2.5-Dimensional Inkjet Fabrication Using UV Curable Ink

Manabu Arita, Mie Yoshino, Shinichi Hatanaka, and Toshihito Kamei; Ricoh Company, Ltd.; Ebina, Japan

Abstract

In recent years, 2.5-dimentional (2.5D) fabrication for reproduction of oil paintings and decoration becomes known. UV curable ink is used for fabrication of 2.5D images because of its good stackability. However, the surface of the structures fabricated by UV curable inkjet printer is granular. Shape accuracy and surface smoothness had a trade-off relation. Therefore, we developed UV curable ink which can control wet-spreadability of the cured ink surface. Then we can switch between both stacking processes for accuracy and smoothness. The cured states and the wet-spreadability are controlled by UV irradiation energy for curing. This technology makes it possible to express the precise profile with shape accuracy and surface smoothness.

Introduction

UV curable inkjet ink printing has already been widely put into practical use, such as various building décor, articles for daily use, auto equipment, sign & display, due to the adhesive ability for various materials, quick drying property and strength [1].

In recent years, UV curable ink has been used for stereoscopic image expression such as painting reproduction or surface decoration [2], taking advantage of the characteristic that it is basically composed of only nonvolatile components and has quick drying properties. In contrast to a conventional planar image, the fabrication can express uneven structure profiles such as raised portions of oil paints, brush touches and canvas cloth precisely. We call this fabrication "2.5-dimentional (2.5D) fabrication". The obtained 2.5D images have concave and convex shapes of millimeter size or submillimeter size on the surface of the planar substrate.

We have developed 2.5D fabrication techniques by applying UV curable inkjet technology, image processing technology and 3D printing technology, and have been engaged in the creating and selling of stereoscopic reproduction images [3].

Figure 1 is a cross-sectional view of 2.5D image fabricated by UV curable ink and an inkjet system. In fabrication of a general two-dimensional image, ink droplets are formed on a flat surface of a substrate. On the other hand, in 2.5D fabrication, color is applied to the surface by color inks after forming the base shape by bulk component ink.

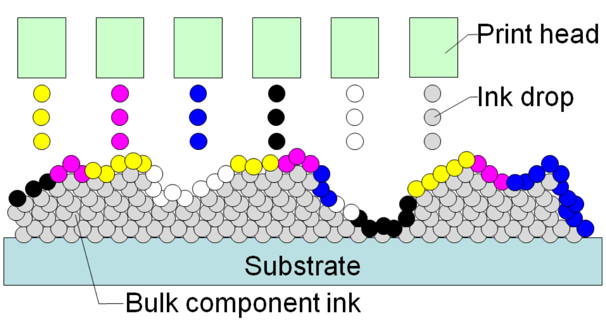


Figure 1. Cross-sectional view of 2.5D image.

UV curable ink for 2.5D fabrication requires high shape accuracy and surface smoothness [4] to express surface profile, resistance against warp [5] and peeling [6], strength and durability against breakage, and high curability for low-energy or high-speed printing. Among them, shape accuracy and surface smoothness are attracting attention as major issues in fabrication of high-definition 2.5D images [7]. In this study, we report on new UV curable ink and a new fabricating method to solve these issues.

Issues of Fabrication of 2.5D Images

In this chapter, we confirmed the conditions under which accuracy or roughness is an issue and we confirmed the trade-off relationship between shape accuracy and surface smoothness.

Properties of UV Curable Inkjet Ink

Since UV curable inkjet ink is basically composed of only nonvolatile components and has quick drying property, it has high stackability of ink droplets. Therefore UV curable inkjet ink is suitable for 2.5D fabrication. Although it is easy to obtain the stacking height with UV curable ink, the surface tends to be granular. For example, 3D printers using UV curable ink are generally equipped with a device that applies pressure from the outside to make the surface more flattened. That is, the surface roughness is an issue in UV ink having high stacking property.

Shape Accuracy

In order to fabricate high-definition 2.5D images, shape accuracy to the input shape is necessary. Here, we definite an issue concerning the shape accuracy.

Stacking structures were fabricated with UV radical curable Ink-A composed of mono-functional monomers under the conditions shown in Table 1 while changing the line width, which was vertical of the structure for accuracy measurement of Table 1.

Table 1. Printing Conditions.

Inkjet printhead	MH5420 made by Ricoh [8]
Resolution	1200 dpi × 1200 dpi
Printing speed	420 mm/sec
Number of passes	8
Ink droplet volume	10 pL/droplet
UV light source	Metal halide lamp
Structure for accuracy measurement	20 mm × 63.5 μm × 0.6 mm horizontal × vertical × height
Structure for roughness measurement	10 mm × 10 mm × 0.6 mm horizontal × vertical × height

Fine lines with different line widths and the same input height with the same number of layers were fabricated and the profiles of the structures were measured with 3D measurement system. Figure 2 shows the relationship between the input line width and the height of the stacking structures. The finer the input line width is, the lower the output height becomes. That is, the height ratio of output to input becomes small. Conversely, width ratio of output to input becomes large although the description of the data is omitted. The output height of 63.5 µm width line is 0.39 mm and the input height is 0.55 mm. Therefore the height ratio of output to input is 0.72. Though this value is accuracy in the height direction, as this value is closer to 1, accuracy in the width direction is also closer to 1 from more than 1. Therefore shape accuracy of both height and width can be evaluated by the height ratio of output to input. We define this height ratio as shape accuracy.

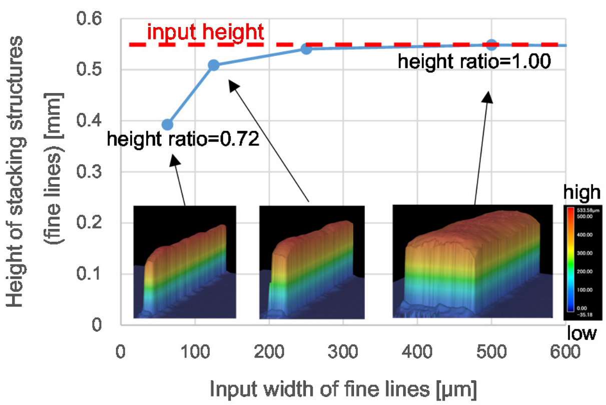


Figure 2. Shape accuracy of fine lines

Surface Smoothness of Stacking Structures

It is known that when the height of stacking structures is increased, the surface roughness increases [4]. In order to express precise 2.5D images, not only steric shape accuracy but also surface smoothness is required. Figure 3 shows the measurement results of the shape of the planar stacking structure samples by 3D measurement system. The input shape (10 mm × 10 mm) for measuring the surface roughness was formed with Ink-A which was composed of mono-functional monomers under the conditions shown in Table 1 while changing the stacking height. The surface roughness S_q is 2.25 µm (height 0.2 mm), 2.94 µm (height 0.4 mm), and 3.21 µm (height 0.6 mm). Even when the stacking height is 0.2 mm, the surface roughness with graininess is seen, and as the stacking height increases, the surface roughness becomes larger. It is necessary to keep the surface roughness to a lower level.

The surface roughness S_q is root mean square height and was calculated based on ISO 25178-2 [9] for the area of the center part 9 mm × 9 mm inside the surface (10 mm × 10 mm) of the structures with 0.8 mm of the L-filter. Unless otherwise specified, the roughness was measured with stacking structures with a height of 0.6 mm.

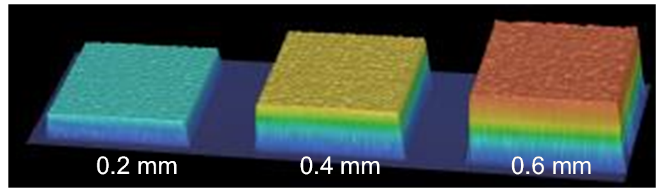


*Figure 3. 3D imaging of stacking structures of Ink-A at 0.2 mm, 0.4 mm and 0.6 mm height. *ten times magnification of height*

Relation between Accuracy and Smoothness

In order to fabricate precise 2.5D images, it is necessary to achieve both shape accuracy and surface smoothness. Figure 4 shows the relationship between shape accuracy and surface roughness of structures obtained by various ink formulations under the conditions shown in Table 1. When the accuracy is high, the roughness is large. And when the smooth surface is obtained, the shape accuracy is low. Therefore shape accuracy and surface smoothness are in the relationship of trade-off. The goal of this work is to present new ink that can lessen this trade-off relationship and can realize both shape accuracy and surface smoothness.

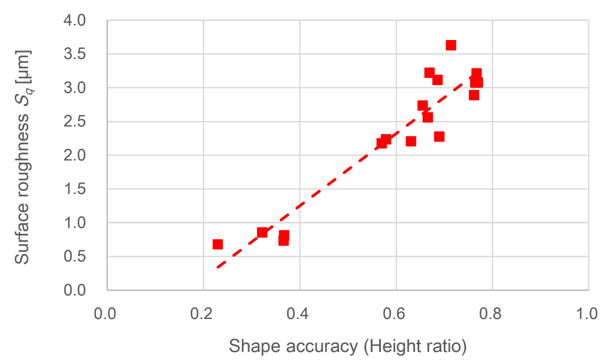


Figure 4. Relationship between surface roughness and shape accuracy rated by height ratio of the fine line height to input height with various inks.

Properties of UV Curable Ink

In this chapter, ink properties for solving the issues described in the previous chapter are explained. Not only ink formulation but also stacking process is used to achieve it, and the latter will be described in the next chapter.

As shown in the previous chapter, the shape accuracy and the surface smoothness basically show a trade-off relationship. We considered that both properties were caused by the shape of the ink droplet, that is, contact angle or wet-spreadability of the ink on the cured ink surface. Therefore, in this chapter, the feasibility of UV curable ink that can digitally switch between the properties which are the trade-off relation is verified. The wet-spreadability is controlled by UV irradiation energy. Switching between poor wet-spreadable process for accuracy (base fabrication) and good wet-spreadable process for smoothness (surface fabrication) enables us to obtain stacking structures with both shape accuracy and surface smoothness.

In the first half of this chapter, the issues with conventional ink are investigated, and in the latter part of the chapter, the achievement of the target properties with new ink is explained.

Relationship of UV Irradiation Energy with Shape Accuracy and Surface Smoothness in Conventional Ink

In this section, experiments were conducted with an ink composed of mono-functional monomers. It is necessary to give the stacking structures enough thickness in 2.5D image fabrication. For this reason, inks with less warpage have been conventionally used [5], and most of them are composed mostly of mono-functional monomers. Therefore, Ink-A composed of mono-functional monomers was adopted. Figure 5 shows the relationship of UV irradiation energy with shape accuracy and surface roughness of stacking structures obtained under the fabricating conditions in Table 1. The printing speed was constant among the experiments and the irradiation dose was adjusted with the power of the UV light source, and the stacking structures were fabricated with each UV irradiation dose. There are no relationships of UV irradiation energy with both properties.

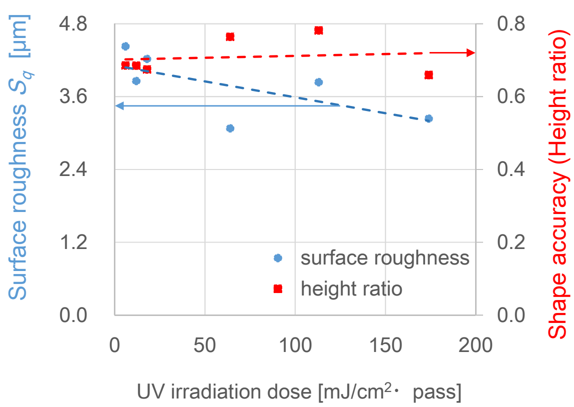


Figure 5. Relationships of UV irradiation dose with surface roughness and shape accuracy in Ink-A (mono-functional monomer).

Cured States of New Ink

In order to control shape accuracy and surface smoothness by adjusting UV irradiation dose with a single ink, we tried to control the wet-spreadability derived from the cured states of the surface of the UV curable ink. We developed new ink. It can be full-cured at high UV irradiation dose and can be half-cured at low UV irradiation dose, and the half-cured state has a solid-liquid separated structure in which only the inside is in cured solid state and the surface is in uncured liquid state.

As the new ink, the formulation using multi-functional monomers was examined in a radical polymerization system. At low UV irradiation dose, it is possible to obtain uncured wet surface by utilizing cure inhibition on the surface caused by oxygen and to keep the separated structure by the crosslinked structure derived from multi-functional monomers.

Table 2 shows the results of evaluating the curability and cured states of Ink-A (conventional ink) and Ink-B (prototype ink) and Ink-C (the new ink). The experimental conditions are shown below. In order to evaluate the deep part curability, formation of a cured layer was prepared with 40 μm thickness by bar coater only in this section. The curability was evaluated based on UV irradiation dose at which the ink was cured. Here, "cure" means a state that does not show liquidity or stickiness. Surface curability was evaluated by palpation on the surface and deep part curability was evaluated by palpating on the back surface of the cured layer (substrate interface) after peeling the cured layer with a tape. In the case that the surface was not cured and only inside part was cured, the uncured ink on the surface was wiped off with a dry cloth, then the tape was adhered, and the cured layer was peeled with the tape and the curability was evaluated. In addition, a partially cured state or a sticky state before full-cured, which is not cured as a whole, is defined as a half-cured state. In the half-cured state, Ink-A composed of mono-functional monomers has stickiness (for example, the surface at 100mJ/cm^2 or the back surface at 300mJ/cm^2), whereas Ink-B and Ink-C composed of multi-functional monomers have wet surface. It is noted that "wet" here means not a "moist" but a state that can be collected as a liquid. In this case, its inside is cured and it is in a solid-liquid separated state.

Table 2. Cured States

	Ink-A	Ink-B	Ink-C
Monomer	Mono-functional	Multi-functional	Multi-functional
Cured state	Sticky	Liquid surface and solid inside	Liquid surface and solid inside
Surface curability	150 mJ/cm^2	150 mJ/cm^2	150 mJ/cm^2
Deep part curability	500 mJ/cm^2	50 mJ/cm^2	20 mJ/cm^2

It is confirmed that this solid-liquid separated state can turn into the solid state during the multi-pass process. The curability of Ink-B and Ink-C in this work is designed so that the solid-liquid separated structure and the wet-spreading appear immediately after one pass in the multi-pass process and the surface is solidified after the multi-pass process.

Relationships of UV Irradiation Energy with Shape Accuracy and Surface Smoothness with the New Ink

Figure 6 and Table 3 show relationships of UV irradiation energy with shape accuracy and surface smoothness in Ink-C.

While the amount of UV irradiation dose has little effect on the curing process of Ink-A, it has a great effect on the shape accuracy and the surface smoothness. Excellent surface smoothness is obtained at low irradiation dose of 64 mJ/cm^2 or less, and high accuracy is obtained at high irradiation dose of 113 mJ/cm^2 or more in Ink-C. It is possible to exchange between the process for shape accuracy and that for surface smoothness by controlling UV irradiation energy with a single ink and constant printing speed. Incidentally, results of Ink-B are omitted because the ink has a problem in surface smoothness described later. Though the height ratio as shape accuracy is not reached 1.0, the condition that the ratio become sufficiently smaller than 1.0 is adopted for evaluation.

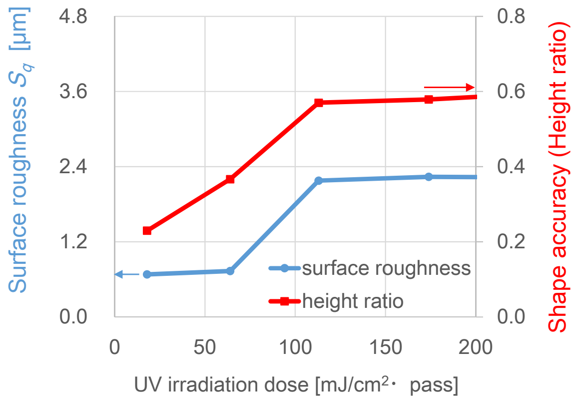


Figure 6. Control of shape accuracy (height ratio) and surface roughness by UV energy in Ink-C.

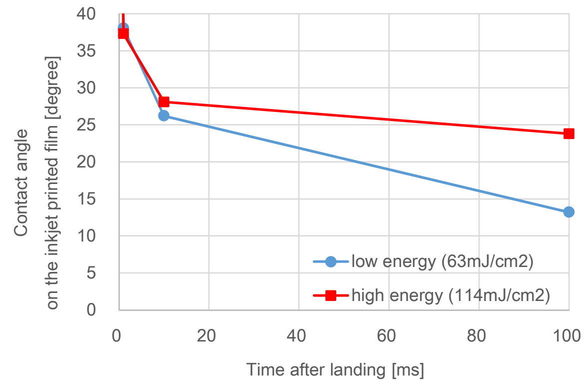
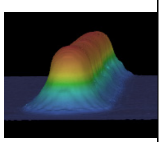
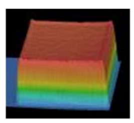
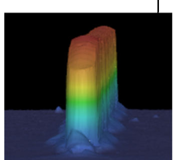
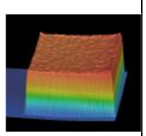


Figure 7. Change in contact angle in each cured state of Ink-C.

Table 3. Stacking structures of Ink-C

UV irradiation dose	Shape accuracy (height ratio)		Surface roughness S_q	
64mJ/cm²		0.37		0.73 µm
113mJ/cm²		0.57		2.18 µm

Wet-spreadability of Ink on the Printed Object

The contact angle of the inkjet droplet of Ink-C on the inkjet printed object was measured to evaluate the wet-spreadability in each cured state (at low and high UV energy). Figure 7 shows the relationship between contact angle and time after landing. The printed object was produced under the printing conditions of Table 1 and the ink droplet was discharged from inkjet printhead. The contact angle at 100 milliseconds after the landing on the printed object is 13.2° on the printed object irradiated with 64 mJ/cm² par pass, and is 23.8° on that irradiated with 174 mJ/cm² per pass. It is confirmed that the ink droplets wet-spread well on the object printed at low energy, whereas they hardly wet-spread on the object printed at high energy. It suggests that the wet-spreadability on the printed object can be controlled by UV irradiation energy.

Surface Smoothness of Stacking Structures in This Work

Figure 8 shows the relationship between the stacking height and the surface roughness of the stacking structures obtained with Ink-A, Ink-B and Ink-C under the UV irradiation condition of 64 mJ/cm² per pass, which is regarded as low energy in this work. With Ink-A composed of mono-functional monomers, the surface roughness is large even at low stacking height. With Ink-B composed of multi-functional monomers, the roughness is small only at low stacking height but the roughness increases sharply as the stacking height increases. The roughness of Ink-B (Figure 9) is coarser and that of Ink-A is finer (Figure 3).

On the other hand, Ink-C with better curability in deep part gives excellent surface smoothness regardless of the stacking height. As shown in Figures 8 and 10, the structures fabricated with Ink-C have a smooth surface irrespective of stacking height. Both kinds of surface roughness shown in Figure 4 (Ink-A in Figure 8) and Figure 9 (Ink-B in Figure 8) is suppressed in Ink-C.

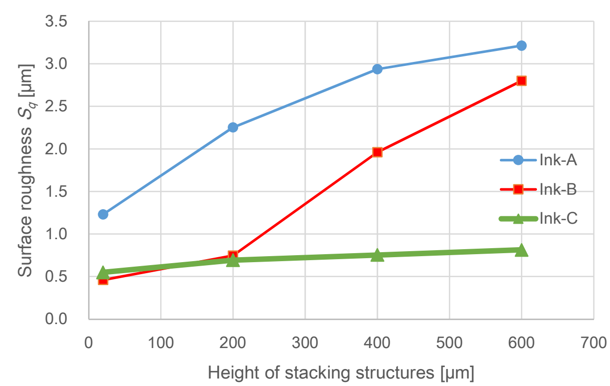


Figure 8. Relationship between surface roughness and height of stacking structures.

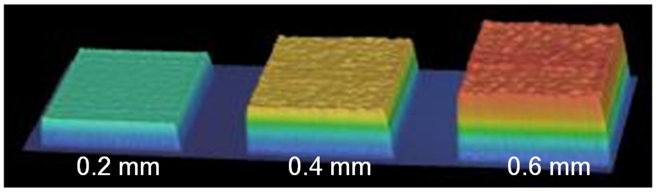


*Figure 9. 3D imaging of stacking structures of Ink-B at 0.2 mm, 0.4 mm and 0.6 mm height. *ten times magnification of height*

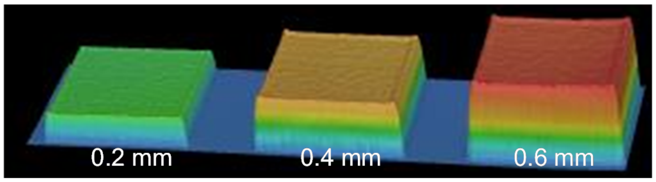


*Figure 10. 3D imaging of stacking structures of Ink-C at 0.2 mm, 0.4 mm and 0.6 mm height. *ten times magnification of height*

Consideration

The feature of the new ink is to show the half-cured state of the solid-liquid separated structure at low UV irradiation as described above. It is considered that the difference in curability between Ink-A and Ink-B, -C is due to the absence or presence of a crosslinked structure. Figure 11 shows schematic diagrams of half-cured states. While Ink-A composed of mono-functional monomers don't form a solid-liquid separated structure but has a sticky state, Ink-B and Ink-C composed of multi-functional monomers has a solid-liquid separated state which has liquid surface and solid inside part. The reason why the half-cured state of Ink-A has stickiness is probably that the obtained polymer has no crosslinked structure and it is dissolved by the monomer before reaction and they mix together. Ink-A also shows a solid-liquid separated structure immediately after low UV irradiation, but becomes sticky instantaneously. On the other hand, the solid-liquid separated structures of Ink-B and Ink-C are maintained even after a lapse of time. This is because the obtained polymers of Ink-B and Ink-C are not dissolved by the monomer because of forming a crosslinked structure derived from a multi-functional monomer.

The reason why shape accuracy and surface smoothness can be controlled by UV irradiation energy is probably that the wet-spreadability can be changed because of the cured surface which is liquid or solid state before the following droplet land on the surface. In Ink-A, even when it is in a half-cured state, it is sticky and behaves as a solid, whereas the surface of Ink-B and Ink-C can exist as liquid and the following droplet can wet-spread immediately after landing.

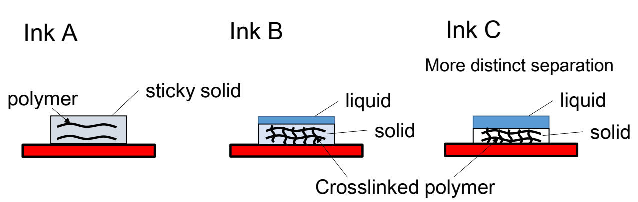


Figure 11. Half-cured states.

One of the possible reasons why the roughness is increased when the stacking height of Ink-B is increased is stress distortion. There are three reasons. First, the type of roughness is coarse rather than granular roughness like Ink-A. Second, the roughness becomes large only when the stacking height becomes high. Third, Ink-B is composed of multi-functional monomers which tend to cause residual stress.

In Ink-C, curing inhibition on the surface by oxygen is utilized, and ink formulation with high curability in deep part is adopted. It is designed to promote the formation of a solid-liquid separated structure and stress relaxation by improving curability in deep part compared with Ink-B. In the case where the difference in curability between the surface and the deep part is small like Ink-B, the entire structure is fixed at the initial stage of curing, then the curing shrinkage progresses, which leads to large strain. On the other hand, the stress of Ink-C can be relaxed because of partial curing.

It indicates that Ink-C has a potential of the sufficient surface smoothness, which can suppress adverse effects caused by multi-functional monomers, and it enables process switching between for shape accuracy and for surface smoothness with the change of the UV irradiation energy.

Compatibility of Accuracy and smoothness

Stacking structures were fabricated to satisfy both shape accuracy and surface smoothness by combining high and low energy processes using Ink-C under the conditions shown in Table 1.

With the total height of 0.6 mm of 30 layers, a plot of the results at each irradiation condition under which all 30 layers were formed with the single irradiation condition and a plot of the results at each irradiation condition under which each 0/30, 20/10, 25/5, 27/3, 29/1, 30/0 layers were formed with the high/low combination irradiation condition are shown in Figure 12. The lower the UV irradiation dose is, the lower the shape accuracy becomes. And the higher the UV irradiation dose is, the higher the shape accuracy becomes. Combination conditions result in satisfying the surface smoothness and the shape accuracy, compared to the single conditions. Incidentally, here we experimented within a power range that could be adjusted and combined with the same UV light source. The compatibility could be further improved if the range becomes wide.

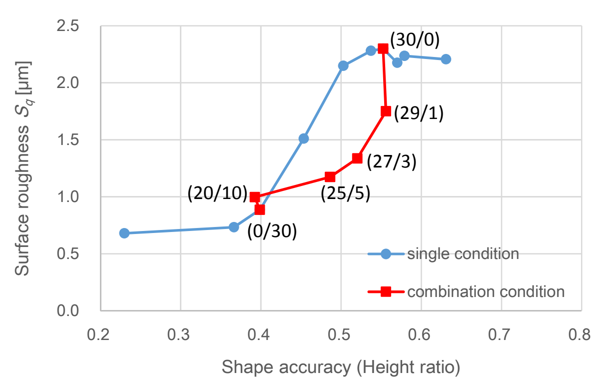


Figure 12. Relationship between surface roughness and height ratio in single and combination UV irradiation condition in Ink-C.

Advantages of This Technology

Not only the process switching method like this work but also using different inks [5,10] can be one of the methods to achieve both shape accuracy and surface smoothness. It is conceivable to use high smoothable ink particularly as color ink for surface forming. However, the color ink cannot be stacked until the rough base structure become smooth because the thickness of the color surface layer is determined based on setting the brightness of the color [10]. Therefore surface smoothness is required at base forming. Though this conventional method requires each of inks for base forming and for surface forming, our method requires a single ink for both processes and the ink properties are variable.

As another method of imparting smoothness, there is a method with delaying UV irradiation after jetting [11]. However, it makes the printing speed limited. On the other hand, our method can control the surface smoothness with the amount of UV irradiation. The method of this work can impart wet-spreadability without limiting the printing speed because UV was irradiated immediately after discharging in this experiment. The distance between printhead and UV light source was 200 mm and the printing speed was 420 mm/s as the experimental conditions.

Since it is a technique to wet the surface instantaneously rather than a horizontal leveling technique, it can respond to a fine shape of 2.5D images.

Conclusion

We developed UV curable inkjet ink which can offer shape accuracy and surface smoothness by UV irradiation energy, and 2.5D images with both properties are obtained by process combining, although both properties have basically a trade-off relationship in conventional 2.5D fabrication. Switching between a temporary half-cured state and a full-cured state can control the wet-spreadability which affects accuracy and smoothness. The half-cured state has liquid surface and solid inside, which is a liquid-solid separated state. Such ink characteristics were obtained by utilization of multi-functional monomers and deep part curability. We can select the processes for accuracy and smoothness depending on the required image or fabrication process without limiting the printing speed.

References

[1] D. S. Nagvekar, “UV-Curable Graphic Arts versus Industrial Inkjet Inks: A Progress Report,” RadTech Report, JULY/AUGUST 2008, pp. 25-31, 2008.

[2] T. P. V. Song, C. Andraud, M. V. O. Segovia, “Implementation of the four-flux model for spectral and color prediction of 2.5D prints,” Proc. IS&T’s NIP32, pp. 26-30, 2016.

[3] RICOH News Release [in Japanese], Retrieved March 29, 2016, from https://jp.ricoh.com/release/2016/0329_1.html

[4] S. Hara, W. Yuhan, K. Sasajima, “Fabrication of Surface Texture using UV Curing Ink-Jet Printer,” Proc. 2013 JSPE Autumn Meeting, pp.201-202, 2013. [in Japanese].

[5] C. T. Weijkamp “Printing system and method of printing a multilayer structure using radiation curable ink,” U. S. Patent 9,469,135, 2016.

[6] Takao Hiraoka, “UV Inkjet Ink Which Has Good Adhesivity to the Metal Substrate and Very Low Toxicity,” Proc. Imaging Conference Japan 2014, the Imaging Society of Japan, pp. 161-163, 2014. [in Japanese].

[7] X. Liu et al., “Characterization of relief printing,” Proc. SPIE 9018, Measuring, Modeling, and Reproducing Material Appearance, 90180P, 2014.

[8] Ricoh Company, Ltd.: RICOH MH5420/5440, https://industry.ricoh.com/en/industrialinkjet/mh/5420_5440/ (accessed 2016-04-01).

[9] ISO 25178-2:2012, “specifies terms, definitions and parameters for the determination of surface texture by areal methods,” International Organization for Standardization, 2012

[10] C. Weijkamp, C. Valade, “Method of elevated printing,” U. S. Patent Application Publication 2016/0361929.

[11] T. Sato et al., “Development of the Wide-Format UV Inkjet System “Acuity LED 1600”,” Fujifilm Research & Development, No. 57, pp. 33-37, 2012.

Author Biography

Manabu Arita obtained his masters in chemistry at Kyoto University in Japan in 2009. After working for developing UV and EB curable materials at a printing company, he entered Ricoh Company, Ltd. in 2014, and he specialized in UV curable inkjet ink formulation design.