ACTIVE DEVICE FABRICATION USING FIBER ENCAPSULATION ADDITIVE MANUFACTURING

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Abstract

Fiber Encapsulation Additive Manufacturing (FEAM) is a novel solid freeform fabrication process in which a fiber and a matrix are co-deposited simultaneously within a single printer along straight and curved 2-D and 3-D paths. Using a FEAM approach in which the fiber is a metal wire and the matrix is a thermoplastic polymer, simple electromechanical devices such as voice coils, inductive sensors, and membrane switches have been successfully produced. This paper will present an overview of the FEAM process, describe several fabricated devices, and discuss recent developments in controllably stopping and starting the wire, and in creating electrical junctions between individual wires, which together enable much more complex devices to be made.

Introduction and Motivation

In recent years a number of researchers have investigated the additive manufacturing (AM) of multi-material, multi-functional structures and active devices. These efforts, which attempt to go well beyond the purely structural and aesthetic dimensions of single-material AM, seek to achieve a higher level of functionality and performance, or significant reductions in size, weight, and cost, for a variety of electromechanical and electronic systems. Such benefits, combined with AM’s intrinsic ability to rapidly produce complex, customized geometries, promise a future in which previously-impossible designs of great sophistication can readily be produced, a future in which AM is truly enabling. An area of interest for the present work, and for which multi-material AM holds great promise, is soft robotics.

Soft robotics has emerged as a research topic of considerable interest [Majidi 2013, Lu and Kim, 2013], in part driven by the desire to create “co-robots” that work safely in close proximity to humans. Moreover, robots with soft bodies and limbs might grasp and manipulate delicate and irregular objects—such as picking fruit off of a tree without damage. They might also move in new and complex ways, and transform their shapes: capabilities that open novel application areas, such as search and rescue operations. The tentacle of an octopus, if it could be emulated artificially, is an example of a device useful in a soft robot that would enable complex motions and shapes. Yet in contemplating how to implement such a device, one realizes there are a very large number of degrees of freedom making it difficult to implement by traditional manufacturing techniques. In some robot designs, one might also wish to provide redundancy of actuators so as to increase reliability and robustness. In both of these cases, there is a fundamental need to provide multiple, distributed actuators, which are not normally found in conventional, rigid robots. Distributed actuators are likely to need closed-loop control, which implies a distributed array of sensors, e.g., one per actuator. Moreover, it can be beneficial to sense the outside world on the entire robot "skin" with reasonable spatial resolution (i.e., an array of tactile sensors); this also requires a distributed approach. Thus, soft robots can achieve their full potential only if their bodies and limbs can be equipped with distributed network of actuators and sensors, and interconnects that allow power and signals to be routed between them.

Requirements and Approach

The problem then becomes how to practically manufacture such a system. Assembling robots with tens to hundreds of interconnected actuators and sensors from discrete components would clearly be costly and labor-intensive, and would likely result in a device of considerable volume and weight (e.g., due to the redundant packages of individual components). This leads to the question: might it be possible to directly, monolithically manufacture functional robot components, and therefore bypass these issues? More specifically, might it be feasible to use a multi-material AM process to literally *print* a robot limb in which all the required actuators, sensors, and wiring are built-in, with no assembly required, such that the limb is essentially ready for use? Indeed, if this could be achieved, the potential applications would extend considerably beyond use in soft robotics.

Monolithic fabrication of macroscale devices through additive manufacturing clearly requires working with both dielectrics having good structural properties and with good electrical conductors. Specifically, electromechanical devices, as well as electronic circuits, depend on conductors for their operation, such as connecting them to signals or power sources, or generating magnetic fields (e.g., in a solenoid actuator or motor). A number of activities in printed electronics—both 2-D and 3-D—have been reported. However, printing good conductors in combination with dielectrics is very challenging. We define a "good conductor"—one suitable for real-world applications with reasonably high currents—as meeting the following requirements:

- Low electrical resistivity and high maximum current density.
- Flexibility, strength, and ductility, ideally similar to a soft metal, allowing the conductor to be strained or absorb impact energy while in use without fracture.
- Thermal stability, so as to remain functional at elevated temperatures.

- Ability to be easily and reliably interfaced to other materials and components.
- Low total cost, so that the conductors do not make the printed device unaffordable for all but a few applications.

Printing of the conductor along with dielectric material introduces additional requirements. At a minimum, the process should be compatible with the processing of the dielectric material, produce a unified structure when completed (so that the two components are well-integrated), offer large flexibility in the device design, and operate at reasonable manufacturing speeds.

Though excellent progress has been made, the most common approach used in printed electronics, namely printable inks, still faces significant challenges. Rather than striving to develop yet another conductive material that might meet the requirements, we have taken a different approach. We acknowledge that the best “good conductor” is—and is likely to remain for the foreseeable future—solid metal wire. Wire has very low resistivity (e.g., 1.7 μohm-cm for copper), allows high current density (e.g., 20 A/mm^2 for chassis wiring, which is important for electromagnetic actuators), is well-characterized electrically, strong, and depending on composition, can be flexible and ductile (e.g., copper). It is thermally stable and is easily interfaced through well-established methods such as soldering, welding, and thermosonic bonding. Moreover, conductive wire is inexpensive, especially compared with silver-based inks, and available in a variety of forms useful for building sensors and actuators. Overall, the favorable characteristics of conductive wires far outpace printable conductive materials compatible with thermoplastics.

Other Research using Wire

Some previous work has considered incorporating solid conductive wires into additive manufacturing systems. A project known as “SpoolHead” aimed at integrating solid conductors directly into printed parts was undertaken several years ago [Bayless et al., 2010]. A system was developed to place wire on top of a printed layer of thermoplastic material, bond it using a heated tip, and cut it. Some simple demonstrations were achieved, but the system had difficulty in bonding the wire securely to the polymer surface and was slow. Additionally, no attempt was made to join wires to one another. More recently, researchers have leveraged earlier work on ultrasonic wire embedding for the production of smart card antennas [Taban, 2003], and applied it to embedding wire into 3-D printed thermoplastic objects. Wire is embedded below the surface by ultrasonic vibration or heating which causes the thermoplastic to reflow [Aguilera et al., 2013]. A workcell has been constructed comprising a six-axis robot that transfers partially-build parts from station to station in a temperature-controlled enclosure [Abriz et al., 2014]. The workcell includes two FDM systems, and apparatus for wire embedding, laser welding (to create junctions), and a CNC mill. This system has been shown to work, but involves costly capital equipment, has much slower processing than typical AM systems (e.g., due to the time required to move parts between stations), and requires that the part be made from a thermoplastic material, so it can reflow.

Fiber Encapsulation Additive Manufacturing

Having selected metal wire as the conductor in our strategy to monolithically print macroscale electromechanical devices, the goal is then to develop an AM process that can print both wire and dielectric material, and do so using a system that is reasonably fast, easily automated, integrated (e.g., a single machine), and affordable. The process we are developing, Fiber Encapsulation Additive Manufacturing (FEAM), has the potential to meet this goal. FEAM has similarities to material extrusion AM processes such as Fused Deposition Modeling (FDM), but provides for the simultaneous, co-deposition and encapsulation of a fiber (metal wire, carbon fiber, Kevlar®, optical fiber, etc.) along with a solidifiable, fluid matrix (dielectric polymer such as molten thermoplastic or thermoset resin, ceramic, etc.) [Saari, Cox, Richer et al., 2015]. As shown in Fig. 1(left), both the fiber and the matrix (e.g., copper wire and thermoplastic resin) form a "coaxial composite" in which the fiber is fully encapsulated within the solidified extrudate of matrix material.

The key challenges in making FEAM a robust process having the versatility to produce a wide range of electromechanical and electronic devices are:

1. Keeping the wire substantially centered within the extrudate, even when following toolpaths with small radii.

2. Controllably starting and stopping the wire, so that wire can be placed where required.

3. Creating reliable junctions between wires with reasonably low resistance: both inter-layer (between layers) and intra-layer (within a single layer).

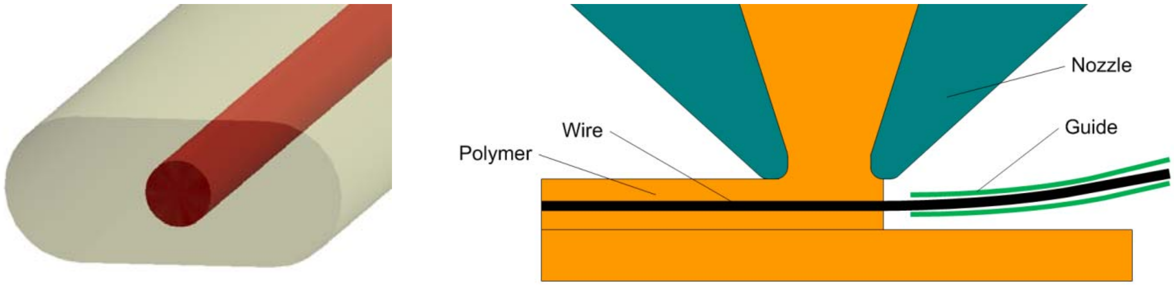

Fig. 1: (left) A coaxial composite; (right) schematic of the FEAM printhead (right).

Progress on addressing the first of these challenges has been discussed [Saari, Cox, Richer et al., 2015]. In this paper, we report on initial results addressing the latter two challenges, and describe several early proof-of-concept demonstrations of FEAM's capability and potential.

The FEAM System

In FEAM, both the fiber (e.g., copper wire) and the matrix (e.g., a thermoplastic polymer such as ABS) are deposited using a single printhead. The printhead comprises an extruder with a nozzle similar to those used in FDM, and a guide positioned to the side of the nozzle orifice, through which the wire is delivered (Fig. 1, right). The axis of the guide is approximately horizontal, allowing the wire to be introduced into the polymer as it is extruded from the orifice while the printhead moves. The printhead must follow a toolpath that is generally curved according to the contours of the layer. Because it is asymmetric, (and the wire must stay within the extrudate and be reasonably well centered), the guide must rotate around the nozzle orifice, remaining approximately tangent to the nozzle velocity. Alternatively, the guide may remain fixed relative to the FEAM system, and the part may rotate around the nozzle. Since the latter approach provides more flexibility and facilitates material handling, it was selected for the FEAM testbed shown in Fig. 2 (left). The testbed incorporates a rotational, or "theta" stage, onto which X and Y stages, which translate the part, are mounted. With the orifice aligned to the theta rotational axis, rotation of the theta stage results in the guide rotating around the nozzle with respect to the part. Fig. 2 (left) also shows the Z stage of the machine and a filament extruder with a nozzle. Not shown in the left-hand figure, but shown in the right-hand closeup, is the wire feeder/cutter mechanism which is mounted to the Z stage, adjacent to the nozzle.

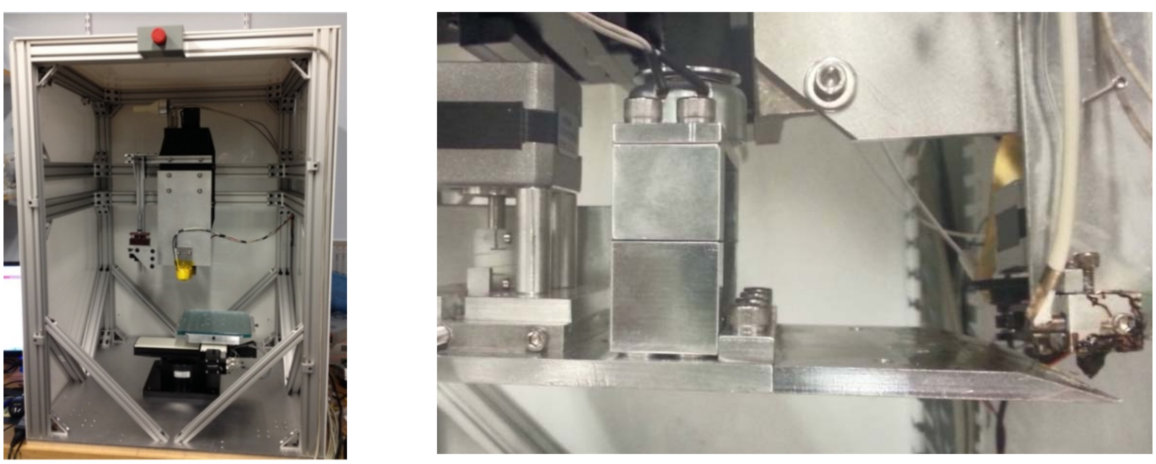

Fig. 2: (left) FEAM testbed; (right) detail of wire feeder/cutter.

Wire may be fed through the guide passively (i.e., once anchored in the solidified extrudate, it can be pulled through the guide) or actively. Active feeding, however, is required for starting the wire after it has been stopped (i.e., cut). The feeder/cutter (Fig. 2, right) includes a stepper motor to feed the wire through the guide, and a solenoid-operated blade to cut the wire. Cutting is performed "upstream" of the guide and nozzle, with each wire segment cut and then pushed through the guide by the advancing wire behind it.

Addressing the Challenges

Wire encapsulation and centering. Initial FEAM experiments focused on producing straight extrudates with nickel and copper wire encapsulated in BendLay Tough [Amazon, 2015], a transparent ABS-like material which allowed the wire position within the extrudate to be more easily evaluated. Results of this were promising, with the wire remaining reasonably centered, so curved toolpaths were evaluated next. By programming the testbed controller to simultaneously move the X, Y, and Z stages to follow a helical toolpath while rotating the theta stage to maintain tangency, "thin" vertical coils were printed from continuous nickel or copper wire (76-127 µm diameter) insulated with BendLay Tough. Fig. 3(left) depicts a fabricated cylindrical coil having an outside diameter (O.D.) of 25 mm and a helix pitch of 250 µm. Several smaller coils are described in an earlier publication [Saari, Cox, Richer et al., 2015].

It was found that when printing smaller diameter coils, the wire would not typically remain centered horizontally and in some cases exited the extrudate entirely. This was addressed in part by reducing the printing speed, suggesting that the molten extrudate required some time to solidify in order to "lock" the wire in place before radial forces on the wire could displace it significantly. In addition, when cooling air was directed by a small nozzle onto the molten extrudate the solidification was observed to accelerate dramatically. No apparent reduction in mutual adhesion of extruded polymer was observed when cooling air was used, and even tall coils (e.g., 150 mm) could be built without any problems. Initial, non-optimized printing speeds that were tested with cooling air have been described earlier [1] [Saari, Cox, Richer et al., 2015], and ranged from 3.2-25.4 mm/s. Very small turning radii could be achieved. Square coils (Fig. 3 (right)) were printed with air cooling and the corner radius of curvature of the wire was measured to be approximately 600 µm [Saari, Cox, Richer et al., 2015]. Testing was later done to determine whether the largest coil could be printed at a higher speed. Indeed, stable printing at a speed of nearly 50 mm/s—comparable to standard, single-material FDM coil—was achieved, and cooling for this diameter coil was not required.

One of the fabricated coils was metallographically mounted, sectioned, and polished, as described earlier [Saari, Cox, Richer et al., 2015]. Horizontal (i.e., X/Y) centering of the wire

[1] Table 1 in that publication has an error in the smallest O.D. shown; the correct value is 2.8 mm

was good, though there were small variations in both extrudate and wire position. Vertical centering was acceptable, though the wire was slightly lower than desired. In more recent tests we have shown that this can be improved.

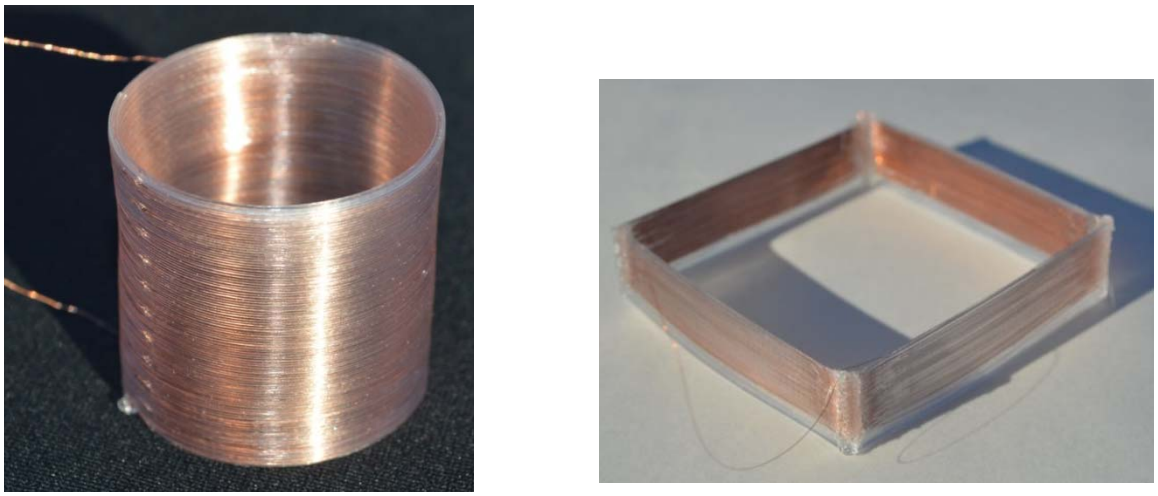

Fig. 3. (Left) cylindrical copper coil approximately 25 mm in outside diameter; (right) square copper coil approximately 25 mm wide.

Stopping and starting the wire. Stopping and starting the flow of the liquid matrix (e.g., extruded thermoplastic polymer) is straightforward, and is common practice in FDM. Doing the same with wire is far more difficult. In the current approach, the wire is cut with a solenoid-activated blade. If the blade is sharp, it cuts with minimal burr, and can be automatically re-fed by upstream drive rollers without jamming. Using the feeder cutter of Fig. 2 (right), test parts such as the “dashed line” part shown in the backlit views of Fig. 5 were produced with 100% feeder/cutter reliability over the duration of the test. In this part, segments of 127-µm copper wire with a programmed length of 3, 13, and 25-mm were fed, cut, and encapsulated—with space between the segments—within BendLay Tough extrudates forming a portion of a slab printed in the same material. In the top frame of the figure, the majority of the slab can be seen, while the lower left view is a closeup showing magnified wire segments. Finally, the lower right view shows the highly-magnified end of a segment. Unfortunately, due to refraction of light through the polymer extrudates, it is difficult to obtain a clearer view of the wire segments.

Printing junctions. Coils produced as described above, in which the wire is continuous and the coil is a 3-D shape may useful as discrete devices, but in the context of 3-D printing a more complex system comprising, for example, a group of electromagnetic actuators, sensors, and interconnects, a standard layer-by-layer approach is required. In other words, coils should preferably be made from discrete curved segments of wire which are cut on each layer—freeing up the printhead to deposit material elsewhere—and then joined electrically at a junction, as in

Fig. 6 (left), where the ends of the wire (here shown with a square cross-section) terminate in inter-layer junctions that allow the electrical pathway to be continued between layers.

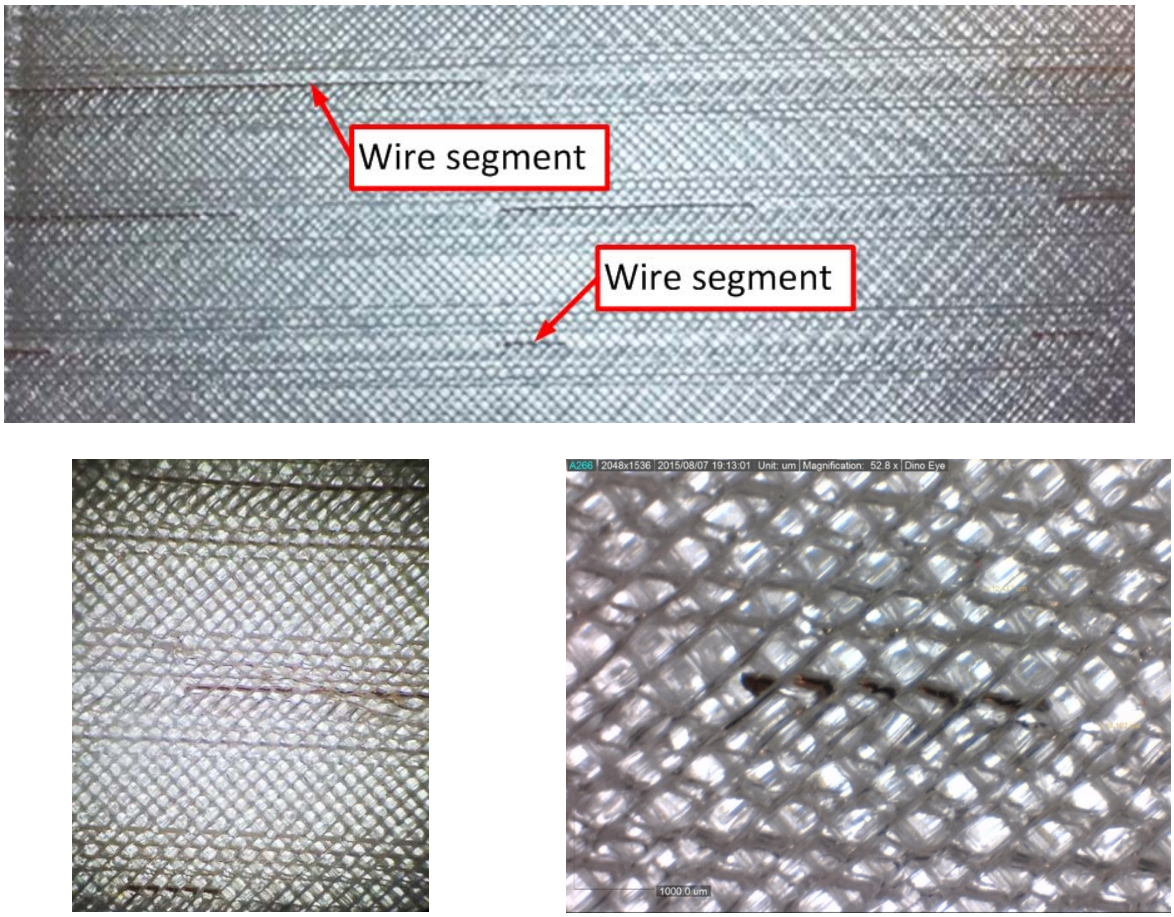

Fig. 5: Fed and cut segments of copper wire encapsulated within a clear polymer part. (top) overview; (bottom) closeup views.

To produce junctions between wires, a number of methods may be used, including laser welding, soldering, and thermosonic bonding. We have chosen to focus on yet another approach, which does not depend on close contact or precise alignment between wires, and has the benefits of speed and relative simplicity. While silver-based inks and related materials have a number of liabilities such as high resistivity, high cost, and questionable mechanical properties, these issues are greatly mitigated if the use of these materials is limited to junctions between wires, not the wires themselves. Indeed, a resistivity as high as 10,000 μohm-cm may be acceptable in such an application, since the distances between wires are short (e.g., 150 μm). Moreover, materials used in junctions are consumed in small quantities, minimizing cost, and because they are short mechanically, they are less fragile. Given this, we are developing a silver particle-based electrically conductive polymer composite (ECPC) intended for junctions. Such a material can be used to encapsulate one or more neighboring wires in an intra-layer junction, shorting them together as in Fig. 6 (right, top). Or, regions of ECPC surrounding wires on adjacent layers will be in electrical contact, shorting the wires together to form an inter-layer junction (Fig. 6 (right, bottom)).

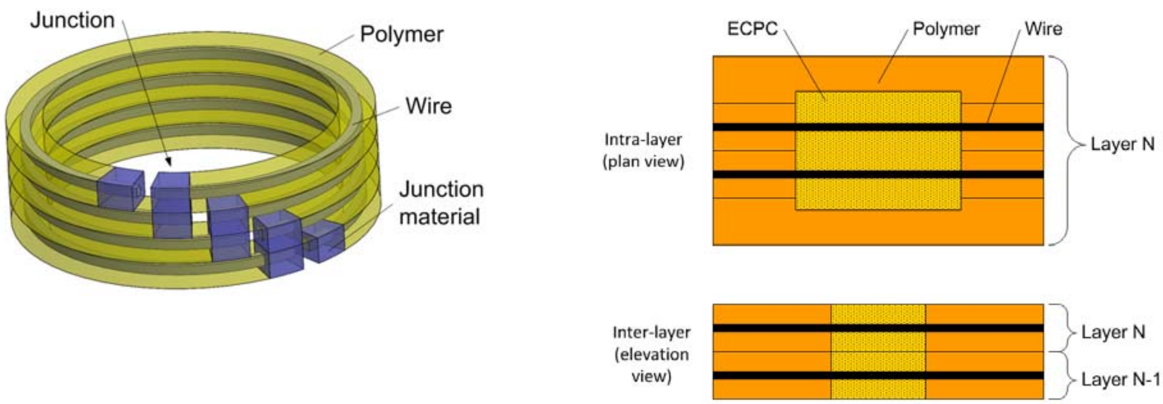

Fig. 6: (left) Model of layered coil with junctions; (right); intra-layer and inter-layer junctions.

ECPCs can be formulated with different polymers, including both thermoplastics and thermosets. An ECPC based on a thermoplastic polymer, however, can be printed using a suitable heated extruder, much like pure thermoplastics are printed in FDM. The key requirements are that the ECPC components (particulate and binder material) do not segregate in the extruder and that the material does not clog a small nozzle and remains sufficiently conductive as-deposited.

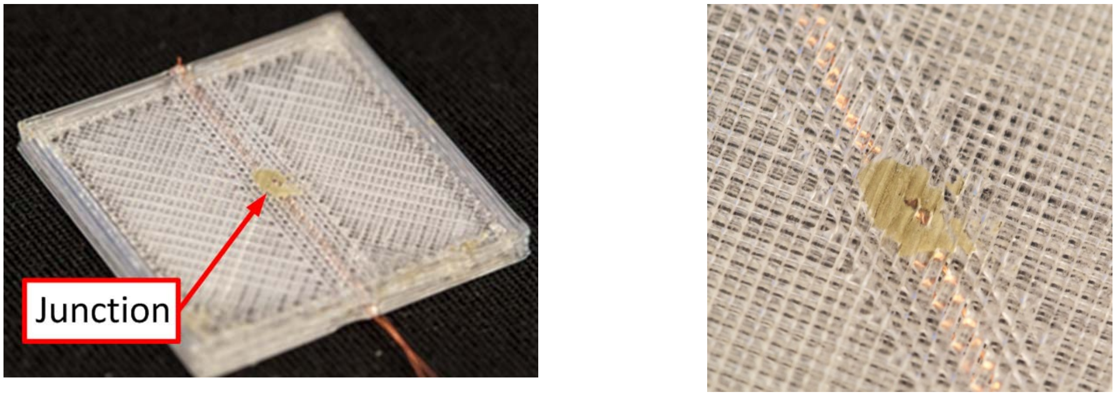

Fig. 7. (left): Intra-layer junction test part; (right) closeup of ECPC junction.

The current ECPC formulation is based on silver-coated nickel powder and a thermoplastic elastomer. It has been measured to have a typical static resistivity of approximately

7,000 µohm-cm, though values as low as 3,000 µohm-cm have been observed. It can also be extruded through the 0.7 mm nozzle of a mini screw-based extruder [Saari, Cox, Galla et al., 2015], though we believe some segregation of elastomer and particles may be occurring, and good control of flow initiation and termination requires further development. Fig. 7 shows an overview (left) and a closeup (right) of an intra-layer junction test part in which two wires having a programmed horizontal separation of 0.38 mm (center-to-center) were encapsulated in BendLay Tough except in a central cavity open to the top surface. ECPC with a resistivity of 10,000 µohm-cm was deposited into the cavity by the extruder, where it rapidly solidified. The resistance between the wires was then measured using a model RM3544-01 resistance meter (Hioki, Ueda, Japan). The best measured resistance of several samples was 250 mohm.

Fig. 8 shows a closeup (left) of an inter-layer junction test part in which two wires separated vertically by 0.25 mm (center-to-center) were encapsulated in BendLay Tough except in a central cavity on each of the two layers. The same ECPC was deposited into each cavity, such that the ECPC deposits overlapped. The best measured resistance of this junction was 110 mohm. A COMSOL simulation of the junction geometry was performed (Fig. 8 (right)) using the nominal wire geometry and the measured bulk resistivity of the ECPC. This yielded a predicted junction resistance of 40 mohm. We believe the higher measured value may be due to voids in the ECPC surrounding the wires, however, this has not been verified.

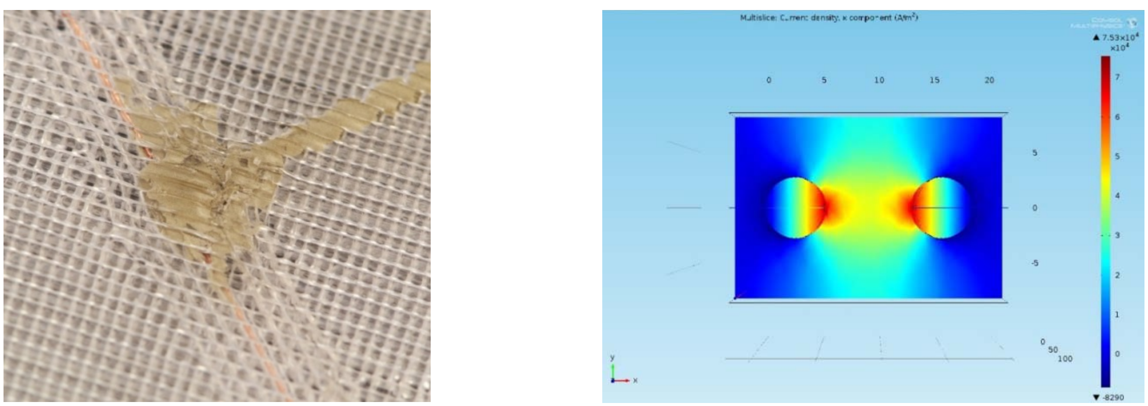

Fig. 8 (left): Closeup of inter-layer junction; (right) COMSOL simulation results.

Demonstration Devices

A number of thin cylindrical coil inductors such as that shown in Fig. 3 were fabricated and characterized, and several devices based on thin coils were demonstrated and described, as were membrane switches using two crossed wires [Saari, Cox, Richer et al., 2015]. Coil-based devices included an inductive eddy current sensor, a linear variable differential transformer

(LVDT), a rheostat, and a loudspeaker. A capacitive force sensor built monolithically from thermoplastic elastomer, BendLay Tough, and copper was also constructed and characterized [Saari, Cox, Galla et al., 2015].

More recently, FEAM has been used to print “thick” coils, in which there are multiple spiral turns of wire on each layer. Thick coils were made with continuous 127 µm copper wire printed in a spiral pattern with 380 µm pitch, without need for junctions. Printing was alternated layer-by-layer between outside-in spirals or inside-out spirals. Fig. 9 (left) shows such a coil, measuring 25 mm O.D. and 20 mm tall. The coil has 800 turns of wire and an approximate resistance and inductance of 54 ohms and 4300 µH at 10 KHz, respectively. The coil was assembled along with a plunger support having ABS flexures, and a frame and plunger printed from magnetic iron PLA (ProtoPlant, Vancouver, WA), to form a solenoid. An iron frame was also made by machining, and a steel plunger was taken from a commercial solenoid.

To test the pull force, solenoids with different frames and plungers were inverted so the plungers rested on a laboratory balance and extended approximately 1 mm from their fully-retracted positions. The weight loss produced by briefly energizing the solenoid with a nominal current of 0.5 A at a voltage of 31V was used as a measure of solenoid pull force. Results are shown in Table 1 for various frame and plunger materials. Clearly, iron-PLA did not perform well, especially as a plunger. This is not surprising since, based on density measurements, this material has an iron content of approximately 10%, making it only weakly magnetic. Also, it can be seen that while use of iron or steel for the frame instead of iron-PLA improves the pull force significantly, the improvement is far less significant than substituting steel for iron-PLA in the plunger.

Fig. 9. (left) Multi-turn “thick” coil inside a cutaway iron-PLA frame; (right) electric bell incorporating coil, complete frame, ball-tipped moving plunger, and metal gong.

The solenoid was also used to create an electric bell as shown in Fig. 9 (right) by placing the flexure-supported plunger beneath a steel gong, and driving it using a square wave oscillator at 30V peak-peak at frequencies of 15-20 Hz. Two configurations were tested: an iron-PLA frame and plunger to which a hard steel ball was added to the tip as shown, and an iron frame with a steel plunger. In both cases, the bell was audibly sounded. While the sound was weak for the first configuration, it was much louder for the second.

Theoretical considerations suggest that significant forces (on the order of several newtons) should be achievable with a solenoid provided with a coil such as that of Fig. 9 (left) and a plunger and frame made from a material having a much higher permeability than is now commercially available for 3-D printing.

Table 1: Solenoid pull force test results.

Plunger Material	Frame Material	Pull Force (gf)	Current (A)
Steel	Fe-filled PLA	≥ 18	0.48
Iron-filled PLA	Fe-filled PLA	1	0.48
Steel	Iron	≥ 32	0.51
Iron-filled PLA	Iron	1 g	0.46

Conclusions

We are developing Fiber Encapsulation Additive Manufacturing, a novel multi-material AM process. Though FEAM can be used in principle with a variety of materials, our current focus is thermoplastic polymer as the matrix and metal wire as the encapsulated fiber, with the goal of enabling the direct, monolithic fabrication of integrated, active electromechanical and electronic devices. For such devices, we are also developing an electrically conductive polymer composite to form junctions between wires. Though much work remains to be done, we have demonstrated good progress toward overcoming the three main challenges of FEAM: achieving good centering of the wire within the extruded polymer with small radii and reasonable speeds; the ability to controllably start and stop the wire to produce short segments; and intra- and inter-layer junctions between wires with low resistance. We have also demonstrated a number of simple devices ranging from solenoids and voice coil actuators to capacitive force sensors and LVDTs.

The primary application driving our work is the fabrication of soft robotic components with built-in actuators (e.g., electromagnetic, which are widely-used and can have excellent performance), sensors (inductive and capacitive), and interconnects. However, other potential applications include rapid, freeform, fabrication of printed circuit boards, wearable electronics [Stoppa, 2014], stretchable electronics, defense systems such as UAVs with built-in antennas

[Wang, 2015] and wing de-icing, and haptic displays. Our near-term research plans include improving the performance of junctions, building coils (such as for solenoids) in a layered fashion, and with integrated high-permeability magnetic materials, creating wire-elastomer structures for soft robotic and stretchable applications, and optimizing wire feeding and cutting.

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Author Disclosure Statement

The authors have no financial conflicts.

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