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Selective Light Sintering of Aerosol-Jet Printed Silver Nanoparticle Inks on Polymer Substrates

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Abstract

Printing silver nanoparticle inks to generate conductive structures for electronics on polymer substrates has gained increasing relevance in recent years. In this context, the Aerosol-Jet Technology is well suited to print silver ink on 3D-Molded Interconnect Devices (MID). The deposited ink requires thermal post-treatment to obtain sufficient electrical conductivity and adhesion. However, commonly used oven sintering cannot be applied for many thermoplastic substrates due to low melting temperatures. In this study a new sintering technology, selective light sintering, is presented, based on the focused, continuous light beam of a xenon lamp. Sintering experiments were conducted with Aerosol-Jet printed structures on various polycarbonate (PC) substrates. Especially on neat, light transparent PC, silver tracks were evenly sintered with marginal impact to the substrate. Electrical conductivities significantly exceed the values obtained with conventional oven sintering. Adhesive strength is sufficient for conductive tracks. Experiments with non-transparent PC substrates led to substrate damage due to increased light absorption. Therefore a concept for a variation of light sintering was developed, using optical filters. First experiments showed significant reduction of substrate damage and good sintering qualities. The highly promising results of the conducted experiments provide a base for further investigations to increase adhesion and qualifying the technology for MID applications and a broad spectrum of thermoplastic substrates.

Keywords: Molded Interconnect Devices (MID), Aerosol-Jet Printing, Sintering, Silver Ink, Light Soldering System

INTRODUCTION

Molded Interconnect Devices (MID) enable the combination of mechanical and electronic functions in one component and therefore open possibilities for further miniaturization of complex mechatronic systems. The MID technology is based upon metalized injection-molded components to realize functional surfaces as well as conductive tracks for electronic circuitry. In subsequent process steps electronic components can be assembled. Currently, metallization of the thermoplastics is mainly done by laser structuring, hot stamping, or two-component injection molding. [1]

However, these techniques require specific substrate materials and chemical post-processing. An innovative approach to increase flexibility and economic efficiency – especially for low production volumes – is to introduce additive manufacturing technologies into the process chain [2]. They allow the generation of forms and functions directly from CAD models without masks and part-dependent tools.

Aerosol-Jet Printing is an additive printing technology that is particularly well-suited for the metallization of spatial substrates [3]. This printing technology allows direct processing of a wide variety of functional inks. The ink is atomized to an aerosol with a carrier gas and transported into the Virtual Impactor, where it is condensed and afterwards directed into the printing head. There a sheath gas is added in order to focus the aerosol stream, before it exits the nozzle (see Fig. 1).

Thus, the distance between nozzle and substrate can be varied over several millimeters without a significant

change of beam width, which is advantageous for 3D printing. The width of deposited ink tracks can be varied from <100 nm up to 10 mm.

FIGURE 1 – Principle of Aerosol-Jet Printing

For printed electronics mostly silver particle inks are used, as gold is expensive and copper is difficult to process due to oxidation.

After printing, subsequent thermal processing is necessary to reach electrical conductivity and sufficient adhesion. This sintering step evaporates the solvent out of the ink, removes the particles' organic coating, and forms metal agglomerations by partially melting and fusing the particles (see Fig. 2). Due to the small particle sizes the required processing temperature is much lower than the melting temperature of bulk material [4]. For silver inks sintering temperatures in the range of 200 °C are necessary. The commonly used

method is heating the entire component in a convection oven. However, this technology is time-consuming and not feasible for substrate materials with low melting temperatures, such as PC or PMMA. Due to those limitations, a variety of selective sintering technologies has been developed as alternatives, such as laser sintering, Intense Pulsed Light Sintering (IPL), microwave sintering, electrical sintering, chemical sintering, and plasma sintering, each having its own advantages and limitations [5]. Moreover they have a limited applicability for sintering on three-dimensional substrates.

Therefore, a new sintering method – selective light sintering – is presented, aiming for a technology that allows using substrate materials with low melting points and that can be applied in the MID process chain. For this, the focused, continuous light of a xenon lamp is used. Sintering experiments with various Aerosol-Jet printed structures and various PC substrates were conducted. The results were analyzed considering adhesion strength and specific resistance, which was compared to results obtained with conventional oven sintering

Nanoparticle ink:

- silver particles
- ▶ organic coating
- solvent and additives

Processing:

FIGURE 2 – Process steps to achieve conductive layers consisting of silver nanoparticle inks

EXPERIMENTAL

For light sintering a Panasonic “Soft Beam” light soldering system, based on a xenon lamp was integrated into a 5-axis handling system. The emitted polychromatic light (see Fig. 3) is focused on the printed layer with a convergence lens and moved over the layout. The focused light beam has a diameter of about 2 mm with a top-hat intensity distribution. The long focal length of about 27 mm provides good conditions for 3D processing. The light’s nominal power P_L can be regulated from 8-20 W.

The utilized ink is a silver ink with a viscosity of 50-100 cP and 45-55 wt.-% of silver. The particles are stabilized by an organic coating and have an average size of <60 nm. The solvents ethylene glycol and butanol give the ink high temperature and time stability and make it well-suited for 3D printing. For wavelengths of 400-500 nm silver nanoparticle inks show increased light absorption (see Fig. 3).

FIGURE 3 – red: emission spectrum of the xenon lamp [6]; blue: typical absorption spectrum of silver nanoparticle inks [7]

As substrate materials, three kinds of PC (glass transition temperature of 140-150 °C) were used:

- Transparent, neat PC, being highly transmissive for xenon light
- 30 % glass fiber filled PC (PC-GF), being mostly absorbent for xenon light
- PC with increased impact strength (PC-IS), also being mostly absorbent for xenon light

For better wetting, the thermoplasts were pre-treated with plasma before printing. Several layout structures common for electronics on MID were examined:

- Linear circuit tracks with a length of 25 mm and widths of 600 μm and 900 μm respectively (thickness of 12 μm and 18 μm respectively)
- Large squares of 20x20 mm² (e.g. for capacitive sensors)
- Medium-sized squares of 5.0x5.0 mm² (e. g. for contacting to the periphery)
- Small squares of 1.2x1.2 mm² (for contacting electronic chip components of the size 0805)

The electrical resistance R is measured with a 4-point probe. Adhesion is measured in pull-off tests according to the standard ASTM D4541.

RESULTS AND DISCUSSION

Transparent PC as substrate material

Light sintering experiments of linear conductive tracks showed that specific resistances of down to four times bulk silver can be achieved. For this, sintering speeds v_L up to 10 mm/s are possible. Thus, the sintering speed is in the same range as the speed of the Aerosol Jet printing process, which offers the potential to combine the print and the sinter system into one processing head to increase manufacturing efficiency.

Additional experiments demonstrated that the printed structures can be moved up to 5 mm out of the light beam focus in z-direction without significant changes of specific resistance. This property facilitates three-dimensional sintering and therefore light sintering appears well-suited for MID applications.

To compare the performance of light sintering with that of conventional oven sintering, reference experiments were conducted. Printed silver tracks were sintered in a convection oven for 90 min. at 120 °C. The results show the advantages of selective light sintering. To

prevent damage to the PC substrate, only insufficient sintering temperatures can be used with oven sintering, resulting in multiple times higher specific resistance than with light sintering (see Fig. 4).

FIGURE 4 – Specific resistances of oven-sintered and light-sintered conductive tracks

Good surface quality can be obtained at thinner sintered lines with a layer thickness of 12 μm , while sintering thicker lines with a thickness of 18 μm can lead to a ruptured, porous surface, if too much power is applied (see Fig. 5).

FIGURE 5 – Influence of light power PL on the appearance of sintered tracks (top: PL = 15 W, bottom: PL = 20 W; $v_L = 5 \text{ mm/s}$)

During sintering of thick ink structures the top layers start to sinter while there is still a high solvent content at the central/bottom layers, leading to explosive evaporation of the solvent, an effect known from other optical sintering technologies [7][8]. With light sintering, this effect can be reduced by adjusting light power and sintering speed.

The impact on the transparent substrate is little. Laser Scanning Microscopy shows small bulges on the edges of the sintered tracks. A possible explanation for this is that light irradiation causes high temperatures within

the silver layer, thus locally melting the plastic substrate by heat conduction. The profilometry also reveals the shrinkage of printed lines due to sintering. Line widths of 600 μm and 900 μm respectively after printing are reduced to 500 μm and 750 μm respectively after sintering. This accounts for a width shrinkage of about 20 % (see Fig. 6).

FIGURE 6 – Profilometry of a track with 600 μm width after printing and 500 μm after sintering

In addition to conductive tracks, also light sintering of areas with various sizes was examined. Previous research showed that a meander strategy and a 75 % overlap of the single sinter tracks (corresponding to a distance d of about 500 μm) is the best strategy to sinter areas (see Fig. 7) [9]. Additionally, the turning points of the moving light spot during sintering were set outside the squares. This way, homogenous surfaces and well-sintered layers can be achieved for all considered area sizes without thermal damage of the silver layer and the substrate.

FIGURE 7 – Sintering strategies for large (a), medium (b) and small (c) squares

In addition to electrical conductivity, also adhesion strength was analyzed, conducting pull-off adhesion tests. On the very smooth surface of the used samples adhesion strength is 3.1 N/mm². On rougher, less transparent plastic surfaces, significantly higher adhesion strengths can be expected. These results show that adhesion strength is sufficiently high for conductive tracks. The question if this is also sufficient for assembling components in Surface Mounted Technology (SMT) on light sintered structures, will have to be analyzed in future investigations.

Non-transparent PC as substrate

Further sintering experiments were conducted with two filled PC types as substrate material. While unfilled PC is largely transmissive for xenon light and therefore remains almost unaffected by it, the two examined filled types PC-GF and PC-IS are highly absorbent of xenon light. This leads to severe substrate damage and non-conductive silver layers because high thermal stress causes decomposition of the silver ink and interruptions of the printed structures (see Fig. 8, images 1 and 3).

For this reason a variation of light sintering was investigated, allowing also the sintering on non-transparent substrates. An optical glass filter is applied underneath the convergence lens that only transmits visible wavelengths, for which silver ink features high absorption (see Fig. 4). The rest of the xenon light, however, that barely contributes to sintering, but possesses a high intensity (see Fig. 3) is filtered out. Even when using higher light power, filtering leads to significantly lower substrate damage and better sintering results (see Fig. 8, images 2 and 4).

FIGURE 8 – Influence of optical filtering on PC-IS (1 and 2) and PC-GF (3 and 4)

For the PC-IS with enhanced impact strength (Fig. 8, images 1 and 2), specific resistances of nine times *bulk silver* could be reached. For the glass fiber-filled PC-GF (Fig. 8, images 3 and 4), the specific resistance is with eight times *bulk silver* even slightly lower. However, it also exhibits stronger substrate damage, probably due to high reflection and deflection of the light caused by the glass fibers [10].

CONCLUSION

Integrating Aerosol Jet Printing into the MID process chain offers high potentials for a highly flexible and cost effective manufacturing. With this additive technology thermoplastic substrates can be metallized using nanoparticle silver inks. For the required thermal post-processing of the deposited inks, selective light sintering is a very promising technology.

Sintering experiments of conductive tracks and various areas led to high electrical conductivities, good adhesiveness, and good surface qualities. On transparent PC specific resistances of up to four times *bulk silver* were reached with minimal substrate damage, a result multiple times better than using conventional oven sintering. On non-transparent PC specific resistances of up to eight times *bulk silver* were obtained, using optical filters to reduce thermal damaging.

To establish light sintering of printed silver structures as a process for the metallization of MID and to ensure a broad spectrum of possible applications, necessary topics of future research are assessing long-term reliability and the technology's suitability for other relevant thermoplastic substrate materials and ink formulations.

In addition to practical experiments, developing adequate simulation models for the printing and sintering processes will increase process understanding, ensure uniformly high sintering qualities, and make the determination of process parameters faster and more reliable.

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REFERENCES

1. J. Franke, *Räumliche elektronische Baugruppen (3D-MID)*, Carl-Hanser-Verlag, Munich, 2013.
2. P. Amend; T. Frick; M. Schmidt in LEF 15 Proceedings, Fuerth, 2012.
3. M. Hedges in MID 9 Proceedings, Fuerth, 2010.
4. P. Buffat; J-P. Borel, *Physical Review A* 1976, 13, No. 6.
5. M. L. Allen, PhD Thesis, Aalto University, 2011.
6. Zeiss Campus: Fundamentals of Xenon Arc Lamps. <http://zeiss-campus.magnet.fsu.edu/articles/lightsources/xenonxen.html> – accessed April 5, 2013.
7. K. Mackawa et al. in ECTC 59 Proceedings, San Diego, 2009.
8. T. Falat et al. in IMAPS 8 Proceedings, Brighton, 2011.
9. J. Hoerber et al. in LEF 16 Proceedings, Fuerth, 2013.
10. J. Korte in *Handbuch Kunststoffverbindungs-technik*, G. Ehrenstein, Ed; Carl Hanser Verlag Munich, 2004; 232-256.