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**LASER SINTERING OF PRINTED SILVER THIN FILMS
FOR FABRICATION OF STRAIN SENSOR DIRECTLY ON
A STRUCTURE (Preprint)**

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Laser sintering of printed silver thin films for fabrication of strain sensors directly on a structure

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ABSTRACT

Piezoresistive strain sensors, commonly known as resistance strain gauge, have many important applications. In this work, an alternative method to fabricate piezoresistive strain sensors directly on the structure of interest is demonstrated using a particle-free silver ink as the sensing material. The sensing material is first printed as a rectangular film on the structure of interest and a conductive serpentine pattern is generated by selective laser sintering. Only the material exposed to the focused laser is sintered and becomes conductive. The rest is washed-off by 1-dodecene solvent, leaving only the serpentine pattern, which serves as the piezoresistive strain sensor. This alternative method eliminates the need for a carrier or backing substrate and thus improves the mechanical coupling between the sensing material and the structure of interest. It also removes reinforcement effect due to the stiffness of the carrier substrate. Results from electrical characterization revealed that laser sintering power is a crucial parameter that influences fundamental properties of the sensing material such as electrical conductivity and work function. In addition, it was observed that there exists an optimum laser sintering power that results in a maximum gauge factor (GF). For strain sensors, the GF is the most important parameter because it is the measure of sensor sensitivity. When the particle-free silver ink was printed as a serpentine pattern followed by thermal sintering on a hot plate, a lower GF was measured. This shows that the alternative method to fabricate piezoresistive strain sensors is more attractive than printing the serpentine pattern then thermally sintering it.

1. INTRODUCTION

Strain sensing is already considered a mature technology. Strain sensors, which are commonly called strain gauges, are widely available commercially. These sensors find many applications in the fields of healthcare, structural health monitoring, robotics, automotive and aerospace [1-4]. Despite the commercial availability of strain sensors, they still constitute an active field of research. This is primarily motivated by some limitations exhibited by commercial sensors. For example, they typically require very careful mounting. The structures of interest, such as airplane wings, that need the strain sensors usually require tedious surface preparation. Improper installation can lead to unreliable strain measurements. Another motivation is the availability of additive manufacturing (AM) technology, which has revolutionized how devices are fabricated. This technology provides rapid prototyping capabilities, lower fabrication costs and non-planar device fabrication capabilities. It has become an enabling technology for many wearable sensor applications [5]. Thus, AM is a very attractive approach to fabricating wearable strain sensors.

There are different techniques for strain sensing but resistance-based methods are still the most widely used. Their sensing mechanism relies on the piezoresistive property of the sensing material. It is worthwhile to note that not all conductive materials exhibit piezoresistive property, which is the ability to change the intrinsic electrical resistivity when strain is applied [6]. Commercial piezoresistive strain sensors, also known as resistance strain gauges, are typically made of metal alloys such as constantan. They are packaged in a carrier or backing substrate such as polyimide, and mounting them on structures of interest is not trivial. The carrier or backing substrate of commercial strain sensors may reinforce the structure under test because it has a non-zero elastic modulus. This is called the reinforcement effect. It can lead to significant measurement errors, particularly when testing lower-modulus plastics and composites. One way to circumvent the reinforcement effect is to eliminate the carrier material. In this work, an alternative method for fabrication of piezoresistive strain sensors that eliminates the carrier material is demonstrated. The method fabricates the strain sensor directly on the structure of interest by additive technique. It can provide better mechanical coupling between the sensing material and the structure. It can also eliminate the tedious preparation steps that are usually involved in the installation of commercial strain gauge. The method is based on laser sintering and it is not limited to a single sensing material. This work focuses

on a commercial particle-free silver ink as the piezoresistive sensing material. It investigates how the laser sintering power affects the fundamental material properties relevant to strain sensing.

2. EXPERIMENT

An FR4 printed circuit board (PCB) was employed as the structure of interest to demonstrate the alternative method for direct fabrication of strain sensors. The PCB, which was cut as a flexible cantilever, had double-sided copper cladding, so a thin insulating interlayer was inserted between the sensing material and the PCB. The interlayer was fabricated by doctor blading a thin UV-curable adhesive from Norland (NEA -121). The sensing material was a commercially available silver ink manufactured by Electroninks (product number EI-616). It was printed as a 5 mm x 8 mm rectangular film on the insulating interlayer by an aerosol-jet printer (Optomec AJ-300) equipped with 830 nm laser for sintering. After printing, a serpentine pattern terminated by large contact pads was generated on the silver film by selective laser sintering. This was followed by a washed-off process using 1-dodecene solvent to remove the material not exposed to the laser. This process leaves only the serpentine pattern, which serves as the piezoresistive strain sensor. For sensor testing, thin copper wires (AWG 40) were attached to the contact pads of the serpentine pattern using a thermally curable silver adhesive from Creative Materials. Curing of the adhesive was performed on a hot plate at 110°C for 15 min. Figure 1(a) shows a photo of the actual serpentine strain sensor on the PCB. The gauge factor (GF) of the sensor is determined by measuring the change in resistance of the sensor when a known strain is applied. To apply strain to the sensor, one end of the PCB cantilever is clamped while the other end is free to be displaced vertically by a known distance. This distance, which is controlled by a caliper, is used to calculate the applied strain. Figure 1(b) maps the strain on the PCB at maximum vertical displacement (50 mm) as calculated by COMSOL. The actual strain on the PCB as a function of vertical displacement was also calibrated using a commercial strain gauge with known GF [Fig. 1(c)]. The details of the GF measurement has been described in previous publication [7].

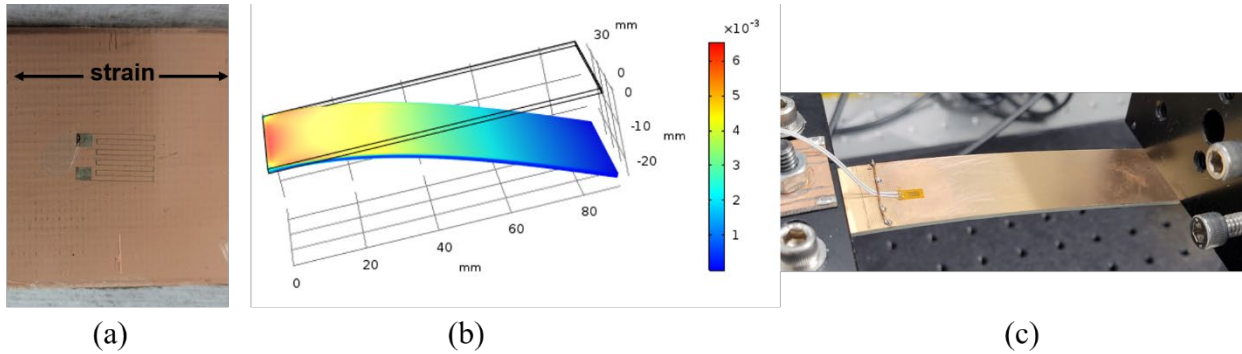


Figure 1. (a) Photo of an actual strain sensor fabricated directly on the PCB cantilever by the method described in this work. (b) Map of the strain on the PCB cantilever at maximum vertical displacement (50 mm) as calculated by COMSOL. (c) Calibration of actual strain on the PCB cantilever as a function of vertical displacement using a commercial strain gauge with known gauge factor.

The effect of laser power on the fundamental material properties of the laser sintered silver films and traces was investigated. These properties were electrical conductivity, work function and GF. Conductivity was measured by four-point probe technique while work function was measured by Kelvin probe technique. In the investigation, laser power was varied from 60 mW to 140 mW while the scan speed was kept constant at 5 mm/s. Further, the performance of a strain sensor fabricated by the alternative method described here was compared to a sensor fabricated by aerosol-jet printing the serpentine pattern directly on the NEA-121 interlayer followed by thermal sintering the pattern on a hotplate at 110°C for 1 h. The performance comparison was based on a cyclic bending test. In this test, the change in the sensor resistance is measured continuously while a pulsed strain is applied. The pulse has period of 60 s at 50% duty cycle. It is generated by displacing the free end of the cantilever periodically at constant vertical displacement.

3. RESULTS AND DISCUSSION

The alternative fabrication method described here is based on laser sintering, which is a thermal process that only heats up locally the spot that is exposed to the laser. It is compatible with any printable sensing material that requires post-print

thermal sintering to be electrically conductive. An example of such material that has been explored is a graphene ink [7]. By scanning the laser in a controlled fashion over a film printed from such ink, conductive patterns on the film can be generated. Despite good GF of this graphene ink, its adhesion is limited to very few materials. Since adhesion of the sensing material to the structure of interest is a very important consideration for strain sensing, other sensing materials with strong adhesion to a broad range of material structures need to be explored. One potential candidate is the particle-free silver ink loaded with adhesion promoter, which is commercially sold as EI-616 by Electroninks. Silver has been reported to demonstrate piezoresistive effect and it has been explored for strain sensing applications [8]. It is widely available as a printable ink for different direct printing tools. The EI-616 ink is particularly appealing as compared to other commercial silver inks for several reasons. First, it adheres well to a broader range of substrate materials. Its post-print sintering temperature requirement is relatively lower. It can be sintered at temperatures as low as 100°C and obtain conductivity that is sufficient for strain sensing. Lastly, if the printed film is not sintered, it can be easily washed-off by 1-dodecene solvent. This makes it possible to generate the serpentine pattern on the printed silver film by selective laser sintering followed by the solvent washed-off step to retain only the sintered serpentine pattern.

The manufacturer of EI-616 ink designed it for thermal sintering and they did not test it for laser sintering. The mechanism of laser sintering may be a more complex process for the EI-616 as compared to thermal sintering on a hot plate due to the high content of adhesion promoter. Thus, as a first step to understanding this laser sintering process, the effect of the laser power on the electrical conductivity and work function of EI-616 traces and films was investigated. The results are presented in Figure 2. The peak in conductivity at 100 mW reveals that there exists an optimum laser power. The low conductivity of EI-616, which is an order of magnitude lower than what has been reported on printed silver [9], is most likely due to the high loading of adhesion promoter. For strain sensing applications however, achieving better adhesion is more important than achieving higher conductivity. The correlation between conductivity and work function strongly suggests that laser power is a crucial parameter that influences the fundamental properties of EI-616.

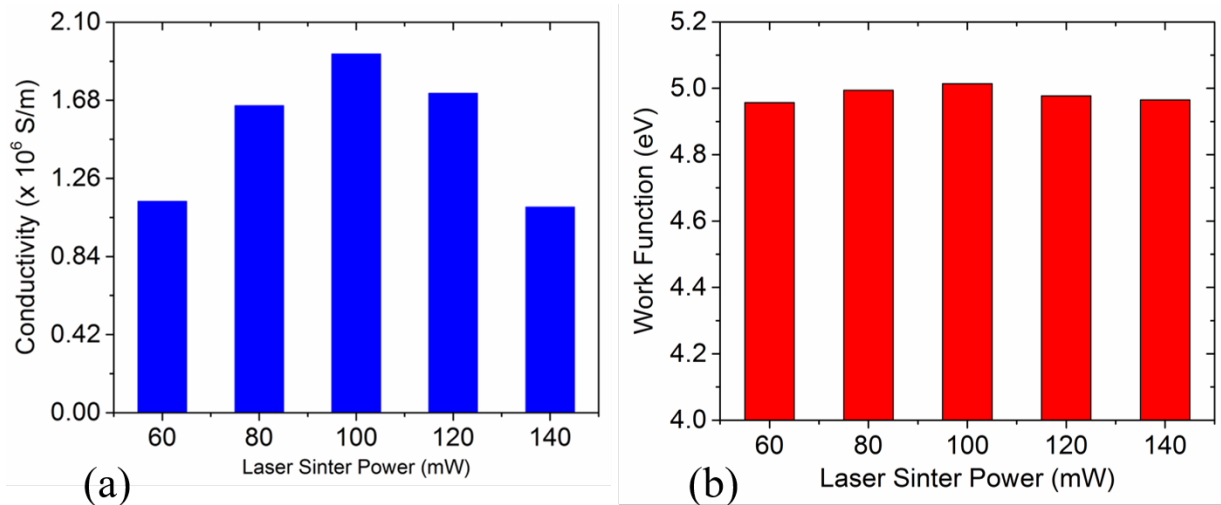


Figure 2. (a) Electrical conductivity of EI-616 traces generated by different laser sintering power. (b) Work function of EI-616 films generated by different laser sintering power.

To further confirm the importance of laser power, specifically for strain sensing, the GF of strain sensors fabricated at different laser power levels was compared. Figure 3(a) confirms that laser power indeed influences the GF, which is the most important parameter for strain sensors. Further, it demonstrates the existence of an optimum laser power that results in the highest GF. For EI-616 printed on NEA-121 interlayer, the optimum laser power is around 70 mW. However, this optimum power depends on the thermal conductivity of the interlayer or the substrate in general. Substrates play a role during laser sintering because they partially diffuse the heat from the material being laser sintered. Figure 3(b) depicts the response to increasing strain of the serpentine strain sensor generated by 70 mW laser power. The response is plotted as a change in resistance dR divided by the un-strained resistance R versus strain. It can be observed that the response is fairly linear up to 0.4% strain level. The slope of the fitted line, which is 2.4, represents the GF of the sensor. This is slightly higher than that of commercial resistance strain gauges made of constantan, which is only 2. The strain sensor fabricated by the alternative method based on laser sintering also exhibited better performance as compared to its counterpart

fabricated by printing the serpentine pattern followed by thermal sintering on a hotplate. This is evidenced in Fig. 3(c), which plots the dR/R versus time of the two strain sensors as pulsed strain is applied. In this test, the amplitude of the pulsed strain is 0.0021. Since the two sensors were fabricated side by side on the same PCB cantilever, both are subjected to the same strain level. Therefore, comparing dR/R is equivalent to comparing GF. From the figure, dR/R of both sensors goes back to zero every time the strain is removed, indicating that the un-strained resistance does not drift. This is a very important property of the strain sensing material. When strain is applied, the sensor fabricated by the alternative method demonstrates higher dR/R which is equivalent to a GF that is 2.8 times higher than that of the sensor fabricated by printing the serpentine pattern followed by thermal sintering on a hotplate.

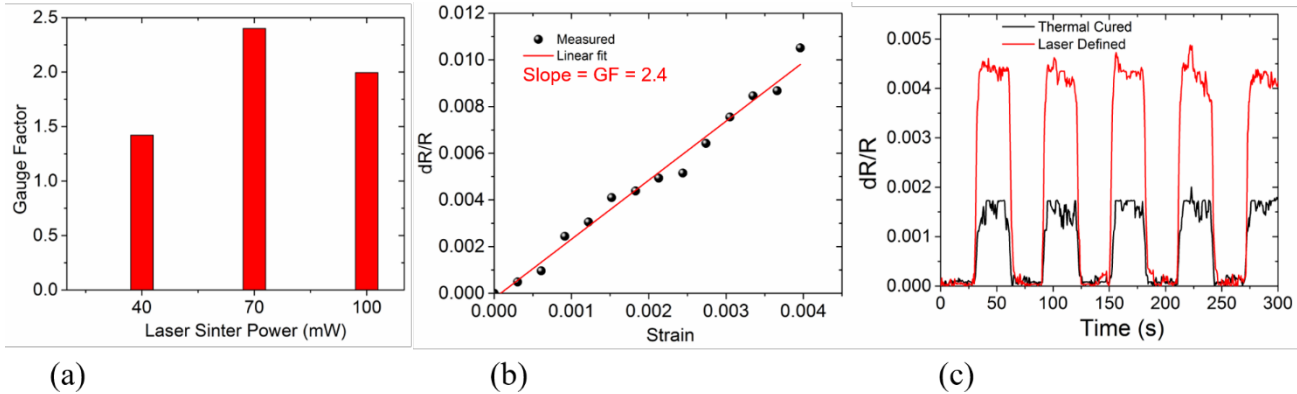


Figure 3. (a) Gauge factor (GF) of serpentine strain sensors generated by different laser sintering power. (b) Response of the serpentine strain sensor generated by 70 mW laser sintering power to increasing strain. (c) Performance comparison between strain sensors fabricated by different methods (laser sintering then wash-off vs. traditional printing then thermal sintering).

4. CONCLUSION

An alternative method to fabricate piezoresistive strain sensors directly on the structure of interest is demonstrated using a commercial particle-free silver ink as the sensing material. It eliminates the need for a carrier or backing substrate. This method can therefore improve the mechanical coupling between the sensing material and the structure of interest. It can remove the reinforcement effect, which usually occurs when testing soft materials due to the stiffness contributed by the carrier substrate. The direct fabrication approach also avoids the tedious preparation steps that are commonly involved in the installation of commercial strain gauges. Gauge factor (GF) is the most important parameter for strain sensors because it is the measure of sensitivity. This work revealed that the laser sintering power is a crucial process parameter that influences the GF of particle-free silver ink. An optimum laser power was identified and it resulted in a GF of 2.4, which is higher than that of commercial resistance strain gauges made of constantan alloy. Furthermore, the strain sensor fabricated by this alternative method based on laser sintering exhibited a GF that is 2.8 times higher than its counterpart fabricated by printing the serpentine pattern followed by thermal sintering on a hot plate.

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REFERENCES

- [1] Guo, J., Zhou, B., Zong, R., Pan, L.c, Li, X., Yu, X., Yang, C., Kong, L. and Dai, Q., "Stretchable and highly sensitive optical strain sensors for human activity monitoring and healthcare," *ACS Appl. Mater. Interfaces* 11, 33589 (2019).
- [2] Zymelka, D., Togashi, K. and Kobayashi, T., "Carbon-based printed strain sensor array for remote and automated structural health monitoring," *Smart Mater. Struct.* 29, 105022 (2020).
- [3] Lei, J-F. and Will, H.A., "Thin-film thermocouples and strain-gauge technologies for engine applications," *Sensors and Actuators A* 65, 187 (1998).

- [4] Da Silva, J.G., De Carvalho, A.A. and Da Silva, D.D., "A strain gauge tactile sensor for finger-mounted applications," *IEEE Trans. Instrumentation & Meas.* 51, 18 (2002).
- [5] Takeda, Y., Hayasaka, K., Shiwaku, R., Yokosawa, K., Shiba, T., Mamada, M., Kumaki, D., Fukuda, K. and Tokito, S., "Fabrication of ultra-thin printed organic TFT CMOS logic circuits optimized for low-voltage wearable sensor applications," *Sci. Report* 6, 25714 (2016).
- [6] Fiorillo, A.S., Critello, C.D. and Pullano, S.A., "Theory, technology and applications of piezoresistive sensors: a review," *Sensors and Actuators A* 281, 156 (2018).
- [7] Aga, R.S., Webb, T.M., Pandhi, T., Aga, R., Estrada, D., Burzynski, K.M., Bartsch, C.M. and Heckman, E.M., "Laser-defined graphene strain sensor directly fabricated on 3D-printed structure," *Flexible and Printed Elec.* 6, 032001 (2021).
- [8] Park, J., Nam, D., Park, S. and Lee, D., "Fabrication of flexible strain sensors via roll-to-roll gravure printing of silver ink," *Smart Mater. Struct.* 27, 085014 (2018).
- [9] Mahajan, A., Frisbie, C. and Francis, L., "Optimization of aerosol jet printing for high-resolution aspect ratio silver lines," *ACS Appl. Mater. Interfaces* 5, 4856 (2013).