The Self-Cleaning Gravure (SCG), A Solution for Gravure Groove Blocking and a Novel Printing Method

Marko Pudas*, Juha Hagberg and Seppo Leppävuori

Microelectronics Laboratory and EMPART Research Group of Infotech Oulu, University of Oulu, Linnanmaa, Oulu, Finland

A novel method, the Self-Cleaning Gravure (SGC) is proposed to provide a new solution for ink removal from gravure grooves for gravure cleaning, as well as a novel printing method. In conventional gravure offset printing, especially with high loads of solid particles and narrow gravure grooves, there is a severe problem encountered with gravure groove blocking. Such inks are usually used to create shiny coatings in the graphic printing industry, and in conductor printing in the electronics industry. Conventional gravure groove cleaning methods are insufficient for the narrow gravure grooves, especially when silver particle containing inks are causing the blockage. This blocking of ink is initiated at the bottom of the gravure grooves. The basic idea of the proposed solution is to introduce a new solvent, some other liquid, or gas into the bottom of the gravure grooves where it is most needed. This may be accomplished by creating a porous layer or channels under the created pattern. The method makes possible more efficient ink removal from the grooves of the modified gravure compared to those of a conventional gravure. It also allows ink to be brought to its surface from below which exhibits gravure of any shape to be used as the direct or indirect printing surface.

Journal of Imaging Science and Technology 48: 375–381 (2004)

Introduction

In the manufacture of electronic circuitry and components by printing layers of inks screen printing has been traditionally used. As it is limited in resolution (150-75 μm) and is also limited by the durability of the screen (<10,000 prints), alternatives are required for electronics manufacturing industry. A widely studied field for electronics is ink jet printing.[1] This is commonly used for graphic printing with resolutions up to 4800×1200 dpi. As metals are deposited for electronics circuitry, expensive nanoparticles are required for ink jet printing and the resulting thickness remains low, whereas electronics requires thick deposits. Using gravure (also known as intaglio or cliché) methods, high metal content inks (50 – 90 wt%) can be printed, thus producing sufficiently thick conductor lines. In most cases, printed conductive inks have metal particles with size ranges of 1 to 10 μm.[2]

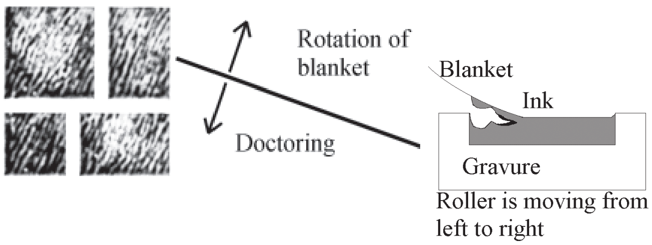
Well known graphic printing methods have been studied for the production of electronics circuitry: pad-printing (down to 50 μm),[3] roller type gravure offset printing (indications of line widths down to 9 μm),[2,4-6] rotogravure (down to 185 μm)[7] and soft gravure printing (down to 25 μm).[8] In gravure printing, ink is transferred under pressure directly from the gravure grooves to the printing target material. In the case of offset gravure printing, ink is first doctored to the grooves (or holes) of a gravure and is then picked up from the grooves by the elastic surface of a pad or a roller. This then moves over the printing target material to print the ink; alternatively the target material can be moved. Ink transfer in gravure offset printing has been studied in a previous work of the present authors.[4,6]

A major problem in electronics printing with the described methods is gravure groove blocking by the ink (ink agglomeration) and its solid particles. Narrow grooves are especially easily blocked. This also worsens the problem of required thickness of ink pickup from narrow gravure grooves, because in general less ink is picked up from narrow grooves compared to wide grooves.[4,5] The more widely used screen printing enables printing of uniform line thickness, but this method is limited in industrial use to line widths of about 100 μm and rough line edges. Ability to print narrower lines with higher line edge smoothness does however make gravure methods a better choice over screen printing for high spatial frequency applications.[9]

Two other major problems also face application of gravure methods: The first is that printing of electrical circuitry requires highly uniform, thick layers and therefore the inks used must have high viscosity.[4] Large areas are often needed too, but these high viscosity inks cause ribbing, which means that different ink thick-

Original manuscript received August 5, 2003

*mtpudas@ee.oulu.fi; phone: +358-40-555-8427, fax: +358-8-553-2728



(a) (b)

Figure 1. (a) 10 × 10 mm light through image of four large image areas printed with viscous metal particles containing ceramic ink, after firing. Pickup direction is clearly visible. (b) Figurative cross-section of ink pickup with ribbing effect.

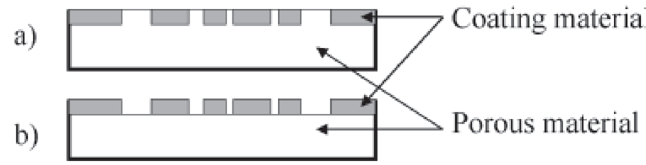


Figure 2. Level and grooved SCG gravure structures with porous material layers.

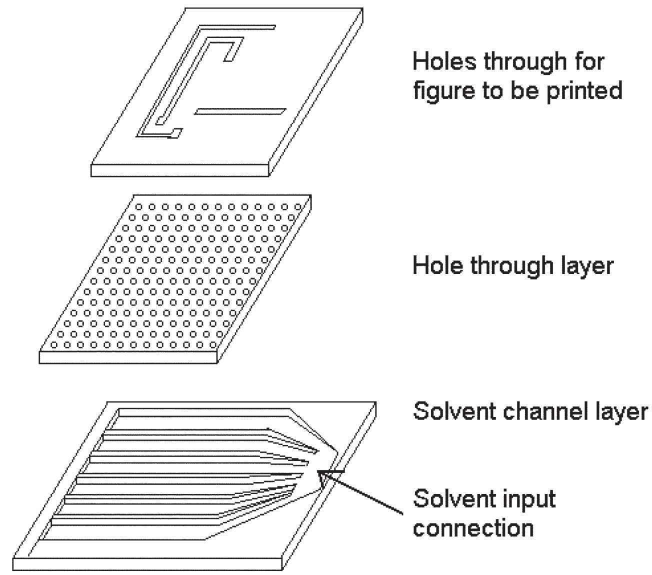


Figure 3. Three levels of a 'hard SCG' gravure with matter channels. Manufactured with electroplating techniques.

nesses form around large areas.[10,11] A large printed area from a conventional gravure with a highly viscous ceramic ink is shown in Fig. 1. The second problem occurs in the graphics printing industry, where doctoring causes wearing of both the doctor blade and the surface of the gravure. With such methods there is usually also a significant loss of printing target material, due to start-up, and a need to clean the gravure.

The gravure groove blocking problem is solved conventionally by occasional cleaning. Cleaning can be best done with brushing and simultaneous spraying solvent of ink or cleaning agent,[12–32] using ultrasonic assistance,[33–37] using different automation for cleaning process,[38–40] different cleaning solutions,[41–43] or coating of the gravure.[44,45] Another approach has been modification of the ink, to make it more soluble. In overall, it has been required as a property of ink, that there is no blocking of gravure grooves which cannot be taken care of with known washing methods. Ribbing has been solved by composing patterns of cells.[46] This however requires the ink to have thixotropic properties in order to avoid void formation on printed areas due to these support spots.

Grooves of a conventional gravure, manufactured by novel methods, are rectangular in cross section and have sharp edges.[47] These outer gravure groove edges can tear cleaning cloths and hairs of a brush do not fit into the narrowest grooves. An environmental point of view has driven recent efforts to decrease the use of solvent and to use water based inks, which can be washed out with water based washing solutions. However, recently studied inks used for printed electronics are not water based.[2,4,6] Washing also causes ink loss and solvent waste. Because of the expensive metals used in electronics, such as palladium, ink washing must be minimized and ink waste must be collected.

In this article, a Self-Cleaning Gravure (SGC) method is proposed to solve gravure groove blocking and increase pickup line thickness with gravure and gravure offset printings. SCG will also be illustrated as a novel printing method.

Background of SCG Method

Ink accumulated in a block at the bottom of gravure grooves has a different composition to ink in general. It has less solvent and in some cases more solid components, which causes the viscosity of the ink to increase. This decrease of the solvent and increase of viscosity can result a cumulative effect, especially with insoluble solid particles. Increasing the solvent content is not always possible for inks requiring a high internal cohesion. In general, it is presumed that ink newly added to gravure grooves by doctoring, gives its solvent to the blocked ink and thus enables it to dissolve or re-wet.[48] Blocking with metal particles may also be caused by a physical blocking, because a gravure groove may be only twice the dimension of the largest metal particle.[2]

To avoid gravure groove blocking, new solvent is needed at the bottom of the gravure grooves. Therefore, the idea of the novel SCG method is to conduct the solvent there directly. This can be achieved by providing a porous layer or suitable channels under the gravure grooves. Schematic diagrams of the level and the grooved SCG structures are shown in Fig. 2. Channels or a porous layer may carry liquid ink, solvent, vapor, or gas (all described here as matter). If completely liquid ink is used, SCG is a novel printing method; transporting ink to the gravure surface from inside of it does not requiring ink doctoring. Accordingly, this kind of printing surface can have any shape. The ink used can be liquid that does not have particles; i.e., dye ink or organometallic ink. Increased solvent concentration at the bottom of the gravure grooves decreases the viscosity of the ink and makes ink movement easier. The flow of matter can also provide the force which pushes blocked ink out of the grooves. In Fig. 3 there is another solution for open channels. This can be created with additive electrolysis methods.

Methods similar to SCG have been described in patents but not realized as generally known techniques. These structures and assembly methods are significantly more complicated, limited in specific shapes, ex-

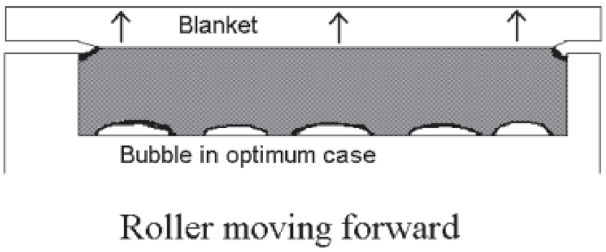


Figure 4. In an optimum case of ink pickup, breaking of the ink layer would begin at the bottom of a gravure groove where bubbles form due to decreased pressure.

pensive and less accurate.[49–51] Using the metal plate version shown in Fig. 2, it is possible to achieve dot and space resolution of 10/10 µm (1270 dpi) with available patterning techniques.

The pressure at the gravure surface has been studied theoretically in conventional gravure printing at the pickup phase and in "roll coating" applications.[52] The pressure profile first shows a strong increase in pressure, which depends on parameters and materials. After the center point of a roller has passed a given point of the image area, the pressure starts to decrease. The pressure decreases below atmospheric pressure, at which point ink is pulled out from the gravure grooves. This may cause gas bubble formation, called cavitation, inside inks with solvents having a low boiling point. It is a desired effect only if bubbles form at the bottom of the gravure grooves as shown in Fig. 4. This is in principle the same effect as pushing gas through the SCG to the bottom of the gravure grooves. In the SCG solution, counter pressure of matter from the bottom of deep grooves is helpful to remove more ink at the pickup stage. Also the effect of ribbing shown in Fig. 1 can be reduced.

Realization of SCG

This section describes practical realizations and benefits of SCG. For better ink pickup and gravure cleaning SCG can be produced as a hard surfaced grooved version to which surface ink is doctored. For the novel printing application, however, doctoring of ink to grooves is not necessary. If the SCG material is metal, very high pressures in printing or doctoring can be used. In other cases, e.g., if the material used is plastic, SCG will be light, easy to make and inexpensive.

With a simple design of an SCG version with solvent channels, ink is first doctored conventionally to the gravure grooves. Ink pickup from there is aided by pressure from inside of the SCG structure. This structure, built from of three or more patterned layers, is shown in Fig. 3: 1) A pattern to be printed, 2) a hole layer made of small dots (leading matter to the bottom of each groove), and 3) matter channels. Patterning of the third layer may be dependent on patterning of the first layer. With a sufficiently high hole frequency in the second layer, there is no need for exact alignment of these layers. Even distribution of matter from channels can be controlled by channel size. Matter channels are connected to one or more outlets from the gravure to the open container or a pump of matter. In the case of graphic dot pattern printing, the first layer may not be needed if hole sizes in the hole layer are made to match the printed dot size and the third layer does not interfere with them. This is possible with, e.g., additive electrolysis methods, which have been shown to produce 9 µm wide lines.[5] Figure 5 shows Scanning Electron Microscopy (SEM) images of a mesh patterned 30 µm deep gravure, with 15-20 µm metallic pole-shapes.

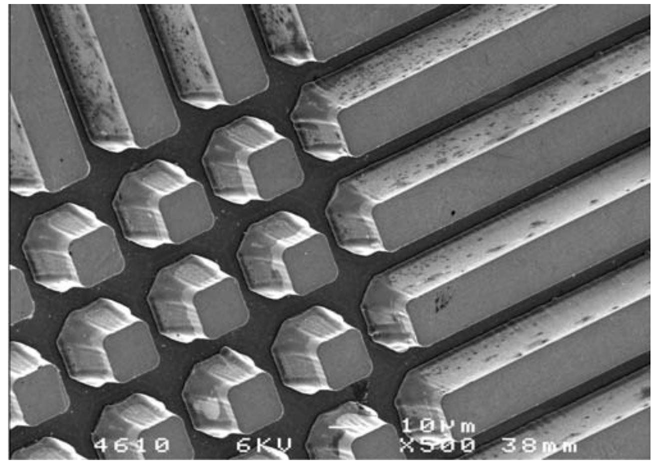


Figure 5. SEM image of mesh patterned 30 µm deep gravure surface.

If SCG suitable for ink doctoring is made using a porous layer, there needs to be a porous layer under the gravure grooves as shown in Fig. 2b. Matter is then led to this layer. Such material can be marketed like polymeric gravure plates, which only require an exposure and developing or alternatively etching with a used pattern.

Another approach is to make an SCG having a plane surface for the printing of a completely liquid ink. This can be done by attaching a hole-patterned plate over the porous polymer. An example is shown in Fig. 2(a).

As a modification from SCG, 'soft surface SCG' comprising a porous layer can be produced. It differs from others in that its surface is made of rubber. If, for example, a non-polar silicone polymer is used, it will repel polar, water based inks and this will reduce 'scumming' or 'streaking' and therefore printing to non-image areas will be better controlled. If the printing target material is hard, SCG may also be only a porous material without a coating layer that has its surface embossed at image areas. This way the printing principle becomes similar to ink stamps. A similar approach where diffused molecules would go through silicone polymer has been suggested for micro contact printing.[53]

Simple Graphic Printer

Simple printer assembly can be done from a cylinder shaped printing barrel with the required matter channels and the SCG printing plate fixed on its surface. An additional elastic roller is required for graphic printing to give counter pressure and ease target material movement. This impression roller can be pressed against the printing barrel by its own weight, by an additional small weight, or by springs. In addition, only printing target material and matter feeds are required. A schematic example of such an assembly is shown in Fig. 6.

Methods of Manufacture

Preliminary experiments were done in order to manufacture the proposed SCG prototypes; 20 µm thick aluminum foil or 30 µm thick copper was laser patterned

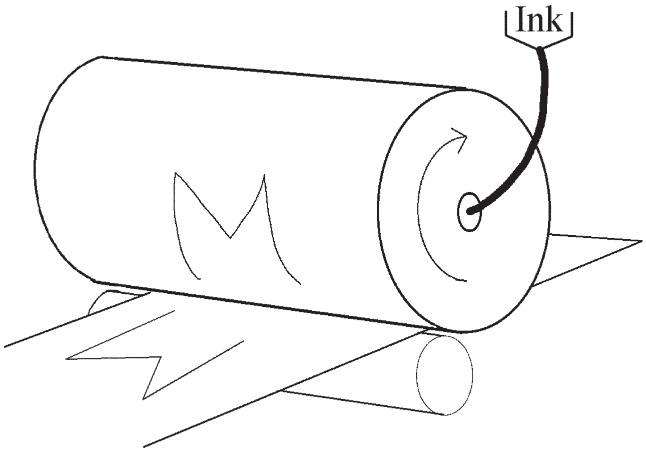


Figure 6. Simple graphic printer assembly for SCG.

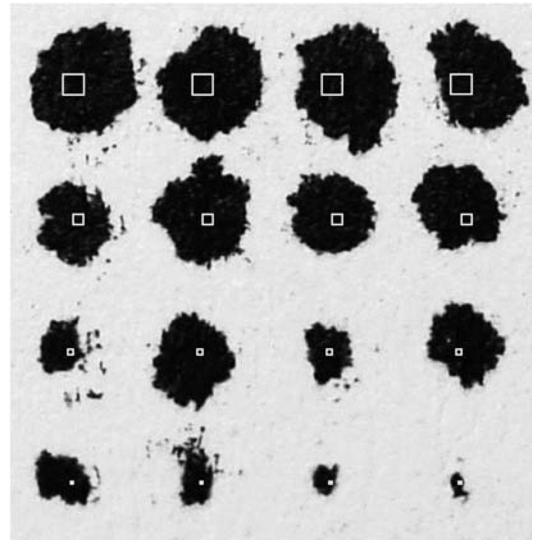


Figure 7. Printed trace from 640, 320, 160, 80 µm wide SCG holes (rectangles in the fig.) with dye ink jet ink and using soft porous SCG.

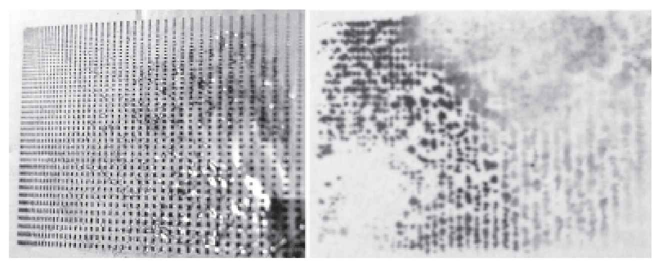
using a pulsed 355 nm Siemens Microbeam 3200 laser. Holes down to 15 µm in diameter were produced. The polymer material used was GUR 2122, from Ticona (www.ticona.com). The molding was made by compression and heating at 150-180 °C or above, to create high adhesion to the porous polymer. Isopropyl alcohol based dye ink jet ink, diluted with ~10 % of acetone, was used.

Level Surface SCG

In lithography, ink is usually spread to the level printing surface, which has polar and non-polar sections. Ink adheres to a surface of similar polarity and so is influenced by the printing plate polarity. One application of SCG is to bring ink to the surface from inside the gravure, so that no inking is needed. A metallic non-image area will repel a non-polar ink. To create a level surface SCG as shown in Fig. 2(a), a porous polymer is molded over a patterned plastic or metal plate: ~0,1 mm thick metal foil with a rough (inner) surface is coated with a photoresist. This is exposed with a dot-image pattern. After developing the photoresist, the exposed area of the metal is etched through, creating a pattern of holes. The photoresist is then be completely removed. For a plastic plate, some other patterning method can be used. Alternatively, patterning can be done with a laser for a variety of materials. The plate with the holes is then placed at the bottom of a mold and porous polymer is molded over it.

The realization of the method was tested with a metallic stencil placed over porous material. Figure 7 shows a dot array of ink (pigment based ink jet ink) printed on paper from square shaped holes of 80 – 640 µm per side. Dot widening can be decreased, by controlling the ink flow and increasing the printing speed.

Another experiment consisted of printing from a metal surface SCG with 15 – 250 µm wide holes (Fig. 8(a)). Porous polymer was molded onto the reverse side to create a smooth surface. The results show (Fig. 8(b)) that most of the dots are printed, and that there is some ink spreading in the manual printing.



(a) (b)

Figure 8. (a) Level SCG with 15 – 250 µm wide holes (same spacing), and (b) the printed result using diluted dye ink jet inks.

Metallic Gravure

This printing surface is similar to gravure manufacturing with an electrodeposition method.[47] About 30 µm thick (or thinner depending on the required gravure groove depth) positive photoresist is first applied to a smooth conductive surface. Then the photoresist is exposed with a positive gravure pattern and developed. A metal (nickel) layer of the required gravure groove thickness is grown in an electroless or electrolysis bath on the areas of the photoresist openings. In order to make the next layer grow, the entire surface is made conductive. A new layer of photoresist is applied and exposed with the dot (hole layer) pattern and developed. Then a metal layer of the required gravure groove thickness is grown. In a similar manner, grooves for matter channels are created as shown in Fig. 3. The final layer can then be uniform. After completion, the SCG is removed by tearing it off. Interlayer adhesion can be enhanced after removing the photoresist by firing (possibly in an inert atmosphere), insofar as an appropriate kind of metal has been used as the conductive layer.

A prototype was created with holes (15 µm wide) laser processed at the bottom of a normal gravure, followed by placing porous material under the gravure as shown in Fig. 9(a). Figure 9(b) shows the resulting print from the gravure, having half of the grooves with holes at the bottom. The effect of ribbing is significantly reduced.

Porous Polymer on Patterned Material

A hard surface is manufactured in a similar manner to that used for Metallic gravure, above resulting in the structure shown in Fig. 2(b). Firstly, photoresist is

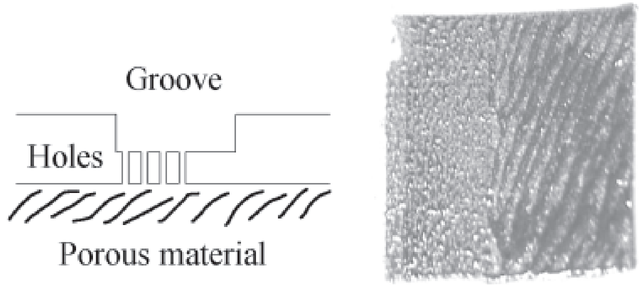
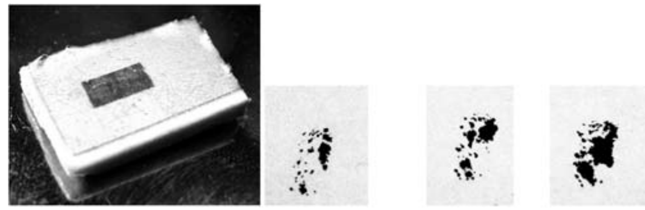
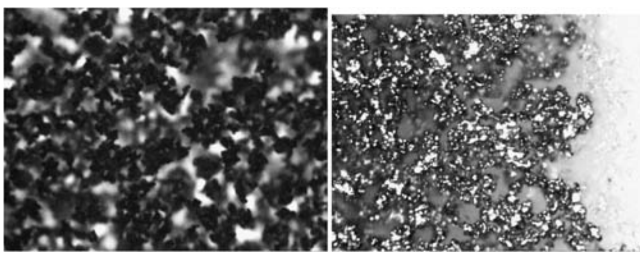


Figure 9. Electrolytically created gravure with holes at its bottom and porous material underneath. (a) Schematic diagram and, (b) printed result from 5 × 5 mm gravure groove, with left side having the SCG structure and exhibiting less ribbing compared to the right side.



(a) (b)

Figure 10. (a) SCG with copper surface having dense dot pattern (~20 × 10 mm) and, (b) three printed traces with increasing pressure (from left to right).



(a) (b)

Figure 11. Porous polymer after (a) sputtering of metal, and (b) electroless deposition of metal. (860 × 660 μm)

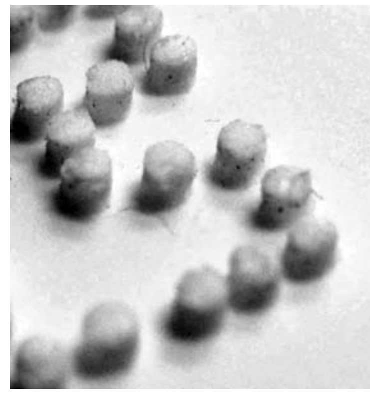


Figure 12. Porous polymer molded on hole-patterned Teflon. (~ 20 × 20 mm)

spread, exposed and developed on a conductive surface. Then metal is grown on that surface, thinner than the photoresist. Then porous material is molded on it and the polymer is heated to solidify it. After removing the resulting SCG from the mold, the photoresist is removed. It should be noted that this kind of gravure with a grooved surface might not be able to withstand doctoring if ink is applied from the top of the gravure. With conductor lines, there are long line areas that can easily peel off, unlike the case of a mesh structure used to print dots. Therefore, dot structures as used in graphic printing can be used for conventional gravure printing, because the surface is uniform with holes, i.e., a mesh. An alternative for this manufacturing method is to first make this gravure with an electroplating method. The resulting gravure metal is grown to cover the whole photoresist pattern. Then subtractive methods such as etching without alignment can be applied to create holes of limited depth. After this, a porous layer is added.

The structure has been demonstrated with a polymer mold over copper which was patterned with a laser to form 15 μm holes (Fig. 10a). The resulting print shown in Fig. 10(b) with different counter pressures used, results in more dot widening with dye ink.

SCG for doctoring was made by laser patterning 1 × 1 mm holes on 100 μm thick steel. The steel was heated (~140°C) on top of a level porous polymer plate to create adhesion. Printing experiments with this pattern resulted in ink pickup and printing thickness (dried) of 40 μm, instead of the conventionally achieved 20 μm.[6]

As yet unrealized possibilities of the method suggest the following manufacturing approaches which are illustrated by preliminary experiments:

Patterning on Porous Polymer

Matter permeable SCG can be made from bulk porous polymer. A catalytic or conductive seed layer is created, e.g., by sputtering with metal (copper) (Fig. 11a). After this, electroless metal (nickel) can be grown over the surface for 1 – 10 μm to make the surface smoother (Fig. 11b). Then an electrolytic metal (nickel) bath is used to increase the metal thickness and make the surface smooth. To create the pattern on this SCG, a photoresist may be applied on the metal, patterned, developed and etched in an acid bath or by another method, such as RIE (Reactive Ion Etching).

Depending on the properties of the photoresist used, it could be applied, exposed and developed over a seed layer. After this, more metal is grown over the exposed non-image areas as in gravure cylinder preparation. As an alternative, laser processing could be used to replace etching, but this can result in an increased processing time. Heating due to the laser beam might also cause the polymer to melt.

Soft Surface SCG

First an embossed negative image or holes are created on a plate of easily workable material such as Teflon, which does not adhere to the materials used or melt at the temperatures used. Then this plate is placed at the bottom of a mold for porous polymer and the mold is filled with porous material powder. After heating and finally removing the plate and resulting porous material from the mold (Fig. 12), high viscosity silicone polymer is applied to the cavities of an embossed pattern. Then excess silicone polymer is removed with a blade and the silicone polymer is allowed to cure. (A tempo-

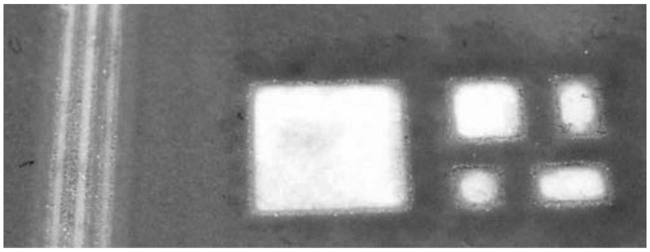


Figure 13. Laminate photoresist laminated on top of level porous polymer, exposed with a pattern and developed. (~35 × 15 mm)

rary coating must be used on the polymer to prevent silicone polymer spreading to the pores).

Photoresist Surface SCG

The porous material surface is coated with a photoresist that does not flow to the inside of the material (such as laminate photoresist commonly used on circuit boards). This photoresist is then exposed, developed and hardened. This yields a selective coating on the surface of the SCG, which can then be used directly for printing (Fig. 13). Usability depends on hardness of the photoresist; solvents that dissolve photoresist, e.g., acetone, can not be used.

Future Possibilities

The authors anticipate that if SCG were to be developed in place of conventional gravure as a replacement for offset printing, some significant advantages might be realized:

- Due to the fact that ink may be pushed out from the gravure, direct printing (without an offset step) may be effected, even to a hard target. This is possible because, at the laydown stage, there is pressure applied from the bottom of the gravure grooves to push the ink out.
- Thicker lines can be printed compared to conventional gravure printing methods. Early printing experiments with SCG, shown in Fig. 2(b), have indicated an ink pickup and printing thickness of 40 μm instead of the conventionally achieved 20 μm.[6]
- Higher printing repeatability because of decreased gravure groove blocking.

The SCG technique dispenses with inking and doctoring because the ink is fed directly to the bottom of the gravure grooves. This enables the use of SCG as a novel printing technique with completely liquid inks. The printing target material or offset material needs only to be pressed against the gravure surface and the ink will be transferred directly from the grooves. The are several advantages anticipated for this novel direct printing method:

- The only wear likely to be experienced by the printing surface is due to direct contact with the target material.
- There is no blocking caused by material being removed from the printing target because, in the absence of doctoring knives or other ink spreading systems, the pressure can be reduced.
- The method enables the use of a very simple and inexpensive printer assembly—the SCG can be mounted on a cylinder and another elastic cylinder is pressed against it. The printing target material is then fed between these rollers.
- With controlled ink flow, there is no printing target material lost and repeated single prints from the SCG are possible. After printing, ink solvent can be pushed though the SCG, thus cleaning it.
- The SCG can be manufactured from polymer, assuming that a sufficiently hard material is available. The manufacture can be done simply by exposing a photosensitive material and developing it to form a photoresist surface SCG.
- Maintenance and cleaning expenses are minimized;
- Very high printing speed is enabled, particularly when SCG is used to print low viscosity inks that flow easily through a porous material. Also using one cylinder SCG, there can be several target material rollers pressing the printing target material towards SCG.
- When ink is brought to the surface of the gravure from inside, the shape of the gravure is no longer limited by the doctoring. For example, a round printing target material, such as an (offset-) pad can pick up ink more easily, with a thicker layer and with less pressure from a concave gravure. Alternatively, a non-planar surfaces can be printed by preparing a custom-made porous SCG.
- With multiple channels inside an SCG structure, many colors can be printed simultaneously. Several layers of channels may be built inside it to deliver ink of each color to the surface at required points.

It should be noted that SCG is also a solution for runtime gravure cleaning for all existing gravure printers. This is especially beneficial with problematic inks and large production series. In graphic printing, gravure grooves are often blocked by fibers from the printing target material.[54]

Conclusions

SCG may be an effective extension of conventional gravure offset printing for printing thicker lines and cleaning gravure grooves during or after usage. The printer does not need to be stopped for cleaning so that SCG can save time and materials. As a new printing method that dispenses with groove doctoring, SCG offers a wide range of advantages at reduced cost. Important benefits are lower printer and printing plate manufacturing costs, a greater number of prints from the same plate, no need for groove cleaning and no other wearing parts on printing surfaces. Manufacturing cost is low due to fewer process steps and lower material costs compared to those demonstrated in patents. In the simplest case, the printer can consist of two rollers, one of which is elastic and the other has SCG on its surface. SCG can be inexpensively made from porous material with a selective coating of a photoresist on its surface. SCG with a metal surface has been demonstrated for production of dye–ink patterns. In addition, the possibility of using arbitrarily shaped gravure surfaces enables larger pickup areas for pad-printing or direct printing of nonplanar objects. Gravures can be produced with a dot and space resolution of 10/10 μm (1270 dpi).

Acknowledgment. This research proposal was supported by Brite/Euram project "Development of a high-resolution printing process for cost-effective production of ultra-fine line electronic circuitry" (BE 97-4607). The New Technology Foundation of Finland has granted an award to the author for this innovation.

References

1. J. B. Szczech, C. M. Megaridis, D. R. Gamota and J. Zhang, *IEEE Trans. Electronics Packaging Manufacturing*, **25,** 26 (2002).
2. M. Pudas, K. Elsey, A. Logan, J. Hagberg, and S. Leppävuori, Methods for evaluation of fine-line circuitry printing inks, *Coloration Technology*, 120(3), 119–126 (2004)
3. M. Lahti, S. Leppävuori and V. Lantto, *Appl. Surf. Sci.* **142**, 367 (1999).
4. M. Pudas, J. Hagberg and S. Leppävuori, Printing parameters and ink components affecting ultra-fine-line gravure-offset printing for electronics applications, *J. Eur. Ceramic Soc.* (in press).
5. J. Hagberg, M. Pudas and S. Leppävuori, Gravure offset printing development for fine line thick film circuitry, *Microelectronics International* **18**, 32 (2001).
6. M. Pudas, J. Hagberg and S. Leppävuori, The absorption ink transfer mechanism of gravure offset printing for electronic circuitry, *IEEE Trans. Electronics Packaging Manufacturing,* **25**, 335 (2002).
7. O. Bagel, E. L'Hostis, G. Lagger, M. D. Osborne, B. J. Seddon, H. H. Girault, D. Brack, U. Loyall, and H. Schäfer, *J. Electroanalytical Chem.* **469,** 189 (1999).
8. J. Hagberg, M. Pudas, M. Kittilä, and S. Leppävuori, Direct gravure printing (DGP) method for prinitng fine line electrical circuitry, *Proc. 2001 International Symposium on Microelectronics* IMAPS, Washington, D.C., 2001, p. 682; ISBN: 0-930815-64-5.
9. B. Dziurdzia, Low cost high performance structures fabricated by advanced film techniques, *Microelectronics International*, **16**, 46 (1999).
10. S. F. Kistler and P.M. Schweizer, *Liquid Film Coating*, 1st ed., Chapman and Hall, London, 1997, p. 157.
11. M. S. Carvalho and L.E. Scriven, Deformable roll coating flows: steady state and linear perturbation analysis, *J. Fluid Mech.* **339**, 143 (1997).
12. K. Yamada, Japan Pat. 5,286,126 (1993).
13. M. J. Pym, World Pat. 9,746,388 (1999).
14. Abe Yoichiro, Eur. Pat. 514,756 (1992).
15. T. Mitsugi, K. Koichi, S. Yoshi, K. Yasuo, and K. Kazuhiko, Japan Pat. 11,268,252 (1999).
16. Itou Masao, Japan Pat. 58,101,058 (1983).
17. Uno Chiyomatsu, Japan Pat. 58,101,060 (1985); US Pat. 4,499,825 (1985).
18. W. Stauffer, US Pat. 5,390,598 (1995).
19. E. Yutaka, EP Pat. 1,055,516 (2000).
20. K. Koizumi, Japan Pat. 63,149,155 (1988).
21. S. Yasuhiro, Japan Pat. 4,093,254 (1992).
22. A. Bonomi, US Pat. 4,236,450 (1980).
23. M. Tomoyasu, S. Toshiya, N. Sadayoshi, I. Masaichi, and N. Hiroki, US Pat. 5,213,040 (1993).
24. R. Kranzlmueller, German Pat. 3,913,616 (1990).
25. F. Koerner, German Pat. 3,151,005 (1983).
26. S. Mitsuhiro, Japan Pat. 10,016,200 (1998).
27. T. Kazuyuki, S. Tadao and S. Masayuki, Japan Pat. 8,244,213 (1996).
28. S. Swiji, U. Hitoshi and U. Takafumi, Japan Pat. 10,324,075 (1998).
29. Y. Kazunari, I. Nobuyuki and M. Masako, Japan Pat. 2,000,141,590 (2000).
30. K. Mitsunobu, Japan Pat. 6,031,224 (1994).
31. T. Kiyotaka and T. Kunihiro, Japan Pat. 8,197,710 (1996).
32. H. Jakob, Eur. Pat. 43,624 (1982).
33. Ultrasonic Cleaning of Rotogravure Cylinders/Summary of ultrasonic techniques (in an aqueous solution) for cleaning cylinders in rotogravure printing processes *Report No: DCN-89-203-080-34-11;EPA/450/3-89/024*, Sponsoring Organization: Environmental Protection Agency, Control Technology Center, Triangle Park, NC, 1989.
34. S. Takurou, Japan Pat. 5,177,177 (1993).
35. J. Lagonigro, A.H. Liers and L.J. Principe, US Pat. 5,291,827 (1994).
36. N. Kenji, Japan Pat. 6,170,347 (1994).
37. H. F. Metzger, US Pat. 6,197,169 (2001).
38. T. Mitsugi, I. Chishiyo, T. Hirofumi, and T. Shunei, Japan Pat. 2,000,218,760 (2000).
39. H. Hitoshi, Japan Pat. 10,309,791 (1998).
40. H. Hitoshi and N. Shinji, Japan Pat. 11,291,440, 11,291,441, 11,291,443, 11,291,444, 11,291,459 (1999).
41. N. Kazuchika, Japan Pat. 10,324,896 (1998).
42. W. Mitsuzo, Japan Pat. 63,125,689 (1988).
43. M. Yosmimasa, Japan Pat. 10,337,855 (1998).
44. I. Nobuyuki, Japan Pat. 4,064,487 (1992).
45. S. Masayuki, Japan Pat. 2000,109,384 (2000).
46. R. H. Leach, R. J. Pierce, E. P. Hickman, M. J. Mackenzie, and H. G. Smith, *The Printing Ink Manual*, Kluwer Academic Publishers, Dordrecht, 1999, p. 78.
47. J. Hagberg and S. Leppävuori, Method for the manufacture of high quality gravure plates for printing fine line electrical circuits, *Proc. SPIE* **3892**, 313 (1999); ISBN: 0-8194-3493-0.
48. R. H. Leach, R. J. Pierce, E. P. Hickman, M.J. Mackenzie, and H. G. Smith, *The Printing Ink Manual*, Kluwer Academic Publishers, Dordrecht, 1999, p. 538.
49. W. C. Huebner, US Pat. 2,615,389 (1952).
50. N. Nobuyuki, I. Nobuyuki and M. Masako, Japan Pat. application number 2000-335,126 (2000).
51. T. Yamamoto, Japan Pat. 4,173,284 (1992).
52. D. J. Coyle, Forward roll coating with deformable rolls: A simple one-dimensional elastohydrodynamic model, *Chem. Eng. Sci.* **43**, 2673 (1988).
53. L. Libioulle, A. Bietsch, H. Schmid, B. Michel, and E. Delamarche, Contact-Inking stamps for microcontact printing of alkanethiols on gold, *Langmuir*, **15**, 300 (1999).
54. P. J. Mangin, J. Silvy and J. H. De Grâce, Offset linting sudies, Part 2, Further contribution to linting theories, *1990 International Printing and Graphic Arts Conference*, Canadian Pulp and Paper Association, 1990, p. 109.