Hybrid Manufacturing Technologies for Electromagnetic Structures

Nicholas A. Charipar, Kristin M. Charipar, Matthew A. Kirleis, Heungsoo Kim, Raymond C.Y. Auyeung, Scott A. Mathews, and Alberto Piqué; Naval Research Laboratory, Materials Science & Technology Division, Washington, DC, USA

Abstract

Advanced fabrication technologies are poised to revolutionize the manufacturing environment. While the development of additive manufacturing technologies for mechanical components has been rapidly evolving, the application of these methods to the fabrication of RF and microwave components has been limited. Hybrid manufacturing processes, which combine distinct techniques such as fused deposition modeling (FDM), and laser micromachining, enable the creation of complex three-dimensional (3D) electromagnetic components. At NRL, we have investigated the combination of 3D printing techniques with direct-write processes that allow for the metallization, laser patterning and room temperature processing of electromagnetic patterns on 3D printed surfaces. The resolution and print volume achieved with these methods are well suited for the rapid prototyping of electromagnetic structures. Several example structures fabricated using these techniques will be presented.

Introduction

The ability to print electronics onto conformal surfaces has become increasingly important as applications demand quick, efficient, and precise fabrication, while, at the same time, minimizing manufacturing costs [1]. By combining several additive manufacturing techniques, such as fused deposition modeling (FDM), along with direct-write methods, including micropen dispensing and laser direct-write processes, antennas and various electronic devices can be printed with relative ease onto 3D surfaces.

Traditional fabrication technologies, such as photolithography, provide a suitable platform for the manufacture of planar electronics and devices. However, these technologies are limited in their compatibility with 3D substrates. Direct-write processes allow for patterning and printing onto 3D surfaces without the need for masks [2]. At NRL, we have integrated two different 3D, non-lithographic, direct-write techniques: laser direct-write and micropen dispensing. Laser direct-write (LDW) can be used either as an additive process, i.e. laser printing or subtractive process, i.e. laser ablation. Micropen dispensing allows for the printing of conductive inks onto 3D surfaces in a fast, reproducible manner. Because traditional lithographic techniques for patterning metal layers become increasingly difficult on conformal surfaces, micropen dispensing has become an important tool for the fabrication of 3D electromagnetic structures. In addition, using fabrication techniques that operate without the need for vacuum (such as thermal evaporation, sputtering, or pulsed laser deposition) allows for rapid prototyping and low-cost manufacturing without the need for expensive vacuum equipment. By combining these two direct-write techniques, complex patterns can be printed on 3D surfaces allowing the much faster fabrication of various types of electromagnetic structures, including antennas and wire grid polarizers.

While direct-write patterning techniques offer several advantages over traditional methods, combining these techniques with 3D printing allows the realization of complete functional objects quickly and efficiently. Conventional 3D printing technologies allow the rapid prototyping of the underlying substrate material, while direct-write patterning provides a fast, flexible method of functionalizing the structure.

In order to demonstrate the combination of direct-write patterning with 3D printing, fused deposition modeling (FDM) has been used to fabricate 3D objects with subsequent direct-write patterning of metal layers. FDM is an additive manufacturing process that involves depositing material layer by layer. Typically, FDM uses plastic filaments, which are fed into an extrusion head where the filaments are melted and extruded through a fine nozzle. By controlling the position of the extrusion head and the rate at which the filament is fed into the head, arbitrary patterns of material can be deposited onto a substrate, layer-by-layer, building up any desired 3D shape. FDM can produce mechanically robust objects with reasonably good resolution.

By using hybrid manufacturing technologies, fabrication of complex patterns, including electromagnetic structures, on conformal surfaces are made possible. Building the 3D object of interest in-house allows for rapid design iteration and versatility to evaluate as projects evolve. Through the combination of direct-write techniques, including micropen dispensing and laser-based processes, with 3D printing of plastic materials, various electronic devices can be fabricated quickly, precisely, and at relatively low cost.

Experimental

Several different advanced fabrication technologies were used to create complex, conformal electromagnetic structures, resulting in a hybrid manufacturing approach. These different methods are described in technical detail in this section.

Laser processing, including laser micromachining, was performed using either a 266nm $Nd:YVO_4$ laser (Coherent AVIA) or a 355nm $Nd:YVO_4$ laser (JDSU Q301-HD), both with a pulse length of 30ns FWHM. Typical energy required to laser ablate material was ~1 J/cm^2. To facilitate faster scanning speeds, galvnometric scanning mirrors (ScanLab HurryScan10) were used to raster the laser beam.

Micropen dispensing was done using a 3cc syringe barrel with a dispensing tip (Nordson EFD). Two different tips were used for dispensing, depending on material viscosity. If the material is viscous enough (> 50 cP), the dispensing can be done by utilizing gravity, where the material is simply dispensed onto the surface as the substrate is translated beneath the tip. If the material is of low viscosity (< 50 cP), this method is not viable because the flow rate cannot be controlled and liquid is dispensed too quickly. In this case, a dispensing head is modified by replacing the tip with a fiber pen tip (Sharpie pen tip, by Sanford, Inc.), where the fibers wick the material from the syringe and simple write the pattern similar to a Sharpie marker. The fibrous tip is in direct contact with the surface, where writing relies on capillarity wicking of the liquid onto the surface.

To fabricate 3D plastic structures via FDM, a MakerBot Industries StepStruder MK7 extrusion print head was incorporated with the existing LDW z-stage. By integrating the extrusion head into the LDW system, both 3D printing of the plastic and laser patterning can be done without having to move or disrupt the part. Because x-y translation stages are used, the part can be laser patterned at any point during fabrication without loss of alignment.

Results & Discussion

A wide variety of electromagnetic and electronic structures were fabricated using the hybrid manufacturing technologies discussed above. In this section, several of these examples will be described.

By combining two distinct additive manufacturing techniques, a 20cm diameter parabolic wire grid polarizer was fabricated. Because both the laser direct-write and micropen dispensing systems are set up on the same table, both manufacturing steps can be completed in succession without disruption or loss of registration of the sample. A 20cm parabolic foam block, made of Rohacell high-performance foam, was mounted onto an x-y translation stage. Before depositing the conductive layer, a thin layer of polyester resin composite was painted onto the surface to protect the foam from any diffusion of the Ag layer. A thin Ag layer (~150 nm) was then applied using a micropen dispensing tip over the entire 20cm surface. The sample was then cured at low temperature (80°C) to remove all solvents from the ink and partially sinter the Ag layer. The Ag layer was subsequently patterned using laser ablation to produce 150µm wide lines with a 730µm pitch. By using galvo scanning mirrors, the laser was rastered over the surface, allowing each grid line to be patterned in one pass. The patterned sample was then cured at 150°C to fully sinter the Ag layer, rendering the lines fully conductive. The completed wire grid polarizer is shown in Figure 1. The ability to both dispense and laser direct-write on this 3D surface was made possible by coordinating the z-stage, which holds both the micropen dispenser and the galvo mirrors, with the x-y motion.

In addition, we have demonstrated the ability to print functional devices onto 3D surfaces using a combination of advanced manufacturing technologies. Because micropen dispensing allows for the deposition of material onto both concave and convex surfaces, antennas can be fabricated on hemispheres. In Figure 2(a), a circular patch antenna printed on a 6" acrylic hemisphere is shown. This antenna was fabricated by depositing Ag nano-ink on both the inner and outer surfaces of the hemisphere using micropen dispensing. A via was laser drilled through the center of the acrylic to allow for a SMA connector to be attached for testing of the antenna. Because acrylic has a low melting temperature, this antenna was cured using a flash lamp. By using photonic curing, conductive inks can be cured at significantly lower temperatures than traditional thermal cures in an oven. The return loss was measured using an HP8510 network analyzer yielding -19dB at 6.6GHz. This antenna is yet another successful demonstration of using a versatile, efficient dispensing technique that is capable of working on conformal surfaces to fabricate fully functional electromagnetic structures.

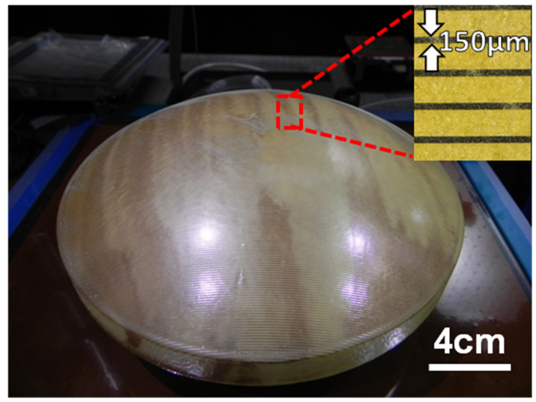

Figure 1. *Wire grid polarizer on 20cm Rohacell foam ellipsoid fabricated using micropen dispensing and laser micromachining (150µm lines with 730µm pitch).*

By using a similar fabrication method to that of the circular patch antennas, electronic devices can be embedded into a 6" acrylic hemisphere to demonstrate a 3D circuit. This is made possible by combining several different manufacturing techniques, including laser direct-write, micropen dispensing, and Lase-and-Place. In this particular example, the 3D circuit consists of an array of LEDs interconnected across the outer surface of the 6" hemisphere. First, several small pockets were laser micromachined to act as receiving pockets for the active LED elements. The LEDs were then embedded into these pockets using a novel process developed at NRL called "Lase-and-Place" [3]. Here, the components to be transferred are mounted on a laser-transparent substrate using a sacrificial polymer layer. Once exposed to laser energy, the polymer layer is ablated, generating a vapor which propels the component onto the receiving substrate. Lase-and-Place is a versatile process that can place or embed onto any surface mm to µm-sized structures, including semiconductor bare-die, SMTs, sensors, and actuators, to name a few. Once the LEDs are embedded into the acrylic pockets, a micropen dispensing tip is used to write conductive lines that electrically connect the active electronic components. The conformal embedded LEDs can be seen in Figure 2(b), where each device is powered on. Conformal embedded LEDs on a 3D surface truly embody the advantages of using hybrid manufacturing techniques to achieve complex, functional devices.

The ability to print electronics directly onto combat helmets provides a significant step forward in creating more compact electronics that help alleviate the weight that a warfighter must carry. By using additive manufacturing, two different antenna designs were printed onto military-issued combat helmets. The surface of the helmet was modeled as an ellipsoid, allowing the z-stage to be programmed to move in conjunction with the x-y translation stages. By doing so, the micropen dispensing tip always remains at the same exact distance above the helmet surface, resulting in a uniform deposition over a large area. Both a broadband spiral antenna (2-18GHz) and a Yagi directional antenna array (3.5-6GHz) were printed onto military-issued helmets using Ag nano-ink. The resolution of the finest features in the antenna pattern is on the order of ~100µm. The fully cured broadband spiral antenna on a military-issued helmet can be seen in Fig. 3. The ability to print onto a practical 3D surface that does not represent a perfect hemisphere demonstrates the versatility of this hybrid manufacturing method.

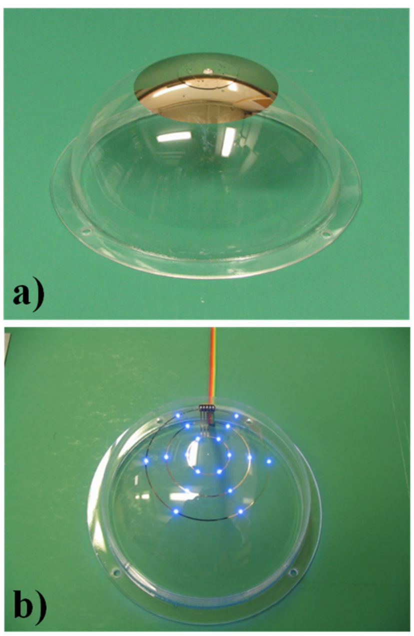

Figure 2. *a) Circular patch antenna (6.6GHz) on 6" acrylic hemisphere printed using Ag nano-ink via micropen dispensing technique and b) embedded LEDs on 6" acrylic hemisphere with Ag interconnect printed using micropen dispensing.*

The examples discussed so far have involved fabricating complex structures on commercially available 3D surfaces. In addition to manufacturing functional structures on these surfaces, such as acrylic hemispheres or Rohacell foam, we have demonstrated the ability to manufacture these structural components using fused deposition modeling (FDM). FDM is an additive manufacturing process that involves depositing material layer by layer. Typically, plastic filaments are fed into an extrusion head that is used to deposit material onto a substrate. The 3D object is realized by building up the extruded material layer by layer. At NRL, FDM has been combined with LDW to allow for the fabrication of arbitrary 3D structures with embedded interconnected devices. To fabricate 3D plastic structures, a MakerBot Industries StepStruder MK7 extrusion print head was incorporated with the existing LDW z-stage. By integrating the extrusion head into the LDW system, both 3D printing of the plastic and laser patterning can be done without having to move or disrupt the part. Because x-y translation stages are used, the part can be laser patterned at any point during fabrication without loss of alignment.

Figure 3. *Broadband circularly polarized antenna (2-18GHz) printed on a military-issued combat helmet.*

To demonstrate the ability to print 3D structures using FDM, an X-band horn antenna was designed and printed using ABS plastic. The printed antenna was conformally coated with Ag nano-ink using a dip-coater (MTI, PTL-100) and then processed at low temperature (~80°C) for 2 hours to render the ink fully conductive. The final horn antenna can be seen below in Fig. 4.

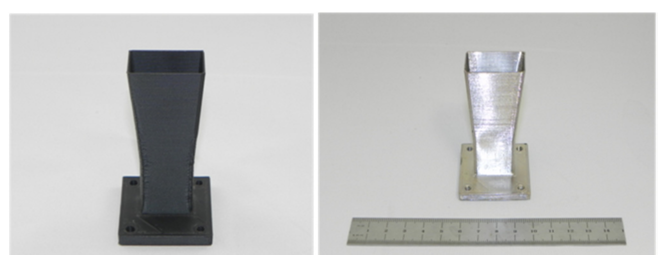

Figure 4. *3D-printed X-band horn antenna before (left) and after (right) metallization using Ag nano-ink.*

By using FDM in combination with laser patterning, we have developed a new technique for the fabrication of embedded electronics called Nickel Laser Patterning [4]. The process begins with 3D printing of an ABS plastic substrate that contains recessed pockets in which electronic components can be embedded. A conformal electroless nickel coating is plated over the entire surface of the plastic. The nickel is then laser patterned to achieve the desired conductive structures using a 266nm laser with a fluence of ~0.5 J/cm^2. To account for z-height differences over the pockets, the laser focus was dynamically adjusted to fully pattern the nickel over the entire substrate surface. The components are attached using conductive epoxy and cured at 80°C (Fig. 5). This process is similar to that of traditional printed circuit boards in which the surface begins as a continuous sheet of copper that is patterned. This process offers the advantage of versatility, having complete control over design and functionality because the entire part is fabricated in-house.

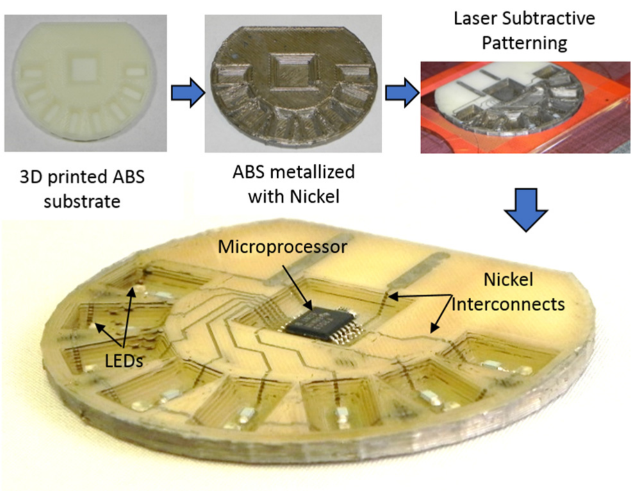

Figure 5. *3D printed embedded electronic circuit via Nickel Laser Patterning.*

Summary

The integration of individual advanced manufacturing techniques into hybrid manufacturing processes allows for the fabrication of 3D electromagnetic structures that would otherwise not be possible. The methods used include substrate printing through fused deposition modeling, along with several direct-write techniques, including dispensing and laser processing. By using these fabrication processes, we have successfully demonstrated a wide variety of 3D electromagnetic structures, including conformal antennas, polarizers, and embedded electronic circuits, to name a few. These hybrid manufacturing technologies offer the advantages of design space flexibility and material versatility, which opens the door for the fabrication of complex, conformal electromagnetic structures.

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Author Biography

Nicholas Charipar received his BS and MS in electrical engineering technology from Purdue University in 2006 and 2009, respectively. Since then he has been working at the US Naval Research Laboratory in the Materials Science & Technology Division in Washington, DC. His research interests include electromagnetics and advanced microfabrication techniques