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Considerations in printing conductive traces for high pulsed power applications

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ABSTRACT

The effect of different substrates, inks and sintering methods on the breakdown of a printed conducting trace subjected to a single millisecond-range pulsed current was investigated. The breakdown current density (J_b) of a trace was found to be strongly dependent on substrate thermal diffusivity, which dictates the peak temperature and the cooling rate of the trace. As an example, a 102% increase in average J_b was observed in switching substrate from glass slide to sapphire. Different inks resulted in significant J_b deviation due to their distinct microstructure difference. Traces with dense microstructure exhibited an average J_b that is 42% higher than their porous counterpart. Different sintering methods also resulted in varying J_b. Traces thermally sintered on a hot plate demonstrated an average J_b that is 74% higher than their laser sintered counterpart. Finally, a simple concept that effectively dissipates heat from the trace was explored. It prevented breakdown when the traces were subjected to a single firing pulse used in detonation. Results from this work offer important considerations in printing conductive traces for high pulsed power applications.

1. Introduction

Additive manufacturing (AM) has started revolutionizing how things are made. In the medical community, its application covers from tissue fabrication to creation of customized prosthetics [1]. It has become an enabling technology for many wearable sensor applications [2]. In the defense sector, AM is being explored to address technical challenges in fuze technology and ordnance sciences [3]. One such challenge is to decrease the time it takes to refresh critical components. An important component in fuze technology that can benefit from AM is conductive trace. Printing of conductive trace, which is inherently additive, is attractive for many other electronic circuit and devices. It can provide different functionality such as antenna [4], electrode [5] and interconnect [6]. It is highly advantageous for rapid prototyping because circuit design can be immediately adjusted to compensate for device performance.

Many inks for printing conductive traces are now readily available commercially. Over the years, their performance in terms of electrical conductivity σ has improved significantly. Additionally, substrate compatibility is no longer a major concern due to the wide variety of available ink formulations. Recent advances in photonic sintering tools now also allow the use of polymeric substrates with a low thermal budget. Most applications of conductive traces, however, are in the low power regime where the most important metric is σ. For that reason, the majority of ink manufacturers have focused on the optimization of σ to make it as close as possible to their bulk material counterpart. For silver (Ag) ink, the σ value has already approached half of bulk Ag [7]. The power handling capability of printed conductive traces is an important, yet largely unstudied property for high power applications, particularly for carrying high pulsed current. In fuze applications for example, a conductive trace can deliver the firing pulse that activates an electric detonator [8]. Thus, it is a primary requirement for the trace to reliably handle high peak current density to minimize its physical dimension. This is important for reducing the footprint and weight of the fuze electronics. However, the behavior of printed traces subjected to a high pulsed current has not been well studied in the literature, particularly the breakdown due to a single pulsed current. Maximizing the breakdown current, which is the pulsed current that causes breakdown, necessitate the understanding of how the choice of substrate, ink and sintering method influence the breakdown mechanism.

In this work, several substrates with varying thermal properties are employed to quantify the effect of substrate on the breakdown current.

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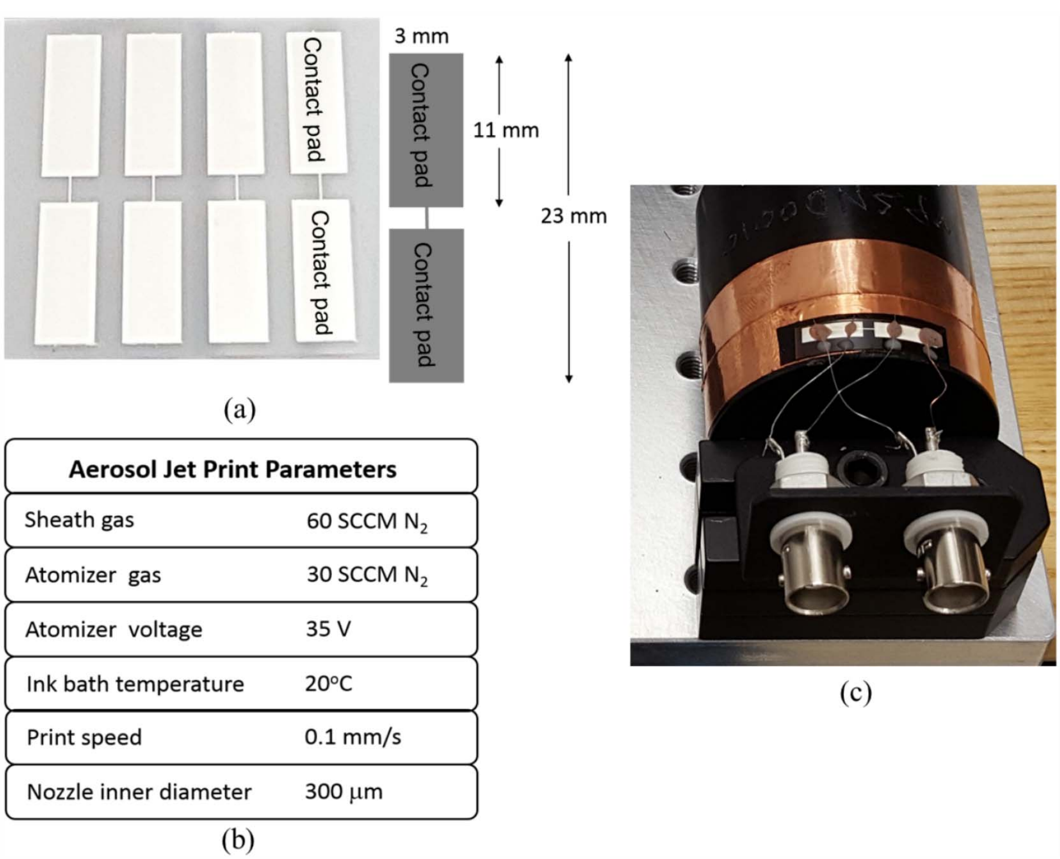
Two commercially available metal nanoparticle-based inks with different formulations are compared in terms of breakdown current and microstructure. Since there is a niche in printing conductive traces on mechanically flexible substrates for fuze applications, different sintering methods are explored. Most flexible substrates have a low thermal budget and are not compatible with conductive inks that require high temperature sintering. This incompatibility can be addressed by employing alternative sintering technique such as laser or photonic flash sintering. This work compares the breakdown current of traces that are laser sintered to those that have been thermally sintered on a hot plate. In addition, the effect of tensile stress bending on the breakdown current is also investigated. This is relevant for fuze applications because flexible substrates can provide unique functionality such as conformable circuit boards that can be rolled and fit into small enclosures. Lastly, a simple method is demonstrated for preventing the breakdown of flexible printed traces subjected to a single firing pulse that is used in exploding foil initiator (EFI).

2. Experimental

The samples for breakdown study resemble a dog bone structure because the narrow conducting trace is terminated by large contact pads at both ends as shown in Fig. 1(a). The figure also provides the dimensions of a sample, which consists of the trace and the contact pads. For studying the effect of substrate and the choice of ink, the traces were printed by an aerosol-jet printer (Optomec AJ-300) equipped with an ultrasonic atomizer. The trace was composed of 3 layers printed serially upward to build the thickness. Each layer only consisted of a single line print to keep its width as narrow as possible. The printing parameters are summarized in Fig. 1(b). After completion of the traces, the substrate was moved to an inkjet printer (Dimatix 2831) to print the large contact pads that terminate the trace. Inkjet printing was used for this step as opposed to aerosol-jet printing because it is an easier technique and provides faster sample turn around when printing simple structures that do not require high resolution. The pads, which consisted of two layers, were prepared with the same Ag ink as the trace. Each layer was printed at 40 μm drop spacing using a single nozzle in the jetting module. The drop volume specification of the jetting module was 10 pL. During printing, the nozzle and platen temperatures were maintained at 30 °C and 40 °C, respectively. The distance of the nozzle from the substrate was set at 0.5 mm. Upon completion of the pads, the samples were sintered by conventional thermal method. Throughout this paper, thermal method refers to baking the samples on a hot plate at 250 °C in ambient air for 30 min. All samples for breakdown study were sintered by thermal method unless specified otherwise.

For the breakdown study, it is more reasonable to determine the breakdown current density J_b of the printed traces because J_b no longer depends on the trace cross-section area. At least three samples were prepared for each J_b measurement to be able to repeat the measurement three times at the same conditions and obtain an average value. To measure J_b, a trace was subjected to a millisecond-range pulsed current coming from a discharging capacitor while under a stylus profilometer (Bruker-DektakXT). This enabled in situ measurement of the thickness profile of the trace before and after applying the pulsed current. Additionally, a static scan could be performed to measure the real time current-induced thermal expansion of the trace or the substrate. The details of the experimental setup can be found in a previous publication [9]. In the experiment, J_b is defined as the peak current density that causes the trace resistance to become infinite. The value of J_b is determined by increasing the charging voltage to the capacitor by 0.2 V increments until breakdown occurs. The time between voltage



Aerosol Jet Print Parameters	
Sheath gas	60 SCCM N_2
Atomizer gas	30 SCCM N_2
Atomizer voltage	35 V
Ink bath temperature	20°C
Print speed	0.1 mm/s
Nozzle inner diameter	300 μm

Fig. 1. (a) Four completed samples on a single substrate and the dimension of each sample. (b) Aerosol-jet parameters for printing the trace. (c) Setup for investigating the effect of tensile stress bending.