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Direct printing of strain sensors via nanoparticle printer for the applications to composite structural health monitoring

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Abstract

A newly developed nanoparticle printer is presented for high resolution pattering of conductive nanoparticles onto the carbon and glass fiber reinforced composites. The nanoparticles are aerodynamically focused to generate nanoparticle beam for high resolution patterns. The resulting conductive patterns are evaluated for the strain measurement of composites for structural health monitoring (SHM). A series of strain sensors are printed onto the composites and their performances are characterized in terms of gauge factor, measurable range, and etc. The presented work leverages the advanced techniques of process and part monitoring of composite manufacturing as well as for the SHM of the composite.

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Keywords: Direct printing; strain sensor; nanoparticle printer; composite health monitoring

1. Introduction

Structural health monitoring (SHM) has gathered a significant importance for the aerospace, civil and mechanical engineering infrastructures [1]. With the developments and efforts in the sensor technologies, monitoring algorithms, and system maintenance models [2-4], SHM has contributed to the efficient engineering tool for the management of system, with reducing repair cost and downtime of the structures or systems.

One of the most essential in the SHM is collecting various kinds of physical quantities by the appropriate sensors, such as displacements, forces, vibrations, acoustic emissions, and so on [5]. With respect to the designed purpose or function of the system, single or multiple types of sensor signals were collected and analysed for the operation diagnosis.

Among various measurable sensor signals, mechanical strain is the most commonly used one, because it is easy to implement and represents the system's healthy status well, delivering lots of physical information including the damaged locations of the structures [6].

The relevant study is particularly important for the composite which is a promising engineering material due to its high strength and low weight. While composite has been used for numerous applications, including transportation, sports goods, and electronic devices, it usually requires much cost and time for repair when they are damaged, compared to other engineering materials. In addition, it is not easy to embed sensors inside the composite structure, because it may cause serious damages to the structure such as delamination or property degradation. In this regard, an effective monitoring solution, avoiding the possibilities of those damages, remains challenges for the SHM purpose of composite structures.

Recent advances in inkjet printing techniques have shown lots of promise for the sensor printing, thanks to its easiness and cost effectiveness [7,8]. The directly printed sensors can be flexibly designed and fabricated for various surfaces and substrates for their sensing purposes. Although lots of studies have been presented for the improvement of inkjet technique,

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the feasibility of printing on a variety of substrate has been issue, because the adhesion between the printing material and the substrate affects the functionality of the printed features [9-10]. Therefore, it is worthwhile to investigate new direct printing method for the feasibility improvement of the sensing applications, particularly the strain measurement applicable to the SHM of composite.

In this study, we present a directly printed strain sensor with solvent-free Silver nanoparticles for the SHM purpose of composite. The strain sensor is embedded into the composite repair patch and its performance is evaluated in terms of the gauge factor, measurable strain range, and the compatibility to various substrates. The aerodynamically focused nanoparticle (AFN) printer is utilized [11], which is a dry and room temperature direct printing technique of solvent-free inorganic nanoparticles, for the strain gauge patterns onto the carbon and glass reinforced plastics (CFRPs and GFRPs). The process parameters of the AFN printer (the excitation valve timing and the stage speed) are investigated and optimized to achieve high resolution (order of 10 μm) conductive patterns. With the optimized printing conditions, successful strain sensors are demonstrated onto various substrates, including the GFRPs and CFRPs. The characteristics of the printed sensors are assessed and compared to a commercial strain gauge by bending tests. The printed and embedded sensors can be used for not only the entire repair process monitoring, but also the SHM as well as the non-destructive evaluation (NDE) purposes of the repaired composites during the service periods.

2. Direct printing of conductive nanoparticles

The nanoparticle printer based on the aerodynamic focusing of nanoparticles, is used for direct patterning of inorganic nanoparticles without solvent, at room temperature [11]. During the process, nanoparticles are focused into a highly focused nanoparticle beam with high impact speed by the effect of aerodynamic focusing [11-12], which is induced by the fast control of excitation and purging. As the process is solvent-free and room temperature direct printing method, it has some advantages for flexibility and compatibility, compared to other conventional printing method such as inkjet printing [11]. Using the nanoparticle printer, continuous conductive patterns of dry nanoparticles are utilized, presenting the versatile capabilities of printed strain sensor, i.e., tunable sensitivity (gauge factor, G.F.), design flexibility, reliable performance, and etc.

In this section, the process parameters of nanoparticle printer for the patterning of Silver nanoparticles (<100 nm, Sigma Aldrich), onto various engineering plastic films, such as polyethylene (PE) and polyimide (PI), are studied and summarized. Those films can be effectively used as the electric insulation (backing layer) between the CFRPs or GFRPs and the conductive nanoparticle patterns. In the nanoparticle printer, the nanoparticle aerosols are generated and aerodynamically focused by the carrier gas, so their speed at the impact and focusing are largely affected by the amount of carrier gas, gas pressure, and nozzle.

Among numerous process parameters of the nanoparticle printer, we reduced those conditions into two major parameters, directly affect the continuous line patterns of the strain sensor. Those parameters are the valve excitation timing, Δ and the speed of collecting substrate, V_S. In Fig. 1, the simplified schematic illustration of the nanoparticle printer is presented depicting those two important process parameters. For given compressor pressure (P_{comp} = 0.1 MPa), chamber pressure ($P_{chamber}$ = 100 Pa), and control period (T_{cycle} = 1 sec), the excitation valve timing, Δ, and the stage speed, V_S, are investigated for the continuous conductive patterns.

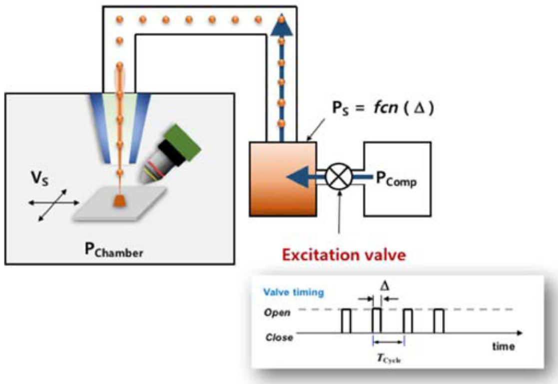

Fig. 1. A simplified schematic illustration of the nanoparticle printer based on the AFN printer.

Focused on the control of the pattern width and height, the selected excitation valve timing was 40 ms and the stage speed was 10 μm/s. A representative printing demonstration (in-situ observation of the nanoparticle printing) is shown in Fig. 2(a). Strain gauge pattern with narrow (around 50 μm width) patterns are printed successfully. Fig. 2(b-c) show the pattern dimensions and its 3-dimensional geometry, respectively. Fig. 2(d) captures the optical image of printed strain sensor (onto the PE film) and the magnified image of printed line, taken by the optical microscope is presented in Fig. 2(e). The same strain gauge patterns are printed onto PI film (Fig. 2(f)) as well as the CFRP prepreg (Fig. 2(g)).

3. Strain sensor printing onto composites

The printing qualities onto various substrates, including GFRPs and CFRPs are investigated, for the prototyping of the printed nanoparticle strain sensors onto composites. The sensors are designed similar with the commercial strain gauge, with thin and long pattern in longitudinal direction and thick and short pattern in latitudinal direction. It helps not only to improve sensitivity in the longitudinal direction but also to reduce the effect on deformation in the latitudinal direction. Designed sensor has 8 lines in the longitudinal direction with a length of 7 mm.

In general, printing on the composite structure is more difficult than conventional hard substrates, i.e., metal or silicon substrate, because the printing characteristics might vary on the polymer resin used in the composite structure. In this section, the printed strain sensors with various backing layers on the top