Resolution Performance of Images Printed by Laser Dye Thermal Transfer

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Microscopic optical image density and resolution performance are discussed for laser thermal transfer printing of the dye sublimation type. This printing method provides high resolution because of the high converging property of the laser beam. In this study, optical density profiles of line images printed by dye sublimation type laser thermal transfer printing were measured and compared with images of the wax type in order to clarify the spread of the printed dots. These profiles were explained numerically, using tone reproduction curves. Resolution performance was evaluated, quantitatively, and the maximum resolution was found to be 10,160 dpi. This value was confirmed by the printed microcharacters. Laser dye transfer printing is feasible for printing not only full-color images, but also fine patterns and microcharacters.

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Introduction

Thermal transfer printing has been used for many practical applications in the field of color hardcopy because of its special merits—simple process, high image quality, and maintenance-free equipment. Although the requirement for higher definition images has been increasing, it is impossible to improve the resolution of conventional thermal transfer printing significantly; the limitation is the size of the heating element of the thermal printing head. For dye sublimation printing in particular, the edge of a printed dot tends to spread because of its possibility of reproducing continuous tone.

Thermal transfer printing using a focused laser beam as the heat source instead of a thermal head provides very high resolution. This laser thermal transfer printing is classified into two types: dye sublimation type[1–5] and wax-melt type[6,7]. For thermal transfer printing of the dye sublimation type (laser dye transfer printing), a printed dot still spreads easily, but very few details are known about it. Thus, the aim of our present work is to clarify the microscopic properties of the optical image density and to obtain a maximum resolution value for laser dye transfer printing.

In this study, optical density profiles of printed line images were measured[8] and explained numerically by means of tone reproduction curves. Resolution performance was evaluated quantitatively,[9] and the maximum resolution was determined for laser dye transfer printing.

Experimental

Principle and Printing Medium. The principle of laser dye transfer printing is shown schematically in Fig. 1. The ink layer is composed of laser absorption material, sublimation dye, and polymer binder. A laser beam focused on the ink layer is absorbed by the laser absorption material, and the optical energy is converted into thermal energy. The sublimation dye is transferred to the accepting sheet, which is in contact with the ink sheet, by means of the thermal energy. The printed dots are very small, corresponding to the size of a laser spot (several micrometers).

Figure 2 shows the composition of the printing media[10] used for these experiments. The dye sublimation type is shown in Fig. 2(a). The thicknesses of the base film and the ink layer are 15 and 1 μm, respectively. An infrared (IR) absorption dye is used as the laser absorption material, a tricyanovinyl dye is used as the magenta sublimation dye, and epoxy resin is used as the binder. The ratio of IR absorption dye, sublimation dye, and binder is set at

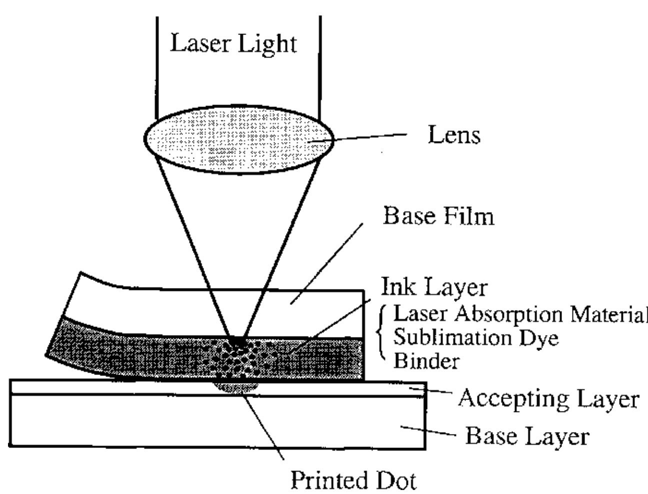

Figure 1. Principle of laser dye transfer printing.

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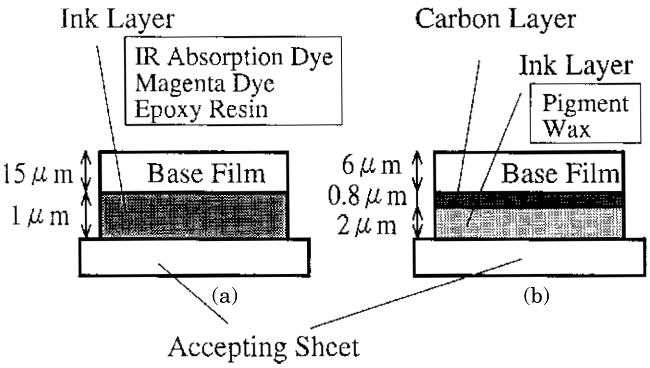


Figure 2. Composition of two types of printing media: (a) dye sublimation type and (b) wax type.

1:2:2 by weight. The accepting sheet is a type commercially available for video printers. The wax-type medium used in this study for comparison is shown in Fig. 2(b). A color ink sheet of the double-layer type (an experimental product, Fujicopian Co., Ltd.) is used in this experiment.

Experimental Apparatus. The schematic diagram of the experimental printing system is shown in Fig. 3, and the specifications of the system are shown in Table I. A semiconductor laser with 90-mW power and 825-nm wavelength is used as the light source. The maximum printing power (output power at the printing medium) is 50 mW. The focusing lens has a numerical aperture of 0.26, and the minimum optical spot diameter is 2.8 μm at the surface of the accepting sheet. Printing media are fixed on the stainless steel drum, which is 32 mm in diameter. Fast scanning is run by the dc motor, which rotates the drum constantly, whereas slow scanning is run by the stepping motor, which drives the laser and an optical system on the moving stage. The origin of the rotating drum is sensed by an optical sensor. By matching the sensor's signal, the dc motor, the stepping motor, and the image data are synchronized by the system controller.

Method of Measurement. The lines are printed, using continuous irradiation of the laser. Then the cross-sectional distribution of the optical density (optical density profile) for the line is measured by a microdensitometer (PDM-5, Konica Corp.) The optical density is measured in transparency mode to optimize the resolving power of the measurement. The slit of the microdensitometer is set at a 1-μm width and 3-μm height to obtain maximum resolving power performance.

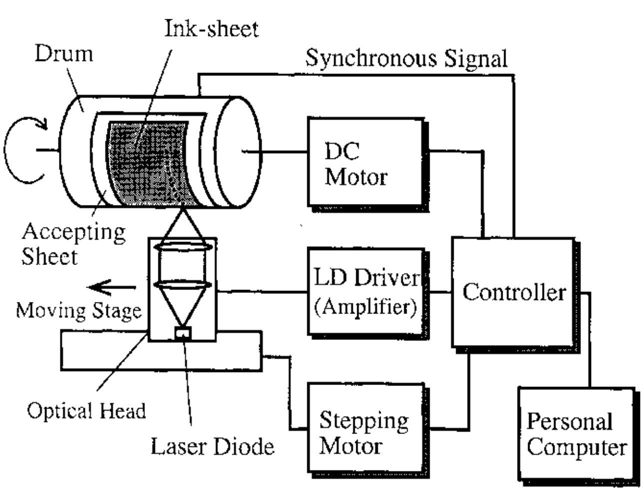


Figure 3. Schematic of the experimental printing system.

TABLE I. Specifications of the Experimental Printing System

Item	Specification
Resolution	~5000 dpi
Printing area	50 mm × 50 mm
Printing power	50 mW maximum
Optical spot diameter	2.8 μm
Wavelength of laser	825 nm
Drum rotation speed (circumferential)	50 ~ 1000 mm/s

The resolution performance of the laser dye transfer printing is measured as follows. Lines are printed at even intervals. Magnified images of the printed lines are input into a real-time image analyzer (Luzex F, Nireco Corp.) by a CCD camera. The distribution of the brilliance level measured by this analyzer is shown in Fig. 4. This measurement was carried out under conditions that provided a linear relation between the brilliance level (arbitrary unit) and the optical density. Then we calculated the ratio of the amplitude (a) to the amplitude in the case of a very long interval (b). This value is different from the modulation transfer function (MTF), because the line width does not equal the interval in this measurement. The value instead indicates the degree of separation of adjacent lines. We termed the value of a/b the *separation ratio*. We evaluated the resolution performance by using the characteristics of the separation ratio with decreasing line interval. The reciprocal of the line interval corresponds to the ordinary line frequency. The line frequency varied from 20 to 250 lines/mm, and the line width was 3 μm when the recording power of the laser was 9.5 mW.

Results and Discussions

Optical Density Profiles. Figure 5 shows the optical density (OD) profiles of the line images with increasing laser power for dye sublimation type laser thermal transfer. The profile exhibits a sharp peak and gentle expansion slope on the skirts. As the laser power increases, the profile becomes larger and of similar shape; then a valley is observed at the center of the profile. For comparison, Fig. 6 shows profiles for line images produced by the wax type laser thermal transfer. The profiles show little expansion on the skirts as compared with dye sublimation type images. There are some roughnesses in the profiles, which can be explained as roughening due to the melting

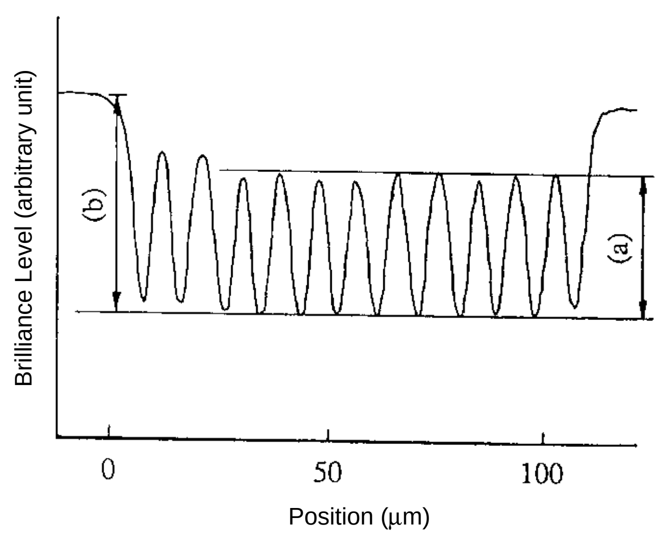


Figure 4. Distribution of the brilliance level for lines printed at even intervals. The valleys and the peaks of the distribution correspond to the lines and the spaces, respectively.

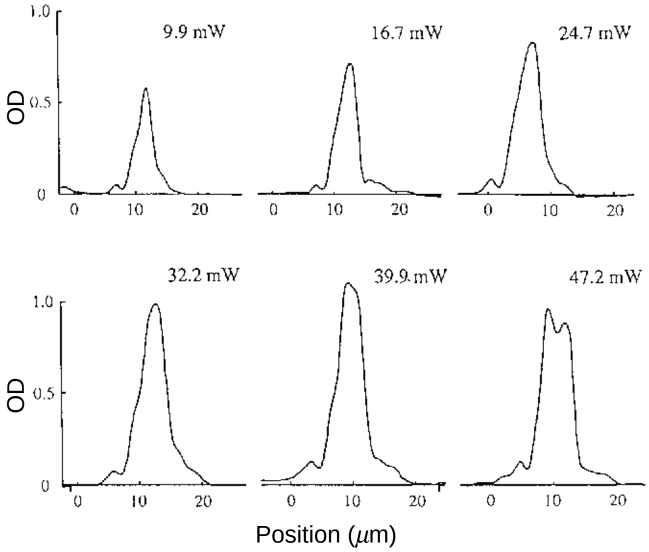


Figure 5. Optical density profiles of line images with increasing laser power for the dye sublimation type images.

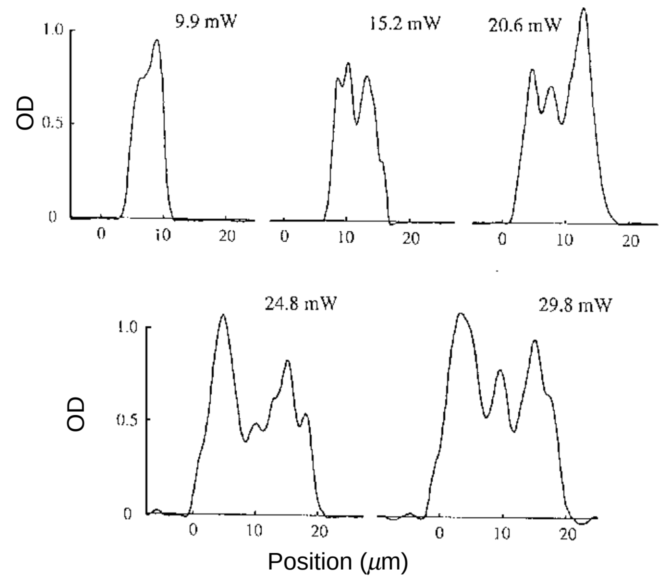


Figure 6. Optical density profiles of line images with increasing laser power for the wax type images.

wax at the interface between the ink layer and the carbon layer. As the laser power increases, line width increases without change of the maximum value of OD. These characteristics differ from those of the dye sublimation images.

Next we will explain the characteristics of the OD profile, using the tone reproduction curve and the distribution of laser light intensity. The relationships between input energy and OD measured from prints are plotted in Fig. 7. The horizontal axis shows normalized input energy. This measurement was carried out with large spot diameter so that uniform OD's could be obtained. These measured points can be approximated by high order expressions. The tone reproduction curve, or the relationship between OD and input energy, is formulated as follows:

$$f_d(X) = -2.34x^3 + 3.47x^2 - 0.144x, \quad (1)$$

$$f_w(x)^3 = 151x^4 - 354x^3 + 295x^2 - 101x + 11.9 \text{ for } 0.375 < x < 0.760, \quad (2)$$

where the subscripts d and w indicate dye sublimation type and wax type, respectively. We confirmed that the distribution of the light intensity of the laser beam at a focal spot was Gaussian, and it is formulated as follows:

$$I(r) = \exp(-2\, r^2/W^2), \quad (3)$$

where W is the spot radius ($1/e^2$) and r is the distance in radius direction. Equation 3 is normalized so that the maximum laser intensity equals unity. The energy distribution expressed by Eq. 3 is diffused by heat conduction in practice. This phenomenon is strictly simulated by numerical analysis. However, for simplification, we introduce the next expression, in which the diffusion of the energy is considered to be the increase of the spot radius:

$$I(r) = \exp[-2\, r^2/(s\, W)^2], \quad (4)$$

where s (>1) is a parameter of the increase of spot radius W. Further, assuming that the relationship illustrated in Fig. 7 always holds in micro regions, the OD profile $D(r)$ is expressed as follows:

$$D_d(r) = f_d\, [k\, I\, (r)], \qquad D_w(r) = f_w\, [k\, I\, (r)], \quad (5)$$

where k is a parameter that expresses the absolute value of laser power. Figure 8 shows OD profiles calculated from Eq. 5 for dye sublimation type and for wax type images. The increase in k and w implies the increase of laser power. OD profiles with increasing laser power are qualitatively in good agreement with the experimental results shown in Figs. 5 and 6. The calculated result for the wax type shows no roughness because it is an ideal case. From the above result, we consider the characteristics of the tone reproduction curves shown in Fig. 7 to be valid in micro regions for both image types.

Evaluation of Resolution. Figure 9 shows the relationship between the separation ratio and the reciprocal of the line interval with various laser powers. High separation ratio at short line interval indicates high resolution. High laser power causes an increase of line width and results in the loss of resolution, but reduced laser

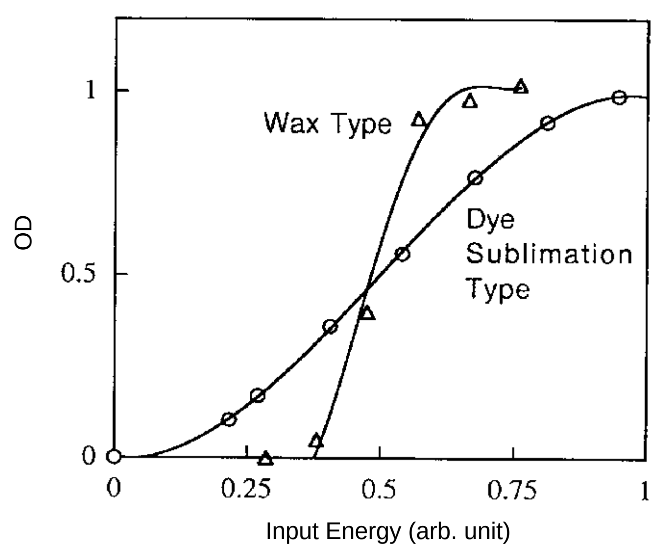


Figure 7. The relationship between optical density and input energy. Circles and triangles show measured points for dye sublimation type and wax type images, respectively. Solid lines show approximate curves.

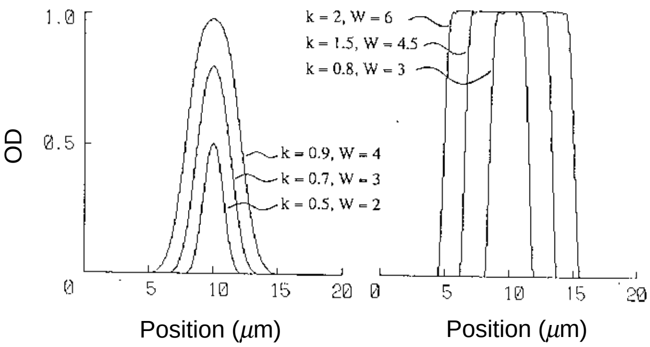


Figure 8. Optical density profiles obtained by the calculation from Eq. 5: (*left*) dye sublimation type and (*right*) wax type.

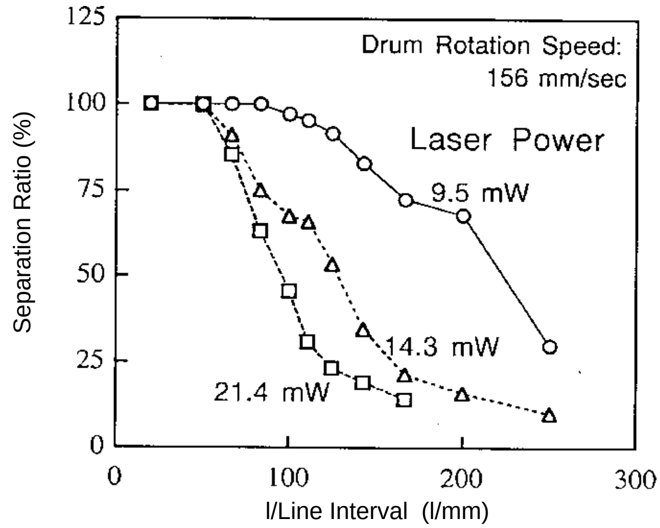


Figure 9. Resolution performance with the variation of laser power.

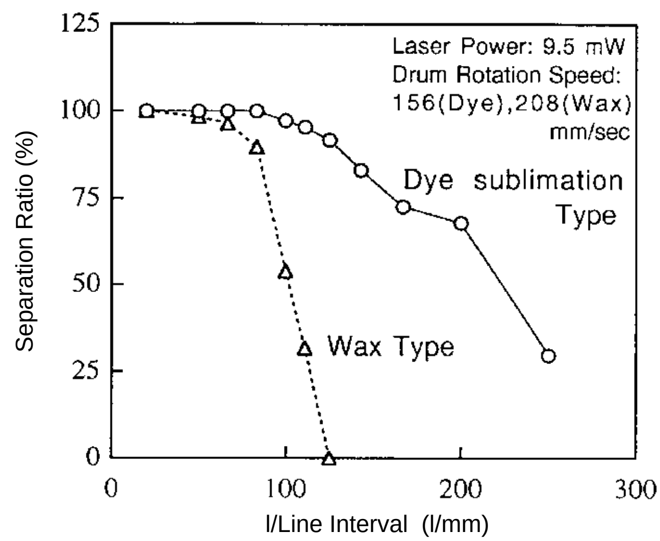


Figure 10. Resolution performance for two types of printing media.

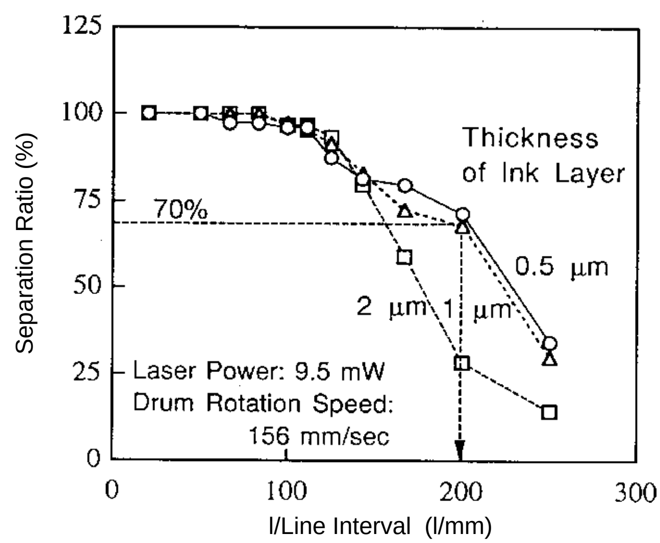


Figure 11. Resolution performance for variations in ink layer thickness.

power leads to low-contrast images. Therefore, optimization of laser power is important. Here we confirmed that optimal high-contrast images were obtained at 9.5 mW.

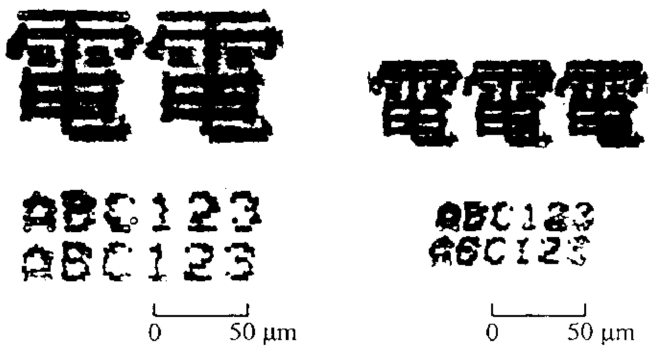
Figure 10 shows the resolution performance of dye sublimation transfer compared with that of wax transfer. The significant feature is that the separation ratio falls drastically with decreasing line interval in the case of wax transfer. This occurs because the edge of the OD profile for the wax type is sharper than that of the dye sublimation type, as shown in Figs. 5 and 6.

Figure 11 shows resolution performance with variations in the thickness of the ink layer for the dye sublimation type. Resolution decreases with thicker ink layers because heat is more easily diffused in thick ink layers, but there is no significant difference between 0.5 and 1 μm. It is thought that thinning the ink layer to about 1 μm can effectively increase the resolution. Here, assuming that the separation ratio of 70% is required for printers, the minimum line interval will be 5 μm (the reciprocal of this line interval is about 200 l/mm) in the case of a 1-μm ink layer, according to Fig. 11. As a result, maximum resolution of this printing system is 10,160 dpi for laser dye transfer printing.

Character Printing. Characters were printed at resolutions of 8470 dpi and 12,700 dpi by dye sublimation laser thermal transfer. Magnified views of printed samples are shown in Fig. 12. The printing conditions were as follows: laser power 9.5 mW, pulse width 12.8 and 19.2 μs, and pulse period 40 and 60 μs, respectively. The printing energy is the same as in the experiment for Fig. 11. A good image was obtained at 8470 dpi. In the case of 12,700 dpi the characters are sufficiently readable, but there are also some unclear parts. The maximum resolution of 10,160 dpi obtained from Fig. 11 is considered to be adequate. In laser thermal transfer printing, although it is generally easy for dye sublimation dots to spread, the resolution is improved significantly by laser printing because of the temporal and spatial convergence of the input energy.

Summary

Microscopic optical image density and resolution performance for laser dye transfer printing were investigated. Optical density profiles of dye sublimation line images were measured and compared with those of the wax type. The profiles were numerically explained in terms of tone reproduction curves. The resolution performance of laser dye transfer printing was quantitatively evaluated through the separation ratio, with the resulting maximum resolution of 10,160 dpi. This value was also confirmed by the printed microcharacters.



(a) (b)

Figure 12. Magnified views of printed laser dye thermal transfer images: (a) 8470 dpi and (b) 12,700 dpi.

From the above results, we conclude that laser dye transfer printing provides very high resolution and is feasible for use in the printing of fine patterns and microcharacters, as well as full-color images.

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