Soft blanket gravure printing technology for finely patterned conductive layers on three-dimensional or curved surfaces

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In this paper, we report on a newly developed printing method called the “soft blanket gravure” (SBG) printing method, which is based on a conventional gravure offset printing method but unlike it, SBG printing uses a very soft and thick offset blanket. SBG printing onto various curved, nonplanar surfaces as well as on planar surfaces using silver ink was successfully demonstrated by optimizing printing conditions such as printing pressure and printing speed. Finely printed conductive silver lines with a 30 µm line width were formed on the curved surfaces. This printing method will have new applications in three-dimensional printed electronics. © 2017 The Japan Society of Applied Physics

1. Introduction

There is a significant trend towards the use of conventional industrial printing technologies for producing electronic devices. Various printing technologies, such as inkjet, gravure, screen, pad, and reverse offset printing methods, have attracted attention, because unlike photolithography, printing technologies have a number of strengths, such as their low processing costs and environmental friendliness. However, it is difficult to fabricate submicron fine patterns by printing. Therefore, printed electronics technology may be effective in specific applications that are difficult to realize with photolithography and other patterning technologies.

One such application is direct printing onto curved surfaces. For example, pad, screen, pad, screen, pad, and reverse offset have been studied for this purpose. In particular, the pad printing method was studied and used for printing color ink onto curved surfaces for decorative applications. However, those techniques are deficient in resolution or productivity for the production of electrical circuits.

Therefore, we have developed a new printing technology, which we named the “soft blanket gravure” (SBG) printing method, that was evolved from a conventional gravure offset printing method. With the SBG printing method, it has become possible to print on curved surfaces with high resolution and productivity.

A conventional gravure offset printer has a thin and hard offset blanket. The offset blanket sheet is made of poly(di-methylsiloxane) (PDMS) on a plastic film and is wrapped around a metallic cylinder. Therefore, it hardly deforms when printing pressure is applied. On the other hand, the SBG printer is characterized by having a soft and thick blanket (“soft blanket”), which can be greatly deformed. The amount of deformation relative to the radius of the blanket roll is typically more than 1.5% in a SBG printer. This large deformation of the blanket roll makes it possible to print on curved surfaces.

The most important printing conditions in the SBG printing method are the printing pressure and printing speed, similarly to conventional printing methods. In a conventional gravure offset printing method, the printing pressure is proportional to the compression depth of a blanket against a printing plate (or substrate). The printing pressure greatly depends on the compressive stress characteristic of the material of the blanket. In the SBG printing method, the printing pressure might be dominated by PDMS properties. PDMS is widely used in various fields and its properties have been studied, including its characteristics as an offset blanket. However, there are no previous reports on its use as a soft blanket.

In this study, we measured compression stress characteristics of the soft blanket and clarified the effect of the printing pressure on the printing results. In addition, since the viscoelasticities of ink and PDMS show a frequency dependence, the printing speed affects the printing results. We endeavored to clarify the printing conditions and properties of the SBG printing method by systematically investigating the influences of printing pressure and printing speed. Moreover, we demonstrated the superior printing capability of SBG printing with a silver ink onto curved surfaces of various three-dimensional objects.

2. Experimental methods

Figure 1 shows a schematic of the operating principle for the SBG printing system, which has three process steps. First, the
ink is scraped with a doctor blade to fill grooves on a gravure printing plate [Fig. 1(a)], which is called the doctoring process. Second, a soft blanket roller receives the ink from the grooves as the roller rotates over the gravure printing plate [Fig. 1(b)], which is called the “receiving” or “off” process. Finally, the soft blanket roller transfers the ink onto the curved substrate [Fig. 1(c)], which is called the “transferring” or “set” process.

We designed and built a SBG printing system based on a conventional gravure offset printing technology. In this initial prototype system and for this study, we used a plate-to-plate printing configuration. In this system, the printing pressure was controlled by the compression depth of the soft blanket [Fig. 1(d)], similarly to various conventional printers.

During the printing operation, the soft blanket moves towards a printing plate and a target substrate in a freely rotating state. The printing plate and the substrate stage are fixed, whereby the soft blanket can rotate owing to the frictional force between itself and the printing plate (or the substrate) surface. In order to produce patterns on curved surfaces, the SBG printer utilizes a very soft and thick blanket made of PDMS as the offset roller. The PDMS material was molded into a cylindrical shape around a metallic roller core to form a soft blanket with a thickness of 15 mm, a diameter of 100 mm, a length of 140 mm, and a hardness of about 1° (ISO 7619).

We used silver ink (DIC GOAGT-93C) consisting of 75–85 wt% solid concentration of silver particles and other components such as binders and solvents.

First, a uniaxial compression test was performed to clarify the stress–deformation property of soft, thick PDMS, compared with thin PDMS. PDMS samples were used for the test, which was the same material as the soft blanket, with thicknesses of 3 and 15 mm. The samples were measured using a compression machine for displacement stress (Yonekura Mfg CARY-M2KN) by applying increasing pressure and measuring the corresponding compression deformation from 0 to 33% at a compressive deformation rate of 10 mm/min.

We next evaluated printability with respect to each of these printing parameters on a flat surface in order to optimize the printing conditions. In our experiments, we used the following printing parameters: compression depth while receiving ink from the printing plate \(h_1\), compression depth while transferring ink onto the substrate \(h_2\), receiving speed \(v_1\), and transfer speed \(v_2\).

First, \(h_1\) and \(h_2\) were changed while \(v_1\) and \(v_2\) were fixed, and next, \(v_1\) and \(v_2\) were changed while \(h_1\) and \(h_2\) were fixed. Then, \(h_2\) was kept the same as \(h_1\), and \(v_2\) was kept the same as \(v_1\). In the printing experiments, we observed the patterns that were transferred onto the glass substrate. Because the silver ink received on the blanket surface from the printing plate was transferred to the substrate completely, we can indirectly observe the receiving condition from the transferred patterns. Microscope images and cross-sectional profiles of the printed line patterns were obtained under “wet” conditions using a digital microscope (Keyence VMH-500) and a confocal laser microscope (Olympus LEXT 61).

Finally, we printed patterns onto variously shaped or curved substrates under the optimized printing conditions, as in the previous experiments. Here, \(v_1\) and \(v_2\) were fixed at 30 mm/s and \(h_1\) was fixed at 3.5 mm (deformation relative to the radius of the blanket roll was 7%), but \(h_2\) was changed depending on the shape of the target surface.

3. Results and discussion

Figure 2 shows stress–deformation curves measured for thick and thin PDMS-based soft blankets used in this study. When the PDMS sheet is thin (3 mm), the stress rapidly increased with increasing displacement. On the other hand, the stress in the thick PDMS sheet (15 mm) only slightly increased with increasing displacement. The stress–compression curves show an almost linear relationship, indicating that Young’s modulus of the thick PDMS-based blanket is almost constant over a wide displacement range. This result indicates that in the SBG printing method, the compression depth of a soft blanket is proportional to the printing pressure.

Next, we determined printing conditions on the planar surface. Figure 3 shows microscope images of printed patterns depending on the printing conditions. In these images, the line width is 50 µm, the gray areas are the patterned silver ink and the yellow area is the substrate. Figure 3(a) shows the dependence of printability on \(h_1\) when \(v_1\) and \(v_2\) were fixed at 10 mm/s. Printability became good at \(h_1\) of 3 mm. Low values of \(h_1\) resulted in spotted patterns, and high values of \(h_1\) resulted in narrow lines. Figure 3(b) shows the dependence of printability on \(v_1\) when \(h_1\) and \(h_2\) were fixed at 2.5 mm. Printability was good at \(v_1\) of 10 mm/s. Moving the soft blanket at a higher speed of \(v_1\) resulted in spotted patterns, and a lower speed of \(v_1\) resulted in patterns with extremely small line widths.

Figure 4 is a summary of the printing conditions obtained on a planar surface when using the soft blanket. In this figure, the horizontal axis is the receiving speed \(v_1\), and the vertical axis is the receiving pressure, which is the same as the compression depth during the receiving process \(h_1\).

In the spotted pattern case (lower right in Fig. 4), when the receiving pressure was low or the receiving speed was high, the soft blanket did not sufficiently adapt into grooves. Moreover, the surface of the silver ink in grooves yielded owing to surface tension. As a result, the soft blanket came in contact with the ink mainly at the edge of the grooves, with less contact in the middle of the grooves, resulting in discontinuous patterns. The soft blanket receives ink from grooves with a spotted pattern, which is a phenomenon that often occurs in conventional gravure offset printing.
In the narrow pattern case (upper left in Fig. 4), when the receiving pressure was high or the receiving speed was slow, the soft blanket adapted considerably in the grooves. When the blanket naturally returned to its original shape after the receiving process, the ink on the soft blanket surface shrank and became narrow. This phenomenon is unique to the SBG printing method, because the blanket used in conventional gravure offset printing cannot be adapted into grooves. Therefore, when the receiving pressure was high or the receiving speed was low, the printed patterns became narrow, and when the receiving pressure was low or the receiving speed was high, the printed patterns became spotted; therefore, the optimum printing conditions were between these values.

We have also printed various narrow silver lines with line widths of 30–100 µm, and we found that when the line widths on the printing plate was narrow, the effect on the printing conditions was large and the printable range was small. However, we found that the optimum \(v_1\) and \(h_1\) ranges were somewhere between those for spotted patterns and extremely narrow line patterns.

We next attempted to print the silver ink onto various curved surfaces under the optimized printing conditions. Figures 5(a)–5(d) show examples of patterns printed onto curved surfaces. Figure 5(a) shows the line and space patterns on a wave-shaped surface, Figure 5(b) shows an electronic circuit patterned on a cylindrical jar, Figure 5(c) shows interconnect wiring for a touch sensor patterned onto a nonuniformly curved surface, and Figure 5(d) shows a mesh pattern printed onto the surface of a spoon. Figures 5(e) and 5(f) show microscope images of the patterns printed in Figs. 5(c) and 5(d), respectively. From these microscope images, we confirmed that the printability onto the curved surface was good.
Lastly, we inspected the profiles of silver lines printed onto a curved surface. Figures 6(a) and 6(b) show a microscope image and the cross-sectional profile of a finely patterned silver line with a line width of 30 µm. The line height was approximately 4.0 µm and the cross-sectional shape was also good. We have succeeded in fabricating various patterns including fine lines onto curved surfaces in spite of the change in the applied pressure during the “set” process. This success is attributable to the fact that the stress in the thick soft blanket only slightly changes, unlike in a thin blanket, even when the soft blanket is deformed markedly, as shown in Fig. 2. We have successfully demonstrated that the newly developed SBG printing method can be applied to the printing of electronic interconnect lines or other patterns regardless of changes in substrate curvature and even to printing on common objects.

4. Conclusions

We have successfully developed a novel printing method, the SBG printing method, for pattern-printed silver layers on curved surfaces under optimum printing conditions. We clarified, by the compression test of PDMS-based blankets, that the printing pressure can be controlled by adjusting the compression depth. In the SBG printing method, when the printing pressure is low, the patterns become spotted. On the other hand, when the printing pressure is high, the patterns become narrow. This is unique to the SBG printing method. The optimum printing conditions are between these pressures.

We also found that we can produce finely patterned silver lines on various curved surfaces under optimized printing conditions, because the transfer pressure only slightly changes even when a soft blanket is deformed markedly.

We considered that the optimum printing conditions might depend on the soft blanket material or silver ink used. Therefore, our future research will focus on improving the soft blanket and ink, which are two of the important components in fine line printing by the SBG printing method.

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