Sensors and Actuators A 162 (2010) 198–201

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

INKtelligent printed strain gauges

M. Maiwald*, C. Werner, V. Zoellmer, M. Busse

Fraunhofer Institute for Manufacturing Technology and Applied Materials Research, Wiener Str. 12, 28359 Bremen, Germany

ARTICLE INFO

Article history:
Received 29 September 2009
Received in revised form 19 February 2010
Accepted 21 February 2010
Available online 1 March 2010

Keywords:
INKtelligent printing
Maskless deposition
Non-destructive testing
Strain gauges

ABSTRACT

Strain gauges for non-destructive testing could successfully deposited by INKtelligent printing®. Metal strain gauges are fabricated by Aerosol Jet® technology, starting with deposition of a polymer isolation layer, followed by a printed metal layer and finally an encapsulation to protect the printed sensor. Characterizations of printed and sintered sensors show a good densification of the printed material which allows high electrical conductivity up to 70% of bulk value. Performance tests of printed sensors show a reproducible and reliable functionality in terms of strain measurements.

1. Introduction

Non-destructive testing, e.g. structural health monitoring (SHM), is a growing market covering lots of application areas like automotive and aerospace [1]. Here, INKtelligent printing® offers a new approach to apply sensor structures directly on surfaces and components with the help of maskless printing technologies, e.g. Ink-Jet or Aerosol Jet®. The benefit is a miniaturized high resolution sensor structure on planar and even non-planar surfaces with continuous measurement possibility [2]. INKtelligent printing® starts with a CAD (computer aided design) layout of the sensor structure. An important issue is the material selection for the deposition of the sensor. In general, printable materials for Ink-Jet and Aerosol Jet® are suspensions containing nanosized particles but also other materials, for example polymers, are possible to be deposited [3,4]. Finally, the suspensions are printed and thermally activated to evaporate the fluid and compact the structures for desired properties. This could be electrical conductivity of a metal or curing of a polymer. Especially printed strain gauges are interesting due to the possibility of non-destructive and continuous measuring of tensile and compressive stress on surfaces and components.

In the present paper, printed silver strain gauges are discussed in terms of material properties and functionality. The fabricated sensors are printed on metal substrates to demonstrate the possibility of direct deposition of sensor structures on surfaces and components. Printed sensor structures consist of three layers, a printed isolation layer, a printed silver sensor structure and a printed encapsulation. SEM (scanning electron microscope) pictures of the silver layer show homogeneous and dense surfaces after sintering at 350 °C but there are still some small defects in the printed structure. Measured conductivities are very high and reach up to 70% compared to bulk silver. Sensor functionality is tested with an additional printed strain gauge for temperature compensation due to the high linear temperature coefficient of resistance (TCR). A commercially available foil strain gauge from HBM Inc., is used as reference sensor. The measurements show a reliable signal of the printed strain gauge over 10^3 cycles, in spite of few pores inside the metal structure. Besides the signal is constant and shows no drift due to the printed temperature compensation.

2. Experimental

2.1. Maskless deposition and sintering processes

Strain gauges are fabricated using Aerosol Jet® technology from Optomec, Inc., (see Fig. 1). Aerosol Jet® allows the deposition of suspensions covering a viscosity range from 0.7 to 1000 mPa s and a particle size up to 1 μm for metals. The functionality of the printing process is shown in Fig. 1 [5]. A so-called "Atomizer" produces an aerosol from the suspension which is carried by a transport gas to the print head. The aerosol is produced either with the help of an ultrasonic source or with the help of a high velocity air stream. The aerosol droplet diameter is between 1 and 5 μm which corresponds to a volume of some femtolitres [6]. Inside the print head a sheath gas (e.g. nitrogen) focuses the aerosol beam and also prevents clogging of the nozzle. Besides the focused aerosol beam allows printing on planar and non-planar surfaces with a minimum line width of around 10 μm. The printing process is followed by a thermal

* Corresponding author. Tel.: +49 (0) 421 2246 124.
E-mail address: marcus.maiwald@ifam.fraunhofer.de (M. Maiwald).

0924-4247/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2010.02.019

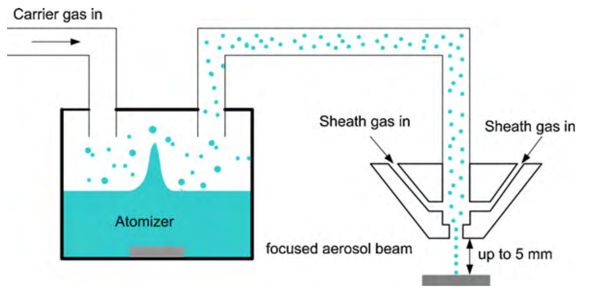

Fig. 1. Schematic diagram of Aerosol Jet® functionality from Optomec, Inc.

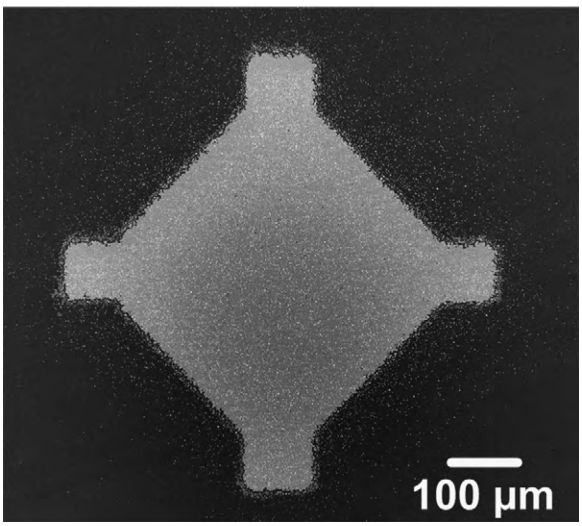

Fig. 2. SEM picture printed van der Pauw structure.

activation step to evaporate the fluid and to compact the printed structures. Here, furnace sintering of printed sensor structures is presented.

2.2. Structural and electrical characterization

Printed and sintered structures are characterized optically by SEM as well as by using a focused ion beam (FIB) SEM to investigate the cross-section of the structures. Electrical conductivity is measured with four point measurements using a van der Pauw test geometry (see Fig. 2) as well as an EP 4 wafer prober from Suss Micro Tec and a Keithley DMM 2001. The height of the printed structures is measured with a white light interferometer (Microprof) from FRT.

2.3. Strain measuring

For testing the sensor performance printed strain gauges are deposited on metal substrates with 150 mm × 25 mm × 3 mm dimensions. Substrates are fixed in a tensile tester and periodically stressed. An additional foil strain gauge is glued on top of the metal substrate as reference. Both strain gauges are connected to a Wheatstone measuring bridge where the bridge voltage is connected to a measuring amplifier. The applied force as well as the resistance change is displayed on a computer (see Fig. 3).

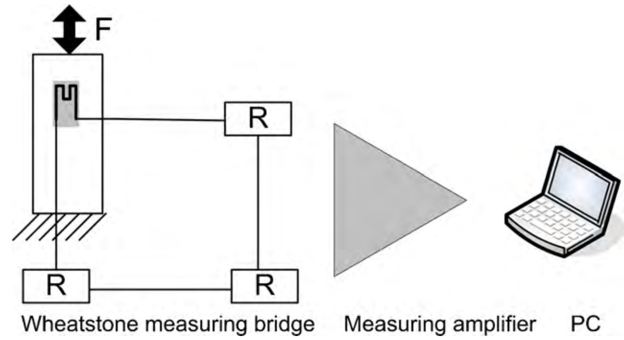

Fig. 3. Schematic diagram measuring setup.

3. Results and discussion

3.1. Structural properties of printed silver

A commercially available silver ink from Advanced Nano Products Co., Ltd., is used for strain gauge printing. This ink contains about 50–60 wt.% of silver with a mean particle diameter of about 20 nm. Besides there are around 20–40 wt.% solvent as well as around 10–20 wt.% additives in the ink [7]. Additives are necessary to avoid agglomeration and sedimentation of the silver particles as well as to lower the sintering temperature. The following figures show SEM pictures of the ink before printing (Fig. 4a), after Aerosol Jet® deposition (Fig. 4b) and after furnace sintering at 350 °C (Fig. 4c) under hydrogen atmosphere (60 min, heating rate 5 K/min). The ink has a homogeneous particle size distribution without agglomerates before printing. After deposition the particles agglomerate to silver spheres with a diameter of around 1 µm and form a porous structure. The reason is the mechanical stress during aerosol transportation from the atomizer to the print head. After sintering at 350 °C the silver particles are connected due to diffusion processes and the surface is dense without pores. Cross-sectional analysis reveals only some small defects in the sintered structure (see Fig. 5) caused by agglomeration after printing as well as evaporated additives in the ink.

3.2. Electrical characterization

Fig. 6 shows the conductivity of printed silver structures in dependence of the sintering time. Here, sintering temperature is 350 °C and sintering time varies from 60 to 600 min. There are no large differences in the measured conductivities of the silver. The conductivities are very high and reach around 50–70% compared to bulk silver ($6.25 \times 10^7\,S\,m^{-1}$) [8]. Higher conductivities are not possible due to the pores in the structure and the additives in the ink which remain inside the structure after sintering. Both effects decrease the electrical conductivity compared to bulk material.

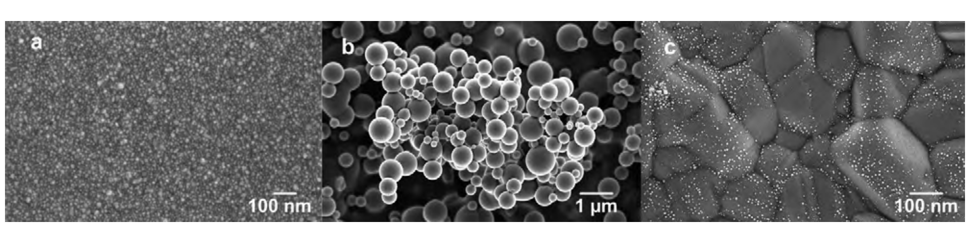

Fig. 4. SEM picture (a) silver ink, (b) silver ink after aerosol printing and (c) silver ink after aerosol printing and furnace sintering @ 350 °C, 60 min, heating rate 5 K/min.