Laser Printing of Conductive Silver Lines

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Abstract

Digital printing of functional electronic devices is a major field of research and developments nowadays. Among others, progress is made to replace or supplement thick-film screen-printing technology by inkjet printing.

Inkjet printing is already a very developed technology to print passive elements of thick-film electronics. In addition to inkjet, a new approach of printing functional elements is launched at the Institute of Automation Technology of the Helmut Schmidt University / University of the Federal Armed Forces Hamburg (HSU). Electrophotography is a very promising way to print conductive and non-conductive thick-film elements. It offers a completely solvent-free method with high printing speed and a high potential regarding precision.

At HSU, a prototype printer is used to print conductor lines on LTCC tape. The corresponding toner is based on conductive silver powder. The approach aims for achieving a complete, conductive layout after firing. The parameters of the printer and its construction are optimized, to gain necessary thickness of lines without losing their sharpness. Several silver toners are utilized and compared. As a result, conductive silver lines are successfully printed and improved in density and thickness.

Introduction

Thick-film electronics are the state-of-the-art technology when electronic circuits have to work under harsh environments, for example in aviation, space, military or automobile applications. These electronic circuits still are mostly manufactured by screen printing technology, especially the basic layout of these circuits, consisting of conductive silver lines.

Screen printing is established and reliable in fulfilling the requirements to print thick-film circuits. Nevertheless, several limitations come with this technology. Especially the lack of flexibility considering frequent changes in circuit layout respectively rapid prototyping, forces new approaches in printing thick-film circuits, in particular in digital printing of these circuits [1].

During the last years, inkjet printing has become a feasible digital printing technology in thick-film technology. In addition to inkjet technology, scientists at Helmut Schmidt University are exploring a new way to print thick-film elements, in this case conductive silver lines: Electrophotography

Electrophotographic printing, commonly known as laser printing, is a technology mostly used for classic printing applications, like office printers, graphic printing and book printing.

The electrophotographic process uses tribo-electrically charged particles, which are developed onto the latent image on a selectively discharged photoconductor and afterwards transferred to a substrate [2, 3].

Using this technology to print conductive silver lines on low temperature cofired-ceramics (LTCC) tape arouses many challenges. For tribo-charging, keeping their charge and using them in a printing system, toner particles need to be non-conductive. In opposition to that, silver is an excellent conductor which qualifies it most as material for conductive lines. Approaches were made to test conductive copper powder in an electrophotographic environment [4], but so far no experience in using a conductor in a complete electrophotographic printing system is published.

Furthermore, enough silver has to be brought on the LTCC substrate to form a conductive line after firing.

This paper documents the approach on these challenges. First, an appropriate printing system is defined and described. Then, the properties of the used silver toners are shown. Afterwards, a study to optimize printer parameters towards layer thickness of printed silver lines on LTCC tape is presented. The results of firing these structures are described thereafter. The paper is concluded with the main experience gained from these studies and further approaches to be taken in the future.

Printing System

For printing prototype toners, especially conductive silver toners, a highly flexible, adjustable and robust printer is required. No off-the-shelf printer, even if adapted, is considered capable of fulfilling these requirements.

Therefore, a special-constructed prototype printer is necessary to adjust the electrical and mechanical printer parameters to toner properties. This printer is manufactured by CTG PrintTEC GmbH in Alsdorf, Germany. The two-component printing system uses a 600×600 dpi print head and an organic photoconductor (OPC).

Unlike common printers, a conditioning drum is placed between the developer station and the OPC. A gap in applied voltages between the developing station and this drum leads to a very homogenous and thick layer of toner on the drum, which is subsequently transferred to the latent picture on the OPC [5].

Transfer from OPC to substrate is realized by a transfer drum, which presses the substrate at the OPC. A voltage is also applied to this drum, so the toner is transferred by electrical as well as by mechanical force.

The CTG printer provides the possibility to replace most components easily, such as developer station, OPC and conditioning drum. It is also possible to modify electrical parameters, e. g. transfer voltage, corona charge and strobe time, by a simple operating interface. Also, many mechanical parameters, such as doctor blade gap and developer magnet angle, can be changed.

Toner

The challenge in printing silver particles is that they are desired to be conductive at the end of the firing process, but must not be conductive for the electrophotographic process. Thus, the particles have to be embedded in non-conductive polymer, striving for complete coverage.

This goal is reached best by creating spherical toner particles, which are shown in **figure 1**.

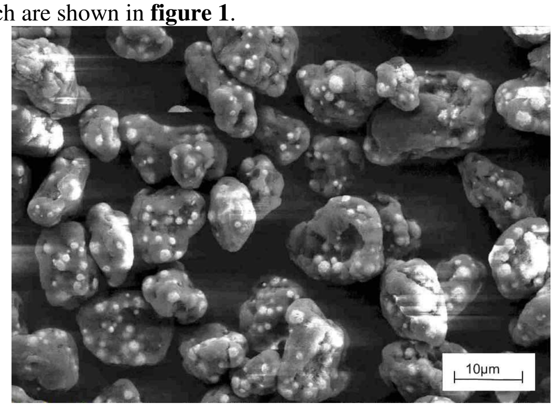

***Figure 1**. REM image of spherical silver toner*

The silver particles are dispersed in "usual" toner material, such as wax and polyester. Furthermore, charge control agents and additives are added to provide sufficient charge and desired toner properties. For the two-component system, a common carrier is used.

Nevertheless, it is a challenge to use silver in the electrophotographic process. Silver is of high density, compared to usual toner ingredients. This counteracts a high charge-to-mass ratio. Furthermore, it is hardly possible to prevent silver particles on the surface of the toner particles. Despite the danger of short-circuits within the printing system, these particles also may cause local discharge.

Thus, silver properties lower the attainable mean charge of the toner particles and lead to a relatively high amount of opposite charged particles, compared to regular toner. The negatively charged toner used in this study also comes with these drawbacks, as **figure 2** shows.

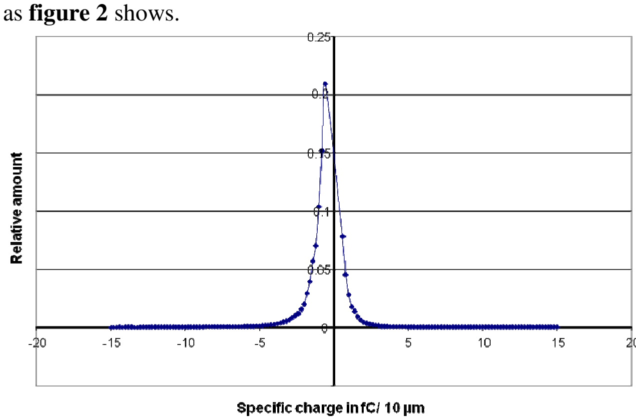

***Figure 2**. Charge distribution of used silver toner*

The tested toner has a medium charge of -1.15 fC/10 µm and contains 18 % of positively charged particles. These values as well as charge distribution of figure 2 are measured with the EPPING q/d-meter [6].

Parameter Study

In this study, electrical parameters of the printing system are varied in order to adjust the printer to newly developed silver toners. The tested parameters are strobe time (exposure time), bias (voltage applied to developer station), conditioning (voltage applied to conditioning drum), and transfer (voltage applied to transfer drum).

The parameters are first tested with regular carbon black toner on paper. Afterwards, they are tested with the same carbon black toner on LTCC green tape with a thickness of 300 µm.

To qualify the results, the layer thickness of the printed structures is measured with a white-light interferometer. Additionally, the prints are examined under a microscope to verify the plausibility of the measurements.

The first three parameters did not yield any extraordinary results. Conditioning and bias always should not differ more or less than 350 V to 450 V. With increasing bias, higher layer thickness is achieved, but also more background occurs. Longer strobe time leads to higher layer thickness, but saturation occurs at a certain level. Also, deformation effects appear with increasing strobe time. A variation in a range from 15 µs to 35 µs is considered to be sufficient.

These results meet the expectations and are validated on paper as well as on green tape.

Continuous increase of transfer voltage is expected to result in a saturation of transferred toner amount. Thus, a maximum of layer thickness will not be exceeded after reaching a certain voltage level [7]. As **figure 3** shows, this expectation is met when printing carbon black toner on paper. After transfer voltage reaches a level of 300 V to 400 V, a maximum layer thickness of approx. 23 µm is achieved.

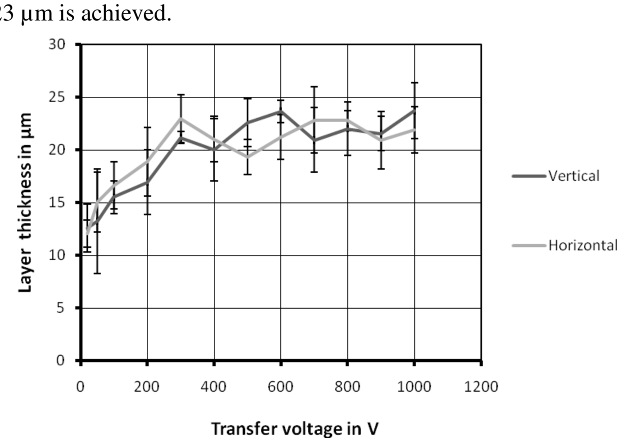

***Figure 3**. Layer thickness of horizontal and vertical structures, printed with carbon black toner on paper.*

In opposition to the previously tested substrates, examination of printing carbon black toner on green tape yields different results. Layer thickness increases with increasing transfer voltage, but saturation is not reached, even with the maximum voltage of 1000 V, as **figure 4** shows.

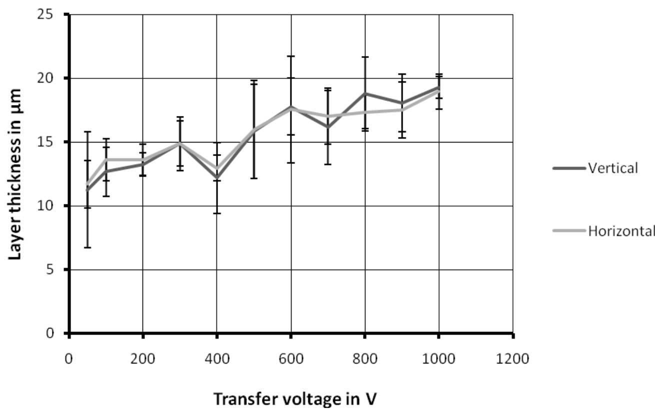

Figure 4. *Layer thickness of horizontal and vertical structures, printed with carbon black toner on green tape.*

This effect is assumed to be caused by the electric properties of the used green tape, which are quite different from those of common substrates like paper. Furthermore, it is much thicker.

The above mentioned results are used as reference for testing silver toner. Bias is set to its maximum level of -1000 V; conditioning and strobe time are varied in the above mentioned ranges. Also, transfer voltage is set to its maximum level of +1000 V. First, silver toner is printed on paper. Corresponding layer thicknesses is in the range of 13 µm.

Afterwards, silver lines are printed on green tape with optimized parameters. The respective silver lines are shown in **figure 5**.

Figure 5. *Silver lines printed on green tape*

Figure 5 also reveals several challenges. Even with optimized parameters, the density of the lines cannot be considered sufficient because conductivity after firing seems very unlikely. Furthermore, the insufficient density leads to inaccurate measurements of layer thickness, when using a white light interferometer. Voids and inhomogeneities cause unreliable results.

Firing Process

As the above mentioned results show, the density of printed conductor lines seems not sufficient for conductivity after firing. Therefore, multiple print cycles are considered necessary. In first tests, silver toner is printed on green tape, in a variation from one to four cycles. Afterwards, these tapes were laminated and fired with different approaches.

High-pressure cold lamination with four layers of green tape turns out to be the method of choice. Heated lamination causes the wax of toner particles to melt. Thus, they adhere to any sacrificial or protection layer applied onto the silver lines. Cold lamination with a pressure of 200 kN leads to sufficient adhesion between the tape layers. Furthermore, no decisive loss of toner the Mylar foil used to protect the silver lines during the lamination process was recognized.

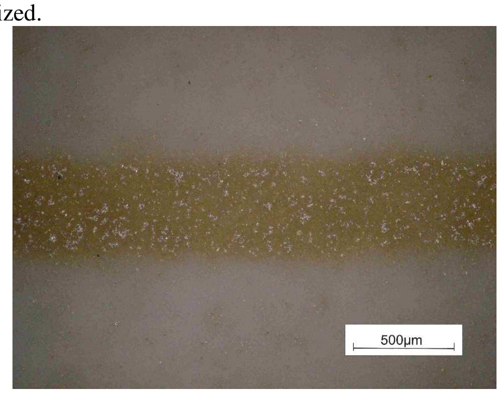

Figure 6. *Silver lines, two printing cycles, after firing*

The laminates are fired in a cycle consisting of a 5°C per minute heating phase up to 850°C, a 15 minute dwelling phase at that temperature, and a following cool down, also with 5°C per minute. A silver line with two printing cycles is shown in **figure 6**. Assumingly, a noticeable amount of silver particles dissolve in the glass of the glass ceramic and are not available to form a conductive line.

A conductive line can be reached after four printing cycles. A resulting silver line is shown in **figure 7.** It is not completely filled, but has certain conductivity, which is measured using a sense-force ohmmeter.

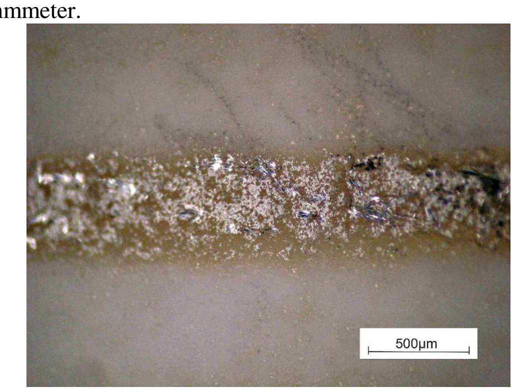

Figure 7. *Silver lines, four printing cycles, after firing*

On a length of 0.5 cm up to 2 cm, resistance values between 0.5 Ω and 5 Ω are measured.

Conclusions

The experiments performed at Helmut Schmidt University prove the possibility of printing conductive silver particles using laser printing technology. After intense research, a first set of conductive lines on LTCC is produced with the methods described in this paper.

However, these results can only be considered as first stages in printing and firing a conductive layout on ceramics. Several challenges still have to be approached. Especially when comparing the presented silver lines in figure 7 to inkjet-printed silver lines of HSU scientist shown in **figure 8**. Further research aims for reaching comparable results.

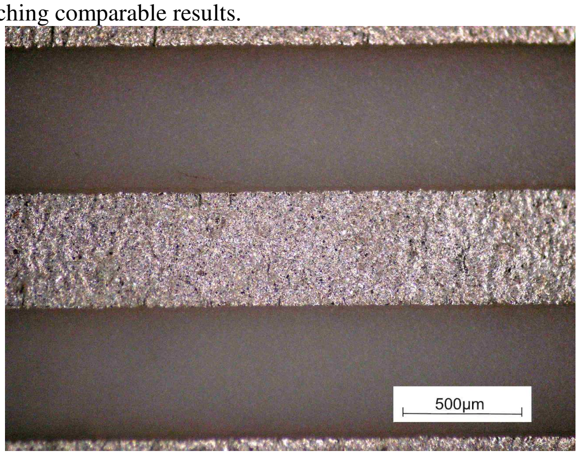

***Figure 8**. Silver lines, inkjet-printed, 20 printing cycles, after firing*

The transfer of toner onto the LTCC tape, respectively the resulting layer thickness and density after one printing cycles are not sufficient yet. Therefore, modifications of the transfer method of the printing system are necessary. In addition, further development of the silver toner is a decisive factor in improving the printed structures.

Also, the effects of green tape as a substrate in the electrophotographic process require further investigation, as well as the effects of the firing process. Furthermore, new or modified methods of measuring layer thickness have to be considered, due to the insufficient density of printed lines in this stage of development.

These efforts aim for printing completely filled silver lines on green tape with sufficient layer thickness after a minimum number of cycles. After firing, a conductive layout with an acceptable low resistance shall be realized. Further innovations are already targeted by Helmut Schmidt University, CTG PrintTEC and Zobrist Engineering and will be implemented in the near future.

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