The Role of a Thermal Dye Receiver in Thermal Dye Transfer Printing – A Modeling Approach

Po-Jen Shih, Narasimharao Dontula, and Teh-Ming Kung; Eastman Kodak Company; Rochester New York/USA

Abstract

The technological advances at Kodak in thermal dye transfer (TDT) printing in recent years have provided consumers with a faster and more affordable thermal printing solution. However, to keep offering retail quality digital prints with ever-increasing printing speed at an ever-lowering cost presents a challenge to researchers in the field of TDT printing technology. In general, the thermal dye receiver comprises a polymeric image-realization layer, usually called the dye-receiving layer (DRL), coated on a base comprising a compliant heat-managing layer (CHML) laminated to or coated on a support such as a cellulose paper base or a plastic film. It is well known that the thermal dye receiver is a multilayered structure and each layer usually possesses specific characteristics in order to make a high-quality TDT print possible. For example, the DRL must be co-optimized chemically with the dye donor layer (DDL) to facilitate the dye transfer efficiency. Also, the dye transfer efficiency is impacted by the thermal dye receiver's ability to provide sufficient compliance for thermal printhead conformity to ensure a good thermal contact between the printhead and the overall thermal media assembly, and at the same time maintain more printing energy at the interface of the DRL and DDL. This paper investigates the physics involved in the fast thermal printing process and the functionality of the various layers in a thermal dye receiver by using a coupled two-dimensional thermal-structural nip analysis.

Introduction

Thermal dye transfer (TDT) printing is often referred to 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 reflective print and transparency materials. Resistive-head TDT 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 TDT printing from other digital printing technologies.

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 intimate contact between the printhead and the dye donor ribbon, and between the dye donor ribbon and the receiver, to ensure high activity of dye diffusion from the dye donor layer in the dye donor ribbon to the DRL of the receiver.

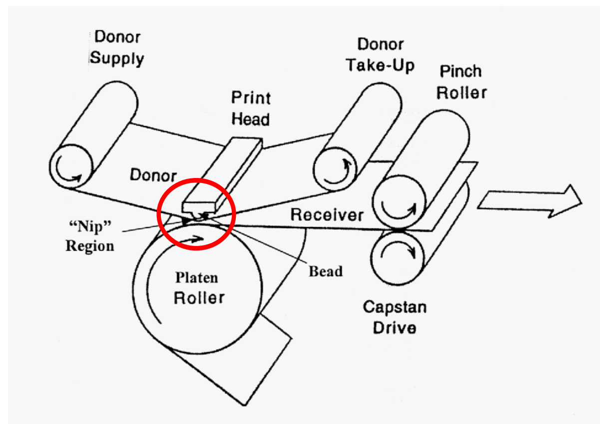


***Figure 1**. A typical thermal printing scheme.*

As described above, TDT printing, even in a very simplified form, involves multiple aspects of physics, such as electrical resistive heat generation, contact and nip mechanics, heat transfer across interfaces concerning contact discontinuity, and heat-assisted dye diffusion. The continued need for higher printing speed and lower media cost have led to the desire for better understanding of the role of each component used in the thermal receiver. This enables a thermal receiver developer to focus on the principal driving factors and to try to find a balance between economy and the overall performance of the thermal receiver when designing a robust thermal dye receiver.

Thermal Dye Donor and Receiver

Kodak's TDT printing process consists of a thermal dye receiver contacting a donor ribbon (a film substrate) that supports three printing dye patches and a clear laminate, wherein the laminate is applied to the printed image to protect and enhance the durability and stability of the final picture print from fingerprints, scratches, stains, light and heat-induced fade, ozone and other gaseous attack, and water damage, as well as to control and manipulate gloss level (e.g., glossy, satin, and matte) of the prints. In addition, Kodak's scientists have developed a robust slip layer that resides on the backside of the donor ribbon that allows the donor to glide smoothly past an extremely hot thermal printhead.

This slip layer ensures highly efficient contact heat conduction and minimizes the chance of the donor sticking to the printhead, which often leads to unwanted line artifacts on the image. More details on the current development of Kodak's thermal dye donor technology are available in reference [1].

Another component of TDT printing is the thermal dye receiver. Although many thermal dye receivers are available on the market, it is well known that the best quality thermal print comes from application of a systems approach where the thermal dye donor and receiver are co-optimized with specific thermal printing systems.

Over the years, Kodak has developed many thermal dye receivers for different printers and market applications. In general, Kodak's thermal dye receiver comprises a polymeric image-realization layer called the DRL coated on a base or a support comprising a compliant heat-managing layer (CHML), which is laminated to or coated onto a substrate such as a cellulose paper base or a plastic film substrate. In particular, the receiver support technology has evolved from a resin-coated cellulosic paper [2] to a multilayered structure that consists of a CHML that is a sandwiched microvoided, biaxially oriented polypropylene (BOPP) laminate adhered to cellulosic paper on one side, and on the opposite side is another BOPP laminate to balance the overall receiver structure [3]. The function of the DRL is multifold: it needs to accept dye molecules from the donor in an efficient manner, and it provides an environment of dye compatibility and stability to prevent dye smear and dye molecule degradation (in other words, preserves image sharpness/contrast and stability over time), while not sticking to the donor patches but adhering to the protective laminate in the printing process.

It is the objective of this paper to investigate the physics involved in a TDT printing process and the functionality of the various layers in a thermal dye receiver by using a coupled two-dimensional thermal-structural nip analysis and a sequentially coupled thermal-dye diffusion analysis.

Simulation Method

Currently there are no commercial multiphysics codes available for solving the coupled structural-thermal-dye transfer nip printing analysis. The theoretical framework regarding the coupling effects of thermal-structural nip analysis and thermal dye diffusion analysis associated with TDT printing is described in the flow chart (Fig. 2). It begins with data inputs that include mechanical and physical properties of thermal media and characteristics of printers and their settings. A fully coupled thermal-stress analysis readily available in ABAQUS/Standard was used to calculate the mechanical and thermal solutions simultaneously. In addition to providing a fairly stable contact algorithm, ABAQUS/Standard also accounts for contact conductance across the interface between contact interfaces, which can be used to investigate the effectiveness of a slip layer (printhead to donor) and the effect of surface roughness of the dye-receiving layer. Mechanical nip results, including deformations, strains, stress, and nip contact, can be used to study the effects of compliance of the thermal receiver and the effects of hardness of the platen roller [4]. The temperature distribution computed for all time increments are then imposed as thermal loading conditions for the sequentially transient coupled thermal-dye diffusion analysis.

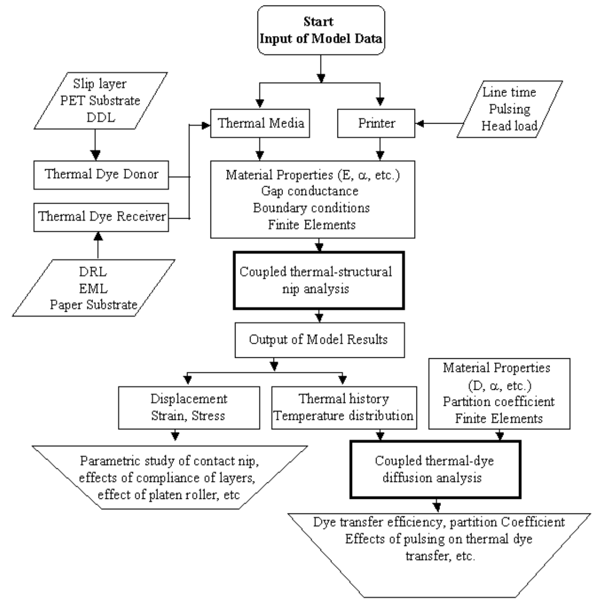


***Figure 2**. Flow chart of the coupled thermal-mechanical-dye diffusion analysis.*

Finite Element Thermal Dye Diffusion Analysis

The TDT process is modeled as a temperature and concentration-driven mass diffusion process. The governing equations are an extension of Fick's law and can be expressed as

$$\frac{\partial c}{\partial t} + \nabla \bullet J = 0 \qquad (1)$$

Where *c* is the mass concentration of dye and

$$J = -D \cdot \nabla c \qquad (2)$$

is mass (dye) flux; *D* is the dye diffusion coefficient and is a function of temperature and dye concentration.

The commercial finite element package ABAQUS is used to model this TDT process. The basic solution variable, namely the normalized concentration, is defined as

$$\phi = c / s \qquad (3)$$

where s is the dye's solubility in the binder of the DDL and the DRL. For calculation purposes the normalized concentration is defined as unity based on a starting concentration *c*, which is obtained from a known dye-to-binder ratio. During printing, the dye diffusion efficiency depends strongly on the chemical, morphological and thermal characteristics of the DRL, existing dye concentration in the DRL, and the solubility of the dye molecule in the DRL. The dye concentration in the DRL is treated as a subject for investigation.

To establish the relationship between Fick's law and the normalized concentration, one can substitute Eq. (4) into Eq. (3). The governing equation of TDT can be written as

$$J = -D \cdot \left(s\frac{\partial \phi}{\partial x} + \phi \frac{\partial s}{\partial x}\right) \qquad (4)$$

Because s is a function of temperature (θ), we can rewrite Eq. (4) as

$$J = -sD \cdot \frac{\partial \phi}{\partial x} - D \cdot \frac{c}{s}\frac{\partial s}{\partial \theta}\frac{\partial \theta}{\partial x} \qquad (5)$$

The two terms in this equation describe the mass (dye) flux that is due to the normalized concentration gradient and the temperature-driven dye diffusion process, respectively [5].

Because of rapid pulsing of the heating element during thermal dye printing, the temperature of the entire domain of interest (printhead, donor, and receiver, etc.) may fluctuate significantly. Dye diffusion coefficients were found to be linearly dependent on temperature in some dye donor layers and DRLs [6-8]. It is well known that diffusion coefficients are a function of temperature and concentration. However, after introducing highly efficient DRLs in our thermal media, it was found that the value of the glass transition temperature of the polymeric materials (compound) chosen in the DRLs is important.

Expressing glass transition temperature of the DRL as a function of dye concentration, the dye diffusion coefficient can be expressed as [9]

$$D = A\,Exp\left[\frac{-B}{\left(T - T_g + C\right)}\right] \qquad (6)$$

where A, B, and C are constant and T_g is the glass transition temperature of dye plus the polymeric binder through which the dye diffusion occurs. As a first approximation, the dye diffusion coefficients are assumed to be the same for the donor and the receiver binder. Typical temperature-dependent dye diffusion coefficients for two donor-receiver sets (highly efficient and less efficient) are shown in Figure 3. Table 1 lists the constants used to construct the curves.

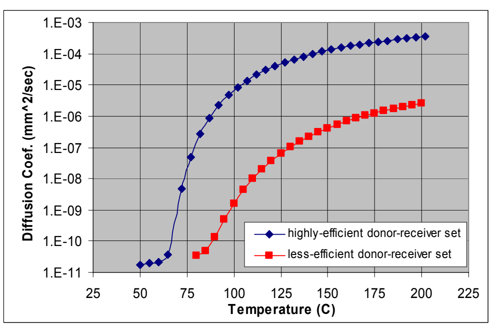


***Figure 3**. Thermally induced dye diffusion coefficient values.*

***Table 1**. Constants used to construct the curves in Figure 3 for dye diffusion coefficient.*

	A (mm^2/s)	B (°K)	C (°K)	T_g (°K)
Highly-efficient	2.5e-3	300	25	345
Less-efficient	1.0e-4	544	43	363

Finite Element Model

To simulate a TDT 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 is transferred through the printhead, which results in an intimate contact between the interfaces, i.e., printhead and dye donor ribbon, dye donor ribbon and receiver, and receiver and platen roller. In the simulation, the printhead is moved toward the left in Figure 4 to mimic printing motion. Figure 4 shows the cross-section of the thermal media and finite element meshing used in the simulation. To obtain a convergent solution, suitable mesh density in the contact area is essential. It should be noted that only the dye donor and dye receiver are meshed for sequentially coupled thermal-dye diffusion analysis. Eight-node quadratic elements CPE8RT and DC2D8 are selected for coupled thermal-structural nip analysis and sequentially coupled thermal-dye diffusion analysis, respectively. For simplification, we chose identical meshes for both analyses in spite of the fact that ABAQUS allows mismatching on meshes.

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 platen roller hardness and the importance of different layers 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), were chosen for parametric studies. Figure 5(a) shows a typical temperature distribution predicted by the present model and Figure 5(b) shows a typical dye concentration contour for both the highly efficient and less efficient dye donor-receiver sets under identical temperature distribution and thermal history.

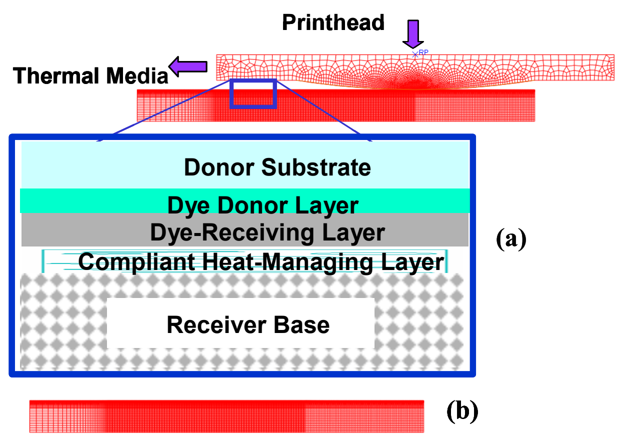
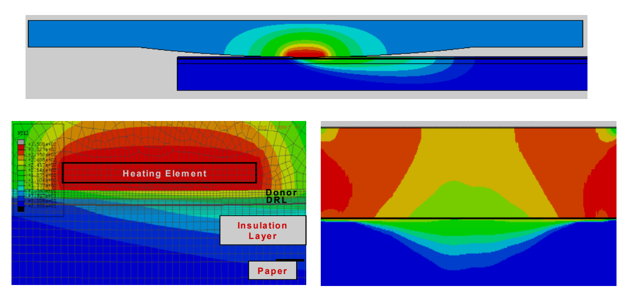


***Figure 4.** Typical finite element mesh for (a) coupled thermal-structural nip analysis and (b) coupled thermal-dye diffusion analysis.*



5(a) 5(b)

***Figure 5(a)**. Temperature distribution in the thermal media and areas close to the heating element. **Figure5(b)**. Dye distribution in the thermal media.*

Effect of Material Properties of Layers Used in Construction of a Thermal Dye Receiver

As stated in the previous section, a typical thermal dye receiver from Kodak comprises a DRL coated on a base comprising a CHML being laminated to or coated onto a substrate such as a cellulose paper base or a plastic film. The first case analyzed is the effect of Young's modulus of the CHML. Figure 6 shows the relationship between the Young's modulus of the CHML and the resulting contact area under the thermal printhead when subjected to identical head load (0.5 N/mm). Highly efficient heat conduction requires intimate contact between printhead and media. Also as pointed out in reference 1, most of the heat transfer occurs at the area directly under the heating element of the printhead. Although the design of the printhead may vary from one supplier to the other, the typical size of the heating element is about 150 µm. The selection of the CHML must allow a nip width greater than the length of the heating element in the printhead. For example, if Young's Modulus, E, of CHML is 1000 MPa, the resulting nip width is about 120 µm (a bit smaller than the heating element assumed as 150 µm), the temperatures within the thermal dye donor and receiver are a little lower compared to the case when a CHML of E = 100 MPa is used (Figure 7). This fact suggests that the distribution of dye concentration will be different, as shown in Figure 8.

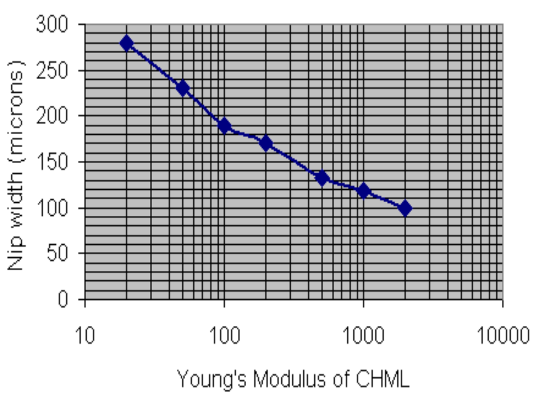


Figure 6. *Nip width vs. Young's Modulus of CHML (simulated at ambient temperature).*

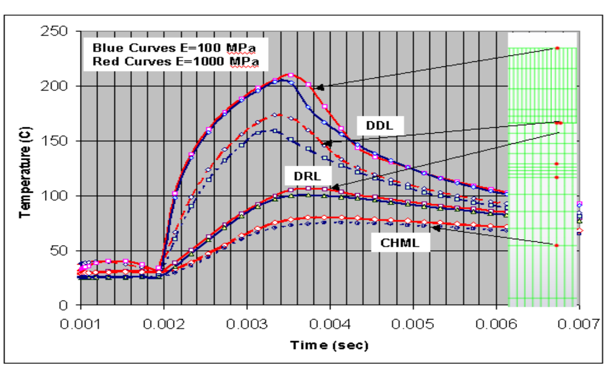


Figure 7*. Effects of Young's Modulus of CHML on thermal history of the thermal dye donor and thermal dye receiver.*

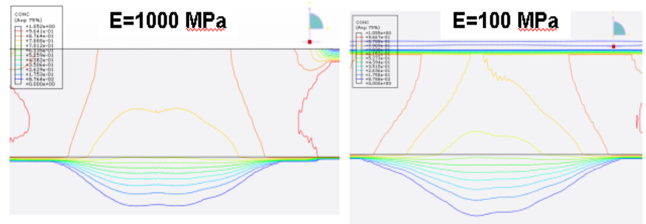


Figure 8*. Effects of Young's Modulus of CHML on thermal dye distribution.*

Conclusions

The coupled two-dimensional 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 critical for determining dye transfer efficiency and therefore the sensitometry and 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 suggested that gaining a better and thorough understanding of the TDT printing process will be very instrumental for scientists to formulate and integrate dye donors and receivers for more advanced and specific thermal printing applications.

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Author Biography

Po-Jen Shih received his Ph.D. in Engineering Mechanics from the Tech. He has worked as a consultant engineer for various business units of Kodak since 1999. He has published more than 20 technical papers and has been awarded 17 US patents.

Narasimharao Dontula is a Sr. Principal Scientist at Eastman Kodak Company. He received his PhD in Chemical Engineering from Clarkson University. Over the past 8 years at Kodak he has worked on the development of various receiver media technologies for silver halide, ink-jet, electrophotographic and thermal dye transfer. He is the author of 31 US patents.

Teh-Ming Kung is a Research Fellow at Eastman Kodak Company. He received his PhD 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 electro-photographic media, and thermal dye transfer receivers. He is the author of 56 US patents.