Mechanism of Dye Thermal Transfer from Ink Donor Layer to Receiving Sheet by Laser Heating

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In laser thermal transfer printing using a dye sublimation type medium, a high definition and continuous tone image can be obtained easily because a laser light focuses on a small spot, and its heat energy can be controlled by pulse width modulation. In this study, we investigated dye transfer depth from the ink layer to elucidate the mechanism of dye transfer. Ink donor sheets composed of a laser light absorbing layer and several color sublimation dye layers were prepared. The results confirmed that the dye was transferred from the surface ink layer in contact with the receiving layer, and also from the bulk of the ink layer in the range of low and high recording energy, respectively. By microscopic measurement after laser irradiation, we find that dye transfer from the bulk of the ink layer corresponds to the creation of a small hole at the ink's surface. Temperature transition in the ink layer by numerical calculation was different depending on the contact condition with the receiving sheet and the spot size of the laser light.

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Introduction

A high definition image with a resolution of more than 2540 dpi and continuous tone can be obtained by using laser dye thermal transfer printing.[1–4] The size of the transferred dots and the amount of transferred dye depends on the spot size of the laser and the irradiation energies to the ink donor sheet, respectively.

It is necessary for continuous tone control to understand the dye transfer mechanism by laser heating. In the previous report,[5] we have discussed a tone reproduction curve which exhibited a type of "S" shape and high gamma characteristics with an increasing thickness of the ink layer. This shows that dye transfer is controlled by temperature distribution in the ink layer. However, it is unknown from which part of the ink layer the dye is transferred from.

In this study, the amount of transferred dye from each ink layer, which is divided into three color layers, was measured by the amount of optical absorption. It was then probed by a microscopic observation of the ink surface after laser heating under the printing conditions where the ink sheet is or is not in contact with the receiving sheet.

Experimental

Principle of Laser Dye Thermal Transfer Printing

The principle of dye transfer in laser dye transfer printing is shown in Fig. 1. The ink sheet is composed of the laser light absorbing layer and color ink layer. The laser light absorbing layer is exposed to the laser light that is focused by an optical lens, and then the laser light energy is converted into heat energy and heats the color dye ink layer. By this energy conversion process, a sublimation dye from the ink layer is transferred to the receiving sheet, and dye images are formed on the receiving sheet.

Preparation of Ink Sheet

A construction of multi-layered ink sheets is shown in Fig. 2. A mixture of IR dye (PA-1006, Mitsui Chemicals

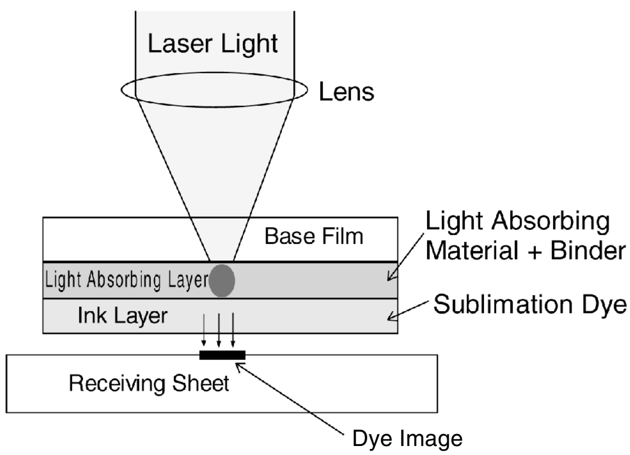

Figure 1. The principle of laser dye transfer printing.

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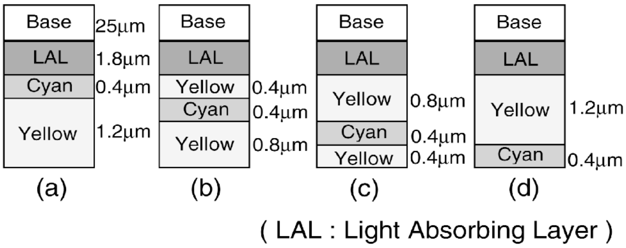


Figure 2. The construction of multi-layered ink sheets.

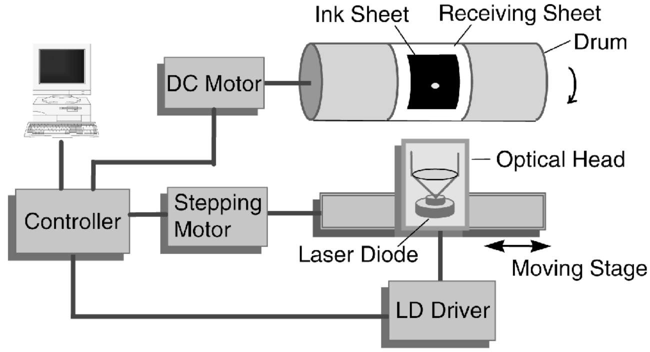


Figure 3. Schematic diagram of experimental printing system.

Inc.) and polycarbonate polymer (Panlite K1300, Teijin Chemicals Ltd.) was coated onto the transparent polymer film by a wire bar coating. Thickness of the laser light absorbing layer is 1.8 μm. In the next layer, yellow (MS Yellow HD-180, Mitsui Chemicals Inc.) and cyan (MS Cyan HM-1238, Mitsui Chemicals Inc.) sublimation dyes were coated onto the laser light absorbing layer by vacuum evaporation. The melting points of yellow and cyan dyes used here are very similar, and are 147°C and 150°C, respectively. The thickness of the cyan dye layers is 0.4 μm, and the sum of the layer thickness of yellow and cyan dye is 1.6 μm consistently. The position of the cyan layer in the ink layer was varied for the four samples. These ink layers are composed of only sublimation dye without a binder polymer. By measuring the amount of cyan dye transferred from this ink layer, it becomes clear from which depth the dye is transferred.

Laser Thermal Transfer Printing System

A schematic diagram of the laser thermal transfer printing system is shown in Fig. 3. There are three main sections: an optical head that includes the laser diode (SDL-7032, Tottori Sanyo Electric Co., Ltd., wavelength: 825nm, laser power: 100mW), a printing drum that performs the main scanning, and a sub-scanning section that moves the optical head using a micro-stage. The laser diode is operated according to the image signals, and the drum rotation and micro-stage movements are controlled by a microcomputer.

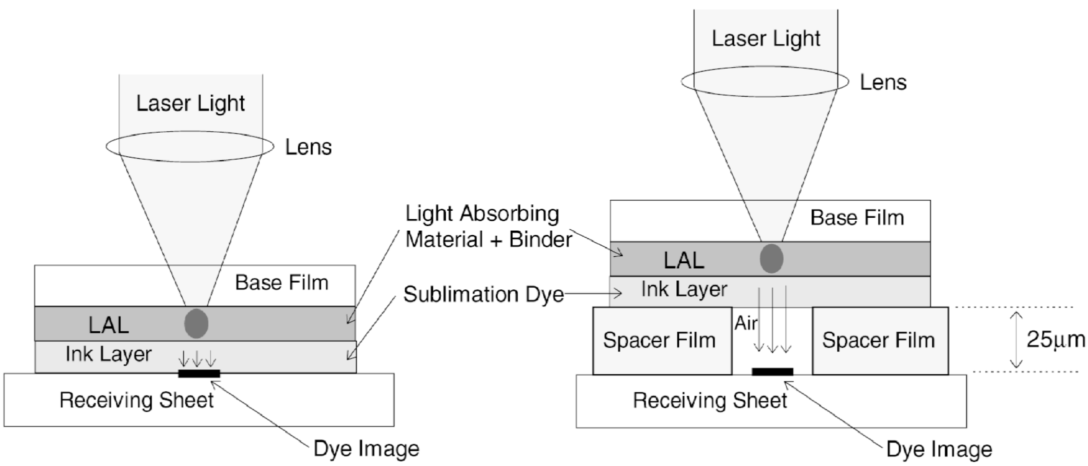
The spot size of a laser light on a printing medium can be changed by hand by controlling the distance between the optical head and the printing drum. Spot sizes of 3 μm and 25 μm were decided on as possible minimum and maximum spot sizes, respectively, in order to flatten irradiating energy density in this experiment.

Printing Condition and Measurement of Transferred Dye Quantity

The dye is ordinarily transferred under the printing condition where the ink sheet is in contact with the receiving sheet as shown in Fig. 4 (a). In addition to the contact transfer, we have also conducted a space dye transfer where the ink sheet is out of contact with the receiving sheet as shown in Fig. 4 (b). The air gap was established by sandwiching a spacer film between the ink sheet and the receiving sheet. The thickness of the spacer film is 25 μm.

A transparent polymer film was used as a receiving sheet in order to measure the absorption of transferred dye. The ink sheet and the transparent film were set on the printing drum. The continuous tone images with eight step grayscale data and a resolution of 2540 dpi were then recorded by modulating the pulse width of the laser under the recording condition in which the laser power was 40 mW. The recording speed was 156 mm/s.

Optical absorption spectra of cyan and yellow dyes are shown in Fig. 5. There is no absorption of yellow dye at the wavelength of 640 nm. Therefore, the amount of cyan dye transferred to the transparent film was obtained separately from the yellow dye by measurement



(a) Contact Transfer

(b) Space Transfer

Figure 4. Schematic diagram of contact transfer (a), and space transfer (b).

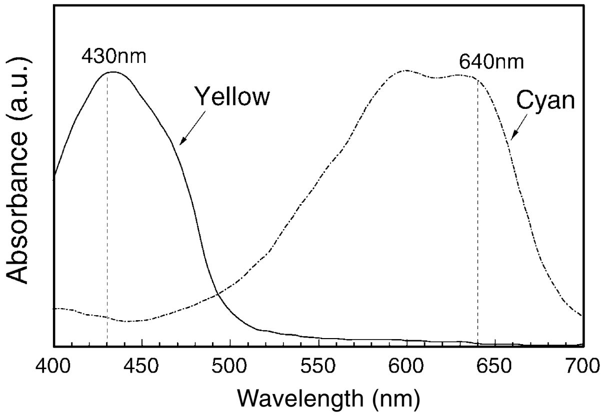


Figure 5. Absorption spectra of transferred dyes.

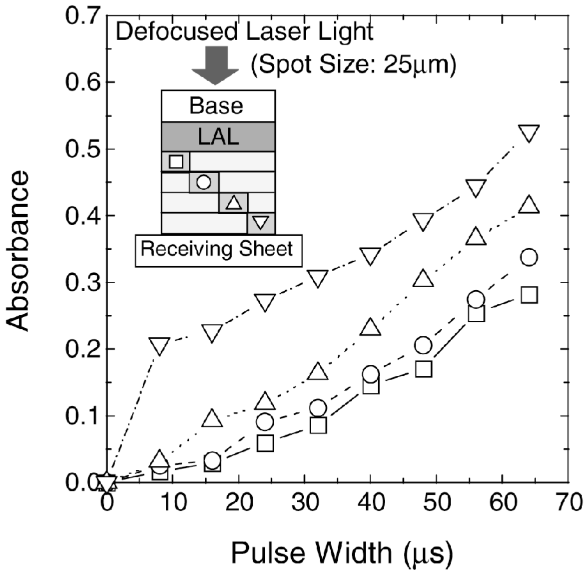


Figure 6. Relationship between absorbance of dye transferred from each of four dye layers and pulse width. Spot size of the laser light is 25 µm.

of the absorbance at the wavelength of 640 nm in the transferred solid image. The absorbance of the transferred dye image is proportional to the amount of transferred dye. Because the absorbance of the full 0.4 µm thick cyan layer is 1.0, the absorbance of the transferred dye image directly indicates the transfer rate of cyan dye from the each layer in the ink sheet to the receiving sheet.

Results and Discussion

Contact Transfer

Figures 6 and 7 show the relation between the duration of the laser pulse and the optical density of transferred dye using laser beam spots of 25 µm and 3 µm width, respectively. There was a lot of dye transferred from the front surface of the ink layer, shown by ∇ marks, and a little from the bulk of the ink layer with short duration pulse widths as shown in Fig. 6. The temperature of all ink layers rises until the melting temperature of the dye under this printing condition, using

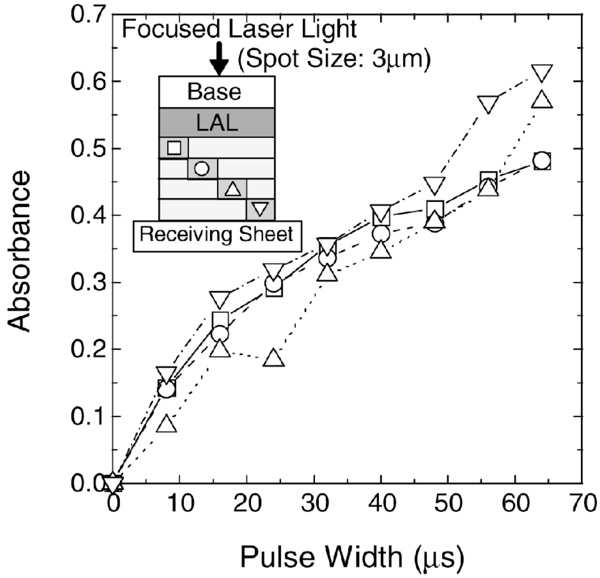


Figure 7. Relationship between absorbance of dye transferred from each of four dye layers and pulse width. Spot size of the laser light is 3 µm.

a laser spot of 25 µm for laser heating. The front surface of the ink layer was transferred to the receiving sheet being in contact with the surface of the ink layer under this laser heating condition. The dye was transferred from the bulk of the ink layer according to the duration of laser pulse width in the range of high exposure energy. On the other hand, dye from all of the ink layers was transferred to the receiving sheet according to the duration of laser pulse width using a laser beam of 3 µm, even in the low exposure energy range as shown in Fig. 7. The cause of this is that the temperature of the laser light absorbing layer is very high, and the difference of temperature between the laser light absorbing layer and surface of the ink layer is very large under the printing condition using a laser beam of 3 µm.

Figure 8 shows SEM microphotographs of pixels at the surface of ink sheet after laser heating as a function of laser pulse duration. Deformation of the ink surface and a small hole were observed at the center of one pixel by laser heating. The creation of this hole corresponds to the transfer of all of the dye layers at once under the printing condition using a focused laser beam or a high irradiation energy for laser heating as shown in Figs. 6 and 7. At the 16 µs laser pulse of the defocus beam, there is no hole, and the dye is transferred from the ink surface being in contact with the receiving sheet. After 32 µs of defocus, the dye was transferred from the bulk of the ink layer and a small hole was created.

Space Dye Transfer

Figures 9 and 10 show the relation between the duration of laser pulse width and optical density of the transferred dye using laser beams of 25 µm and 3 µm, respectively, under the condition that the ink sheet is not in contact with the receiving sheet. Dye cannot be transferred at a range of low exposure energy using a laser beam of 25 µm. The dyes can be transferred from the four layers together at the pulse durations longer than 30 µs. There is thus a different dye transfer mechanism, compared to the contact dye transfer between the ink and receiving sheets. Using a focused laser beam

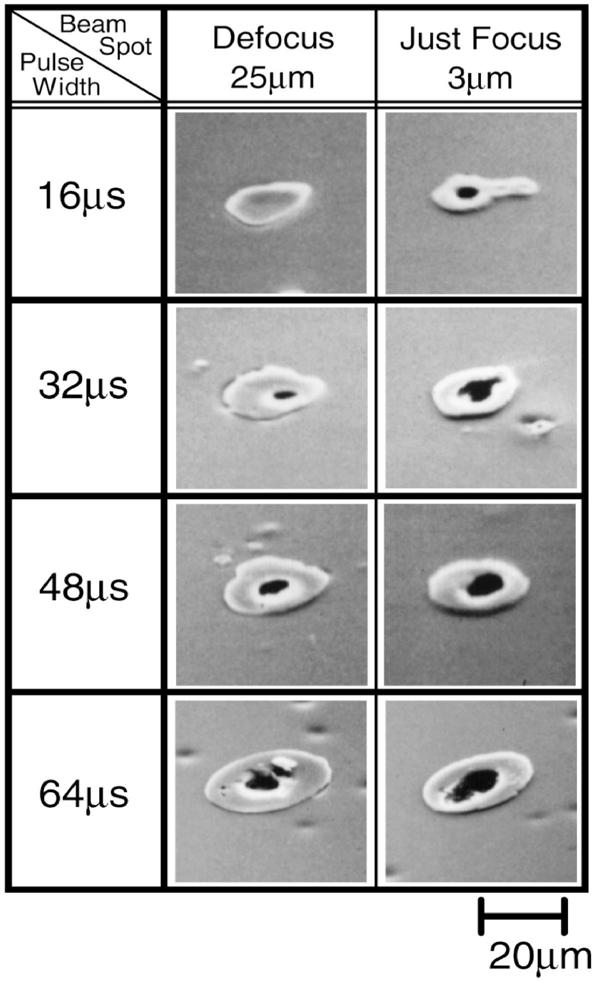


Figure 8. SEM microphotographs of pixels at the surface of the ink sheet after laser heating under the printing condition of contact transfer.

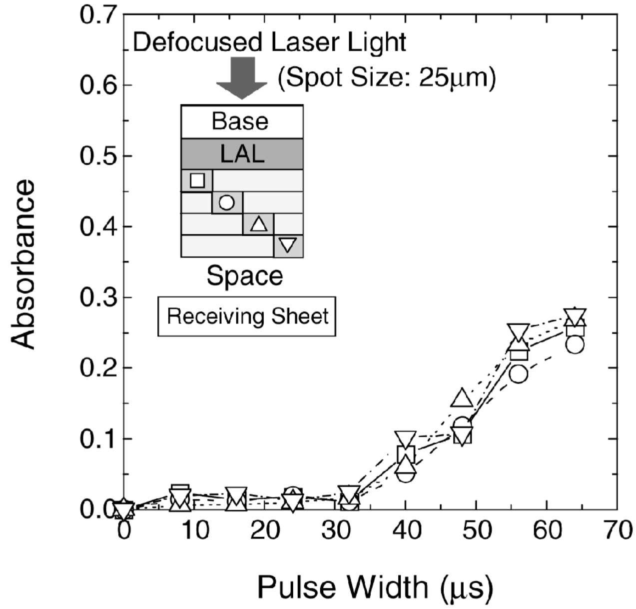


Figure 9. Relationship between absorbance of dye transferred from each of four dye layers and pulse width. Spot size of the laser light is 25 µm.

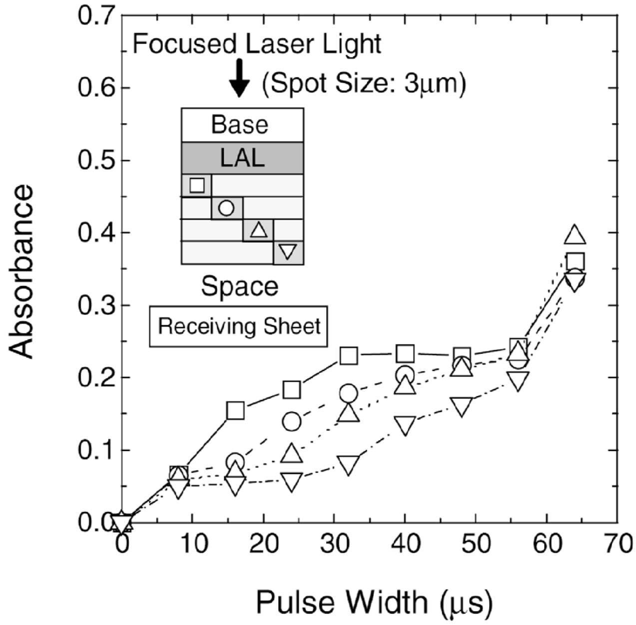


Figure 10. Relationship between absorbance of dye transferred from each of four dye layers and pulse width. Spot size of the laser light is 3 µm.

with a 3 µm diameter, the dye layer near the laser light absorbing layer was transferred first, and the front surface of the dye layer was transferred to the receiving sheet in the pulse duration range longer than 30 µs.

Apparently the dye near the laser light absorbing layer explodes out and crashes into the front surface dye layer under the printing condition using a focused laser beam. Figure 11 shows SEM microphotographs of pixels at the surface of ink sheet after laser heating under the printing condition of space transfer. The deformation of the ink layer was observed at the low energy exposure range using a defocused laser beam. Deformation of the ink layer is caused by a melting of the dye. Different from the contact dye transfer, the dye cannot be transferred only by a deformation due to the existence of an air gap. Both the deformation and small hole were observed in all pixels using a focused laser beam and at the high energy exposure range using a defocused laser beam. The creation of this hole corresponds to the transfer of all dye layers at once as shown in Figs. 9 and 10, which is the same as the phenomena at contact dye transfer. There thus is a possibility that the phenomenon occurring at the high exposure energy is close to the laser ablation transfer,[6,7] even if the time scale of the laser duration is of the microsecond order.

From the comparison with the experimental results of Figs. 6 and 7, the dye transferred from the surface of the ink layer increases on contact between the ink and receiving sheet. Dye was transferred through the air gap between the ink and receiving sheet on laser heating both by vaporization and ablation.

The sublimation dye used in this experiment was originally used for conventional dye thermal transfer type printers such as a video printer, where the dye is first melted and then changed to a gas by slow heating. However, in a rapid heating such as a laser heating in this case, the dye is changed from a solid to a gas instantaneously. When the dye layer is in contact with the receiving layer dye can be diffused easily, and the dye molecules themselves can be moved by laser heating.

Numerical Calculation of Temperature

The temperature of each ink layer is calculated using an equation of thermal conduction. The heat generation of the laser light absorbing layer takes into account the Gaussian distribution of laser light intensity and Lambert–Beer's law. Figures 12 and 13 show the temperature transition at the center of the laser light spot using a 25 μm beam under the condition of contact and space dye transfer, respectively. In Fig. 12, the temperature at point (a) rises simultaneously with laser irradiation and falls immediately after laser pulse irradiation. This thermal response is delayed by being distant from the laser light absorbing layer. The temperature of point (d) at 50 μs duration is 150°C. The surface layer has already transferred at the pulse width of 50 μs as shown in Fig. 6. The melting point of cyan dye is 150°C by measurement with a differential scanning calorimeter. If the transfer temperature of a dye corresponds to the melting point of the dye, 150°C, the transfer of the surface layer can start after the pulse duration time of 50 μs in calculation, which is different from the experimental result. One of the reasons is that a solid image was recorded in the printing experiment in contrast to an isolated pixel in the calculation. Therefore, the temperature of the ink layer in the printing experiment was higher than the calculated value, owing to the influence of laser pulse irradiating the neighbor pixels. Another reason is that there may be a small air gap between the surface ink layer and receiving sheet, because there is no pressure on the ink and receiving sheets. As shown in Fig. 13, the temperature of the surface ink layer is higher than that for the contact transfer shown in Fig. 12, due to heat insulation from the air gap.

Figure 14 shows the temperature transition at the center of the laser light spot using a 3 μm beam under the condition of contact dye transfer. The temperature at point (d) reaches about 260°C because of high energy density at the center of the laser light spot by using a focused laser light. In our temperature calculation, it is assumed that the physical properties of the laser light absorbing layer are not changed by laser irradiation, and the absorbed laser light is completely converted into heat energy. However, the actual temperature did not rise so high, because the laser light absorbing layer was damaged by laser irradiation.[8] In Figs. 12 and 14, paying attention to the relative difference of temperature between point (a) and (d), the decreased levels of temperature from point (a) to (d) are large for Fig. 14 in comparison with Fig. 12. The cause is that the heat generated on a small area by using a focused laser light diffuses not only in the thickness direction, but also over the surface by thermal conduction. This observation supports the discussion of Fig. 7.

Conclusions

The dye transfer mechanism of laser thermal transfer is discussed on the basis of experimental results using the multi-layered color ink sheet consisting of cyan and yellow dye layers. The contribution of individual color ink layers to the transferred dye image was thus obtained by the measurement of optical density of the transferred dye layer. The dye layer of the front surface of an ink sheet in contact with a receiving sheet

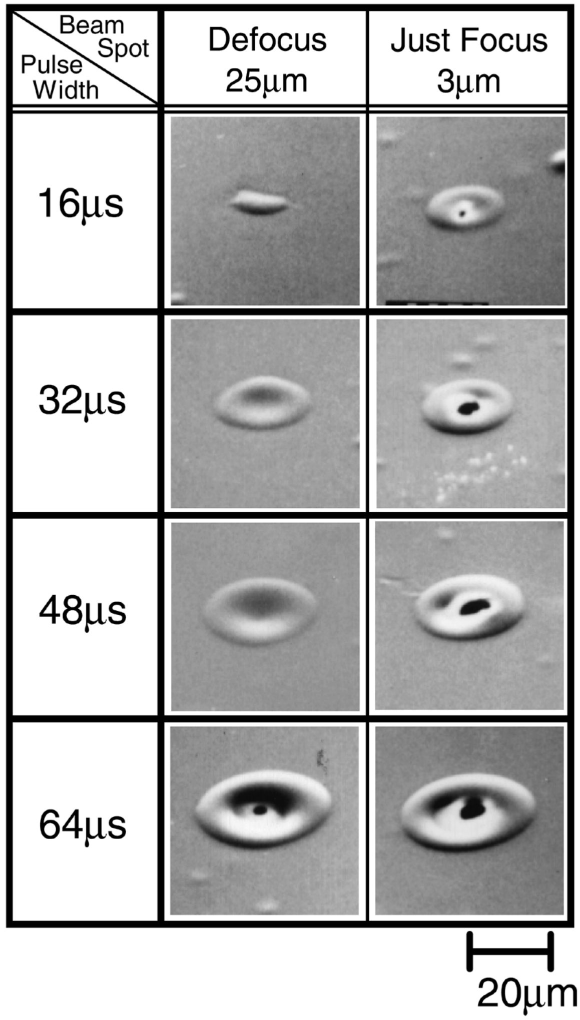


Figure 11. SEM microphotographs of pixels at the surface of the ink sheet after laser heating under the printing condition of space transfer.

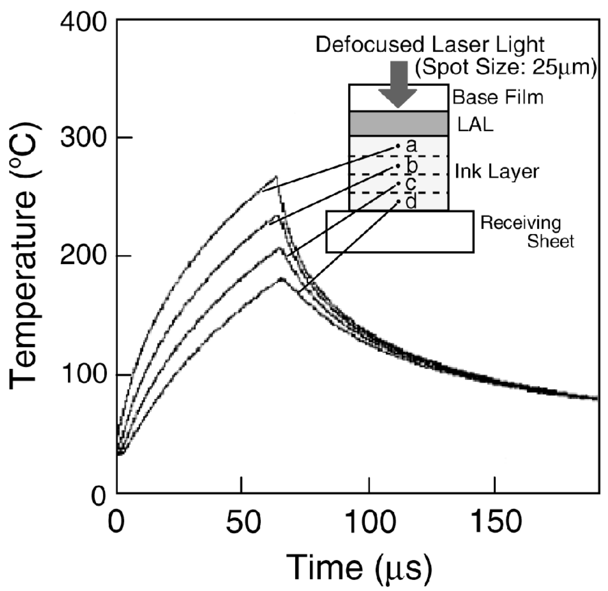


Figure 12. Temperature transitions at the four points in the ink layer obtained by numerical calculation. Spot size of the laser light is 25 μm.

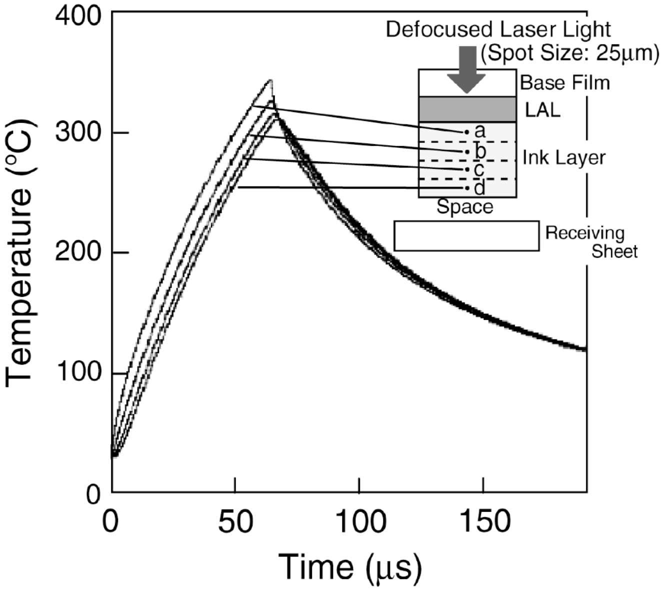


Figure 13. Temperature transitions at the four points in the ink layer obtained by numerical calculation. Spot size of the laser light is 25 μm.

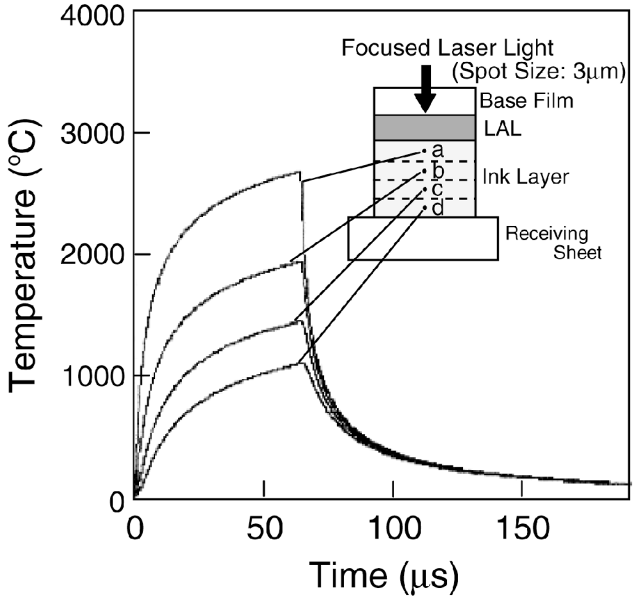


Figure 14. Temperature transitions at the four points in the ink layer obtained by numerical calculation. Spot size of the laser light is 3 μm.

was transferred at the range of low exposure energy. All color dyes were transferred at once under the laser heating condition in which a laser beam was focused on a small spot on a laser light absorbing layer. Further, the efficiency of dye transfer was lower, under the laser heating condition where the ink sheet was not in contact with the receiving layer.

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