation among gaps is ignored because of its minor secondary effect.

The surface interaction model includes heat conduction effects between the contact surfaces flowing across the interface and is modeled by

$$q = k_g (T_A - T_B) \qquad (1)$$

where q is the heat flux per unit area crossing the interface from point A on one surface to point B on the other, T_A and T_B are the temperatures of the points on the surfaces, and k_g is the gap conductance. Predictions using gap conductance ranging from 10 to 20 mW/mm^2•°C results in good agreement with experimental data from previous studies [1–3].

Numerical Results

A series of simulations were run to study the thermal history of the dye donor-receiver assembly under various printing conditions, and also to study the effects of hardness of the platen roller and the importance of different components used in the construction of the thermal media of the dye donor ribbon and the receiver. The range of printing conditions, such as printhead loads (from 0.1 to 1 N/mm), heating element temperature (from 300 to 450 °C), and printing speed (from 15 to 65 mm/s), are chosen for parametric studies. Figure 4 shows a typical temperature distribution predicted by the present model. Also in Figure 4, the width of the heating element in the model is exaggerated for meshing purposes and should be much smaller in reality. However, because the prescribed temperature boundary conditions are used for heating elements, the size effects of the heating element do not have a great impact on calculated results. Acting like heat sinks, the massive heat insulation layer and the silicon single-crystal substrate of the printhead dissipate most of the thermal energy generated by electrical pulsing of the heating elements. Only a small portion of the thermal energy generated is used for thermal dye transfer. Furthermore, because of the motion of the thermal media assembly and fast printing speed, the thermal energy from the heating element does not transfer far into the media. It is believed that, for a time domain of several milliseconds, thermal joint resistance of the contact area represents a huge thermal barrier for heat transfer across interfaces even though an extremely high value of contact conductance has been chosen in the calculation.

Figure 5 shows the temperature gradient of various layers in the media and pressure distribution underneath the printhead. No matter how smooth we make the thermal media, microscopic voids will still exist, and a proper contact (nip) pressure is required for efficient heat transfer and dye diffusion. While higher head load will flatten out microscopic hills and valleys on the surface of the donor and receiver and thus increase the actual contact conducting area, unnecessarily high nip pressure may result in donor wrinkle problems and reduce printhead life caused by excessive wear. In general, the smoother contact surface and more compliance in one or some layers in the donor/receiver assembly may help minimize the nip load while achieving the desired contact area under the printhead.

A typical thermal history of the thermal media during printing simulation is shown in Figure 6. Locations of the nodal points shown in the insert of Figure 6 were plotted. As stated earlier, there exists a discrepancy in temperatures between the dye-donor layer (DDL) and dye-receiving layer (DRL), and between the donor top surface and the printhead whose temperature is about 350 °C (not shown in Figure 6). While the implications of this prediction require further investigation, one would postulate that this temperature gradient across the interface could be plausibly related to the dye diffusion mechanism. If so understood, an optimized thermal history of DDL and DRL for a designed sensitometry (optical densities across the range of thermal printing energy) may be achievable through a better understanding of the physics involved in thermal dye transfer printing.

Effects of the Hardness of the Platen Roller

To investigate the effect of the platen roller's hardness on the relationship of nip load and nip width, the model was run under a wide range of platen roller hardness with related modulus ranging from 5 to 500 MPa while all other parameters were kept constant. Figure 7 shows the required linear head load (the printhead load across its width in N/mm) to achieve a designed nip width (contact area underneath the printhead) using different rubber covers for the platen roller. Results suggest that the compliance (or modulus) of the platen roller does not play a key role in predicting the localized contact area immediately under the nip of the printhead.

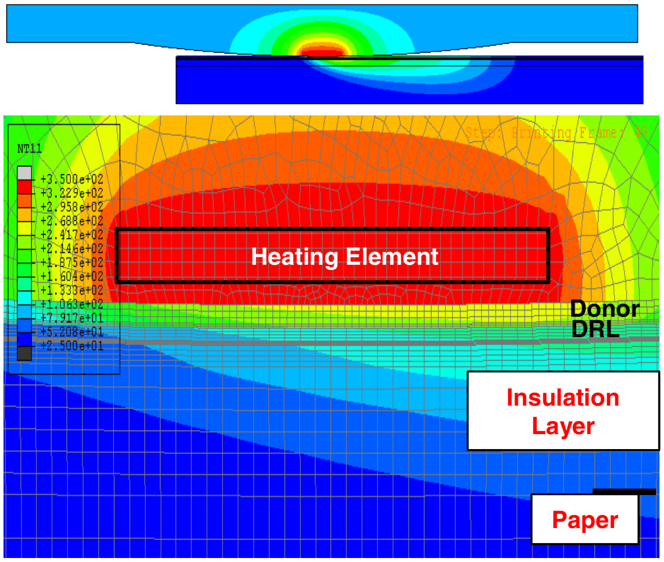

***Figure 4**. Temperature distribution in the thermal media and areas close to the heating element*

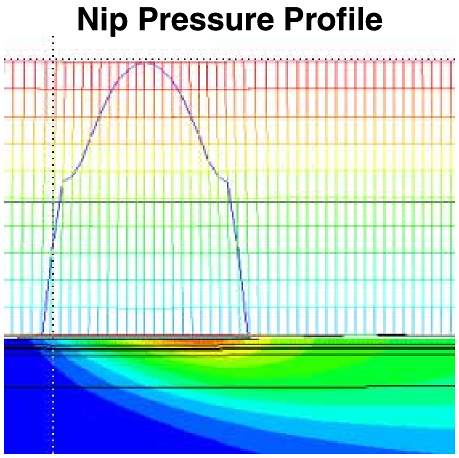

***Figure 5**. Nip pressure profile and temperature distribution around the printhead.*

Conclusions

The coupled thermal-structural nip analysis implemented by ABAQUS/Standard has been successfully used to study the physics involved in thermal dye transfer printing. The temperature distribution, thermal history, and contact pressure distribution are calculated using various system parameters including printhead temperature, printing speed, and head load. It is believed that controlling the temperature gradient in the thermal media is a critical factor determining thermal dye transfer sensitometry and the subsequent image quality.

The present model has also been shown to be very useful in studying the effects of the thermal and mechanical properties of individual layers in the dye donor and receiver thermal media on overall performance of the thermal media and printer. It is

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suggested that by gaining a better and thorough understanding of the thermal printing process; for example, a knowledge of how heat is generated and transferred through various layers of thermal media will be very important for scientists to formulate and integrate dye donors and receivers together for all thermal printing applications.

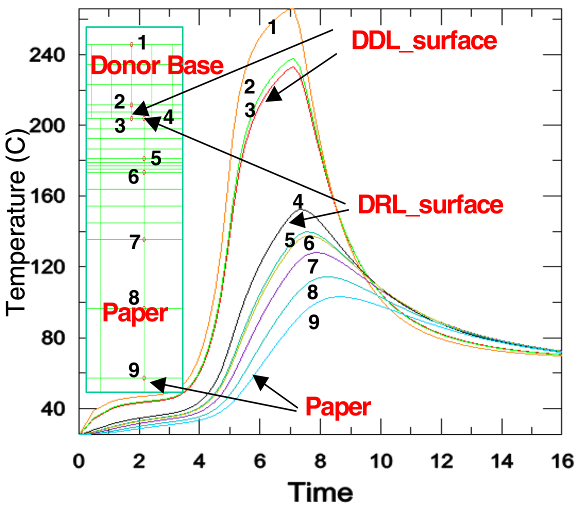

***Figure 6**. Thermal history of the media during printing simulation (line time = 5 ms; printing speed = 15 mm/s; temperature is in °C and time is in ms)*

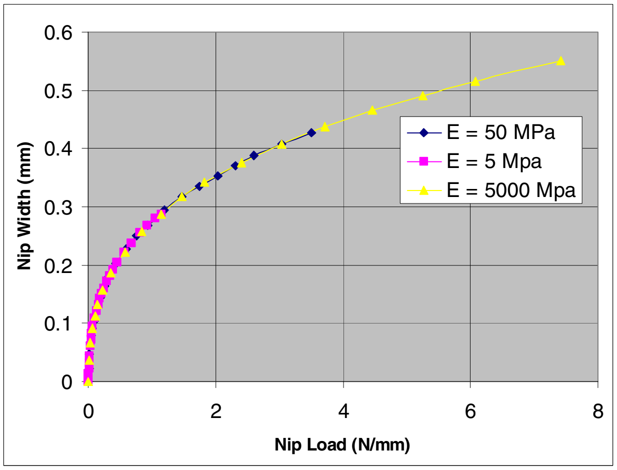

***Figure 7**. The effects of hardmess of platen roller base cushion on contact nip width.*

References

[1] E. J. Ozimek, IS&T 50th Annual Conf. (1997).
[2] E. J. Ozimek, IS&T NIP20, pg.984 (2004).
[3] E. J. Ozimek, IS&T NIP19, pg.371 (2003).
[4] J. E. LaFleche, R. C. Benson, K. S. Stack, and S. J. Burns, *Int. Symp. Information Storage and Processing Systems* – ASME, 2, 21 (1996).
[5] K. Setani, E. Sasaki, and Y. Takeda, “Thermal Control Method for Sublimation-Type Thermal dye Transfer Printing,” *SPIE-Hard Copy and Printing Technologies*, 1252, 144 (1990).
[6] M. Bahrami, M. M. Yovanovich, and J. R. Culham, “Thermal Joint Resistances of Conforming Rough Surfaces with Gas-Filled Gaps,” *Journal of Thermophysics and Heat Transfer*, Vol.18, No.3 (2004).
[7] ABAQUS User’s Manual v. 6.5

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Po-Jen Shih received his Ph.D. in Engineering Mechanics from the Virginia Polytechnic Institute and State University. He joined Eastman Kodak Company, Research & Development, in 1999, and currently works as a consultant engineer for various business units of Kodak. He has published more than 20 technical papers and has been awarded more than 10 U.S. patents.

Teh-Ming Kung is a senior research associate at Eastman Kodak Company. He received his Ph.D. in Material Science from the University of Rochester. He has been working on the development of various media technologies for digital color printing, such as organic photoconductors, inkjet and electrophotographic media, and thermal dye transfer receivers. He is the author of more than 52 U.S. patents