Aerosol Jet® Printing onto 3D and Flexible Substrates

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ABSTRACT

As technology continues to produce smaller and more intricate systems, we find that they cannot always be supported by conventional processing techniques. The chief issue is that traditional multi-step fabrication techniques require a rigid, planar framework for the entirety of the production. By using a three dimensional (3D) additive manufacturing approach, systems can have improved integration, smaller packaging footprints, fewer steps, less waste, reduced weight, and potentially lower fabrication costs.

Here we demonstrate how direct-write printing has establishing itself as an enabling technology for production of both circuits and sensors on 3D and flexible surfaces that could not otherwise be fabricated with conventional techniques. For the past five years QUEST Integrated (Qi2) has been utilizing an Optomec Aerosol Jet® (AJ) direct write printing system that can deposit a variety of materials onto nearly any type of substrate, provided the materials have compatible surface energies. A key advantage for AJ is that the process is non-contact, allowing for nearly any surface topography provided the surface of interest can be exposed to the nozzle. Through internal process development, varied contract research and extensive experience with inks and deposition, Qi2 has developed broad AJ deposition expertise that can be offered to customers for a wide variety of new projects.

INTRODUCTION

Qi2 has a long history of contract engineering, research and development, with a strong focus on commercialization of instrumentation and automated inspection systems for Non-destructive Testing (NDT), Structural Health Monitoring (SHM) and Quality Control markets especially in the energy, transportation, and aerospace sectors. The AJ system has strong potential for a new generation of tools for these applications.

Direct-write (DW) printing is an additive manufacturing technology in which material is deposited in layers to produce desired features. DW is used for direct printing of functional electronic circuitry, components and sensors onto flexible, low temperature, and non-planar surfaces without any special tooling. In general, a CAD/CAM element is coupled to a DW printing device containing an “ink” of the desired material, allowing for selective patterning. Inks are generally composed of some functional material, such as nanoparticles or polymers, suspended in a liquid carrier. This approach is distinctly different from traditional subtractive manufacturing methods where large area deposition, photolithographic chemicals, and toxic etchants are used to remove material to obtain the target pattern.

Optomec Incorporated (Albuquerque, NM) developed and patented the Aerosol Jet® (AJ) technology for fine-feature material deposition. An aerosol of fine ink droplets is created by pneumatic or ultrasonic methods and propelled in a gas stream onto the substrate as illustrated in Figure 1. The AJ process utilizes an innovative aerodynamic focusing technique to collimate this dense aerosol mist of material-laden micro-droplets into a tightly controlled beam of material that can produce features as small as 10 µm or as large as several centimeters. Coupled with a motion control system that moves either the print-head or the substrate, high resolution patterns can be created using CAD based-programs to produce distinctive features as well as wide area conformal coatings. Commercially available Aerosol Jet print-heads can print feature sizes below 10 µm with optimization and are capable of depositing high viscosity (up to 1000 cP), high particle loading (>70 wt%), wide viscosity range inks well beyond the range of conventional inkjet writing. One of the most advanced characteristics is the non-contact deposition, enabling traces to be printed over steps, curved surfaces, and conformally on 3D objects while printing with a nominal standoff distance of up to 5 mm. With process optimization, successful deposition has been demonstrated up to a 10 mm standoff.

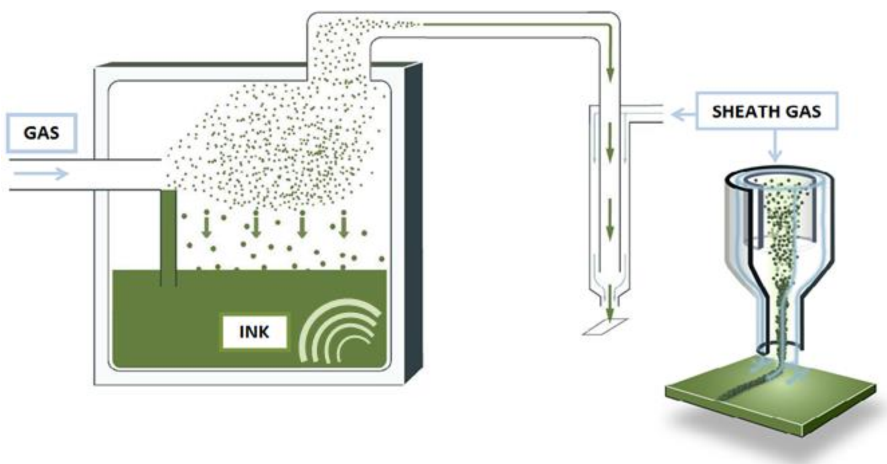

Figure 1. Detailed schematic of Aerosol Jet technology in which aerosolized ink is focused over a 5 mm standoff. (Figure courtesy of Optomec, Inc.)

With the AJ system, there is wide variety of functional materials that may be atomized. The primary materials are conductive, insulating, resistive, dielectric and biological based inks[1]. Conductive inks typically include metallic nanoparticles (such as silver, gold, copper, nickel, platinum), or conductive organics (PEDOT:PSS and carbon nanotubes). Insulating inks may include dissolved polymers, UV epoxies, adhesives, and thermoset resins. While most inks require some post-deposition thermal processing, the AJ printing system is also equipped with an NIR laser for sintering metallic nanoparticle inks in-situ on temperature sensitive materials ($T_m \leq 120°C$).

Qi2 has adopted an AJ business model that incorporates internal projects and a unique research and development service that allows customers with and without AJ capability the benefit of Qi2's process development expertise. This paper briefly highlights concepts where AJ printing can enable advanced systems on 3D and flexible substrates.

STRUCTURAL HEALTH MONITORING (SHM)

With increasing complexity and increasing requirements for part lifetimes, the military and aerospace industries are actively seeking means to monitor critical parts during service and provide better reliability and performance outcomes. Current methods require non-destructive inspection (NDI) between uses, but this is not enough. By integrating monitoring systems into the part, regardless of shape or size, critical structures can be monitored in situ without additional weight or significant costs.

Metallic Structures: One application implemented at Quest Integrated (Qi2) demonstrates the usefulness of printing a self-sufficient monitoring system directly onto the web of an F-15 wing component. By directly depositing the circuitry onto the part, one is able to eliminate fixed connections and the addition of bulky rigid material to a hot spot location. In this system, an antenna is used that allows for ongoing wireless evaluation. The AJ focusing sheath gas of the printer allowed the nozzle to remain inside the flanges yet 10 mm from the web plane. Below in Figure 2, are images of the aircraft component and fabricated health monitoring circuit. The coating of the component had several surface imperfections, which required a dielectric material to be patterned first to ensure electrical insulation for the printed conductive traces. Discrete electrical components were attached with conductive silver epoxy.

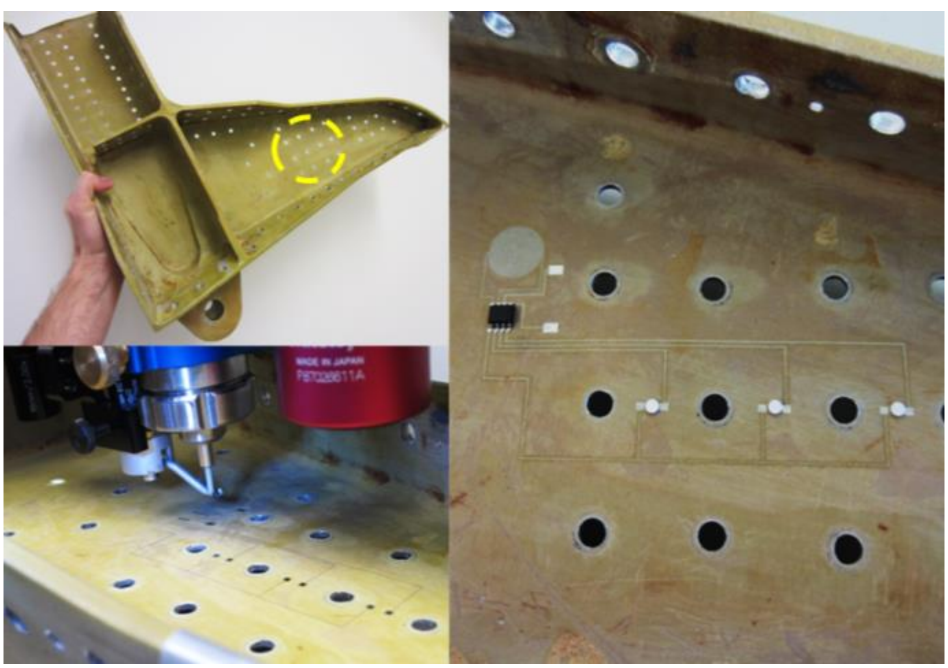

Figure 2. (Top left) F-15 component, (Bottom left) deposition of monitoring circuit, (R) final product. Concept developed by Qi2.

Composite Structures: Composite materials provide significant structural advances to the aerospace, sporting goods, medical, and automotive industries. Similarly, there are continuing demands to understand their behavior during usage to evaluate performance and failure mechanisms. AJ provides a low temperature process that can be applied to complex structures to embed sensors and circuitry either partially or completely.

For this project, a SHM system was deposited onto a thermoformed flap rib made of a 6-ply Satin 5H carbon/PPS composite structure. The design included a strain gauge and transmitting antenna next to a high stress location. To print the entire circuit in a single deposition, the composite rib was oriented in a way such that both pattern receiving sides remained at a 45° slant with respect to the print-head, as shown in Figure 3. Ink and process conditions allow for a variable standoff of 2-10 mm. Further applications are described in conference papers, SPIE Smart Structures and Materials[2] and SAMPE 2013 proceedings[3].

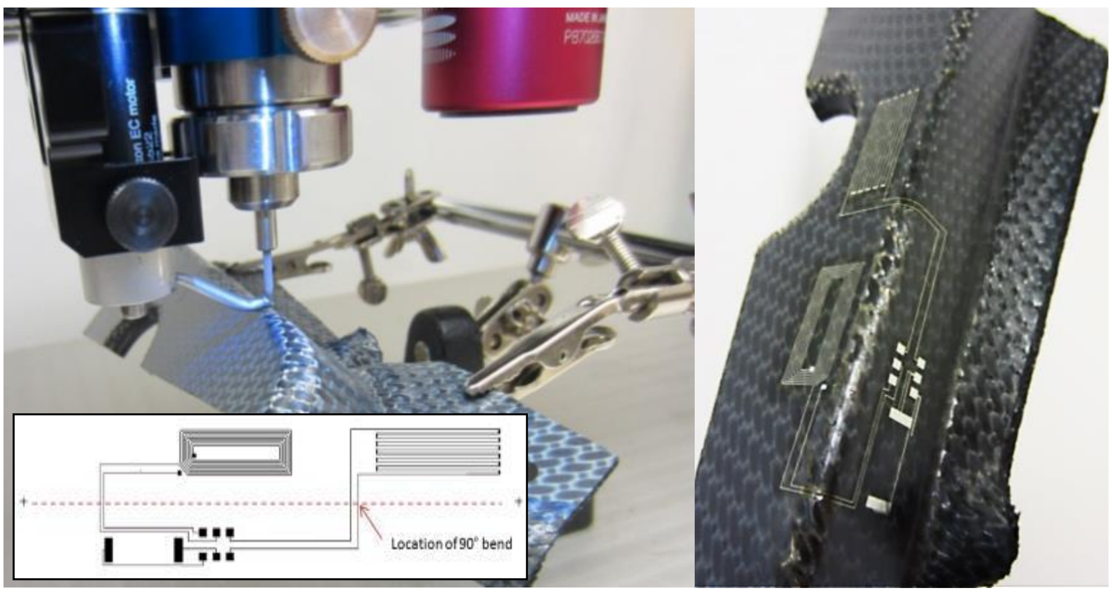

Figure 3. (L) Composite oriented in a clamp fixture with the associated CAD layout (inset), (R) printed circuitry and strain gauge. Concept developed by Qi2.

Strain Gauges: Similarly, AJ provides a unique approach for implementing strain gauges (SG) to both simple and complex shapes. By depositing an insulating resin with strong adhesion, strain gauges less than 2 microns thick can be printed across planar, non-planar, and flexible surfaces.

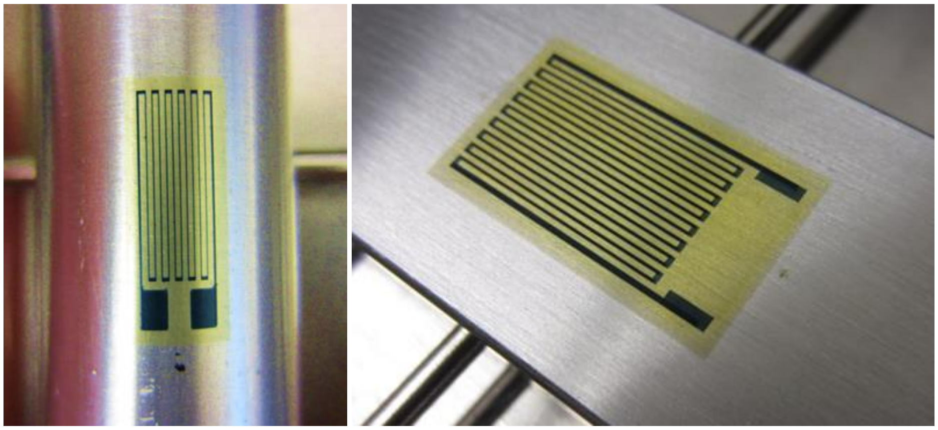

Figure 4. (L) Strain gauge on stainless steel pipe, (R) SG on aluminum bar

3D PRINTING

Additive manufacturing can overcome many conventional design limitations by providing innovative fabrication techniques at lower costs. The most popular is the use of Fused Deposition Modeling (FDM printing) in which 3D parts are created by extruding layers of thermoplastic material at relatively high resolutions. These parts have been used to create models, prototypes, and final product applications.

AJ provides a complementary process that furthers this approach to additive manufacturing. For example, Figure 5 illustrates a 3D printed case (made of ABS plastic) that previously encapsulated a conventional, rigid circuit board. Instead, the PCB was replaced by directly printing the circuitry onto the inside of the case with no intermediate processing required. The use of low temperature sintering nanoparticle inks allows the sintered traces to reach 25% of bulk silver conductivity on the temperature sensitive ABS plastic (glass transition temperature of 105°C) without any degradation of the polymer shape. Also shown is how AJ printing conforms with good resolution to the textured surface formed by the extruded ABS bead layers. The non-contact deposition provides robust connections even for micron-level surface textures.

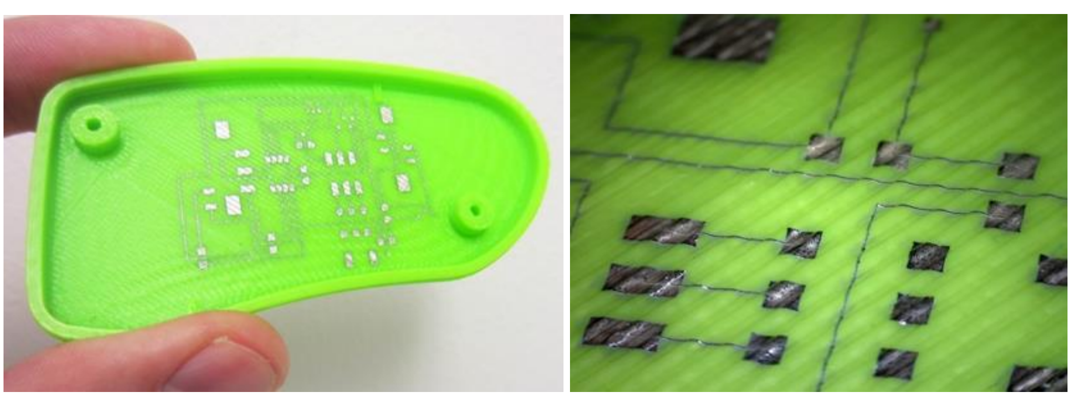

Figure 5. (L) Printed circuit on ABS printed case, (R) enhance view of printed ABS surface

FLEX CIRCUITS

Typical printed circuit boards (PCBs) require large, thick conductive traces connected with vias and separated by rigid insulation layers throughout the board. AJ printing has introduced a resource-conserving additive process for manufacturing flexible circuits on nearly any flexible substrate. The mask-less AJ printing system allows for rapid fabrication of multilayered circuits and sensors[4]. Circuits can also be scaled down below conventional geometries with use of highly conductive inks and fine pitched features.

AJ printing allows use of a wide variety of inks that cannot be processed by inkjet or screen printing methods. For multi-layered circuitry, both low and high viscosity materials can be deposited in alternating layers to form small, flexible interconnects. An example is shown in Figure 6 demonstrating the multi-layered fabrication steps. The shown part was to be embedded in a SHM system on an aircraft component[2]. The circuit was required to withstand relatively high voltages (~100 V), which mandated the use of high performance materials to ensure excellent conductivity and dielectric strength. This configuration utilized silver nanoparticles and dissolved polyimide inks. The printed interconnects had resistances ranging from 0.1 - 5.0 Ω. The polyimide has also been shown to protect the Ag layers effectively from any chemical attack in a >100 hour test in a salt corrosion chamber, simulating conditions found in an aircraft structure.

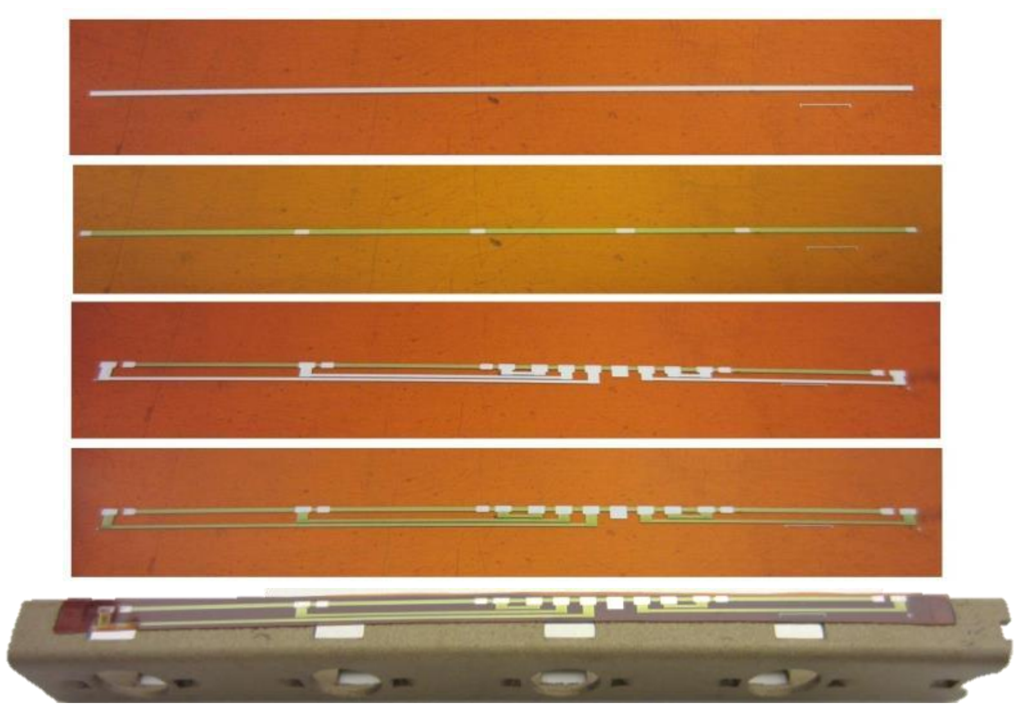

Figure 6. Serial images of AJ printed multi-layer flex circuit and final mounting to part

PRINTED SENSORS

Flexible and conformal sensors fabricated by additive manufacturing offer many advantages by increasing the versatility of the sensor and potentially reducing material and fabrication costs.. Here, we present several flex sensors designed for damage detection on composite structures. The success of the sensors was highly dependent on the synergy between ink capability and printing process development specifically optimized for AJ.

For example, damage detection transducers were jetted onto composite and flexible surfaces. The transducers were fabricated by printing a highly piezoelectric polymer, polyvinylidene fluoride (PVDF), between conductive electrodes, shown in Figure 7. Under mechanical pressure, the PVDF layer generates an electronic signal proportional to the applied pressure[2]. Because PVDF has a low Curie temperature, the top electrode was fabricated with a room temperature curing conducting polymer, PEDOT:PSS.

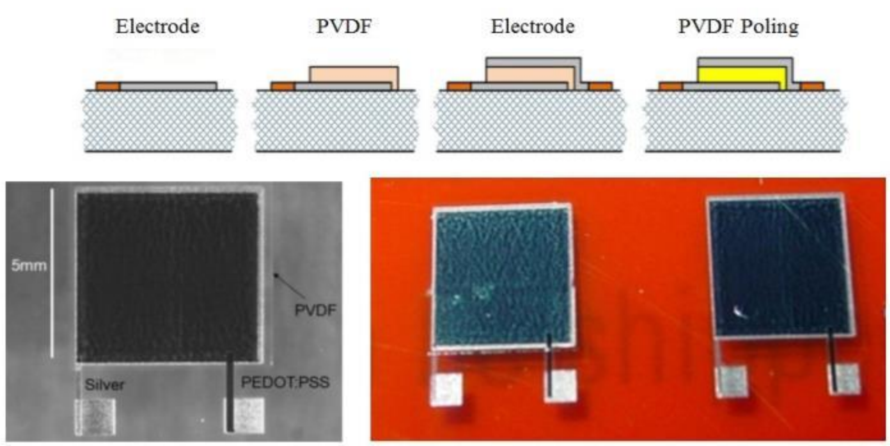

Figure 7. (Top) Sketch of fabrication process for direct-write pressure transducer, (Bottom left) Illustrated transducer on glass, (Bottom right) PVDF transducer printed on Kapton foil.

The technology also provides an advantageous approach for fabricating interdigitated electrodes of varying materials and spacing for applications ranging from medical diagnostics to resistive and capacitive fluctuations used for sensing applications. The interdigitated water sensor in Figure 8 was comprised of silver (Ag) and copper (Cu) electrodes. The electrodes were printed using Ag and Cu nanoparticle inks. The water sensor was integrated as an embedded sensor to monitor water induced corrosion on targeted aircraft components[2].

Figure 8. Interdigitated water sensor consisting of Ag-Cu electrodes (Ag – left, Cu – right).

PRINTED HEATERS

A fractal-based heating element was deposited onto the leading edge of a glass/epoxy rotor blade[5]. The unique standoff capabilities of AJ printing allowed for direct fabrication on the changing radius. During deposition the print head remained stationary with the substrate fixed to a motion controlled platen. Printing programs were designed as 2D projections onto the 3D surface. To conform to the curved leading edge section, the pattern was segmented into three separate prints requiring the part to be oriented differently for each step as illustrated in Figure 9. The printed heaters were then subjected to a relatively low voltage to produce significant heat, also shown.

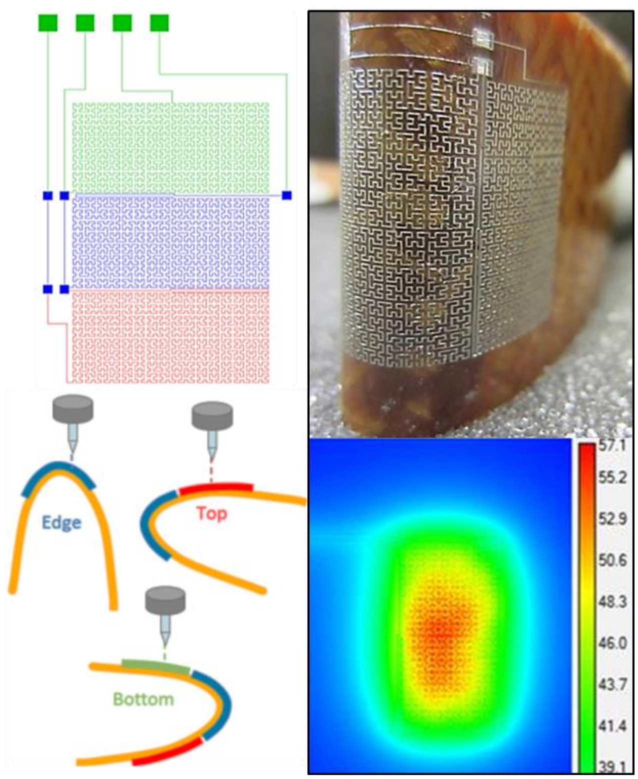

Figure 9. (L) Heater pattern in color to illustrate serial printed segments, (Top right) Printed top side and leading edge, (Bottom right) Thermal IR image of printed heater.

PRINTED PROBES AND COILS

The focused aerosol beam offers a matchless deposition technique for fine pitch coils on planar and non-planar substrates alike. The innovative sheath gas focused printing technology allows for precise control of fine features down to 10 µm in width over varying surface topography. Figure 10 (left) illustrates both circumferential and conformal coils on a 1.4 mm diameter tube[6] to fabricate miniature, flexible magnetic probes with cleanly resolved oscillations. Figure 10 (right) shows a conventional RFID coil on polymer-coated paper.

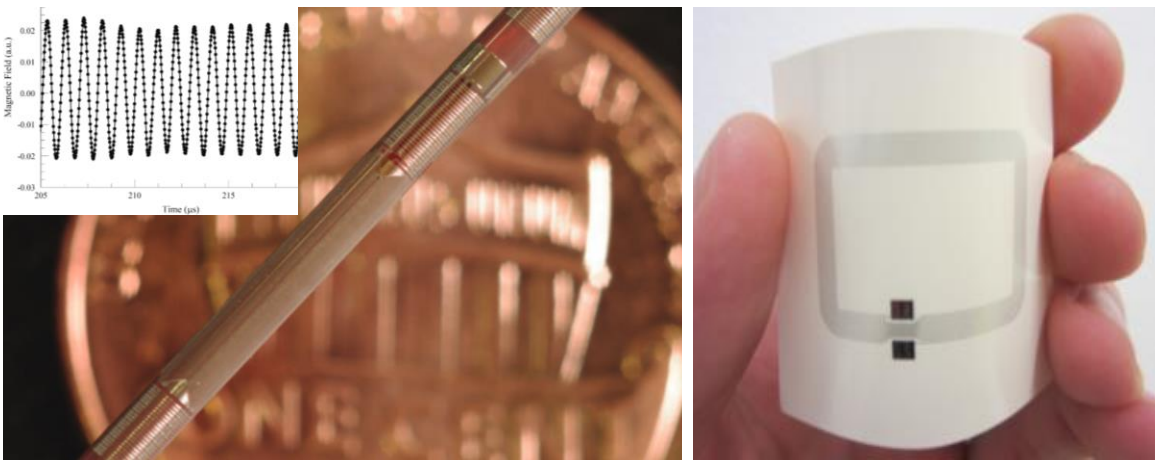

Figure 10. (L) Three-channel, three-axis conformal probe on 1.4 mm diameter tube[6] over a penny, (R) RFID coil on paper

CONCLUSION

The Aerosol Jet printing process fills the gap where many emerging technologies are limited in ink properties, standoff distance, cost, and processing time. In this paper, we have presented some projects where Qi2 has used the Aerosol Jet as a premier technology for fabricating sensors and structural health monitoring systems directly onto flexible and 3D surfaces alike. The unique focused aerosol stream deposited features uniformly across the substrate at standoff distances ranging from 1 to 10 mm. Printed features used inks of various viscosities ranging from water (1 cP) to beyond that of motor oil (>1000 cP), which is far beyond the range of most conventional printing techniques. The system as configured is ideal for rapid prototyping, short product development cycles and cost-effective low-volume manufacturing, with print design and process development generally able to be completed in a day or two.

ACKNOWLEDGMENTS

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