

Bridging the Manufacturing Gap between Macro and Micro Devices

Arthur L. Chait
CEO & President
EoPlex Technologies, Inc.
3698 Haven Avenue
Redwood City, CA 94063
Phone: 650.298.6501
Fax: 650.361.9071
Email: achait@eoplex.com

Abstract

Many manufacturing methods exist that can produce a variety of complex parts. However, a significant need is still unmet in techniques that allow the design and volume production of small, complex, 3-D parts, which contain several different materials. This “Gap” is especially evident for sintered ceramics, metals and ceramic-metal composites. High Volume Print Forming (HVPFTM) is a new technology that helps fill a critical portion of this Gap. HVPFTM provides engineers with new design rules that allow unique designs to be made at low cost from a variety of materials. The technology is a clean-tech additive process and is able to replace some older methods that require etching, machining and other processes that can have negative environmental impacts. The process creates thousands of parts simultaneously at low cost. This new technology is being used to lower the costs and improve the design of existing products and to develop designs that were not cost effective or even possible before. Examples are given in miniature antennas, semiconductor packages, energy harvesting devices and fuel cell parts. HVPFTM builds devices using 3-D voxels of material or “microbricks” and, as a result, offers the potential for a new class of low-cost metamaterials. The metamaterial applications are still under development and the early results are introduced in this paper.

Keywords

Print-Forming, Voxels, Cell Phones, QFN, Metamaterials, Antennas

The Gap

A significant Gap exists in the manufacturing methods that can be used to produce high volumes of miniature ceramic-metal devices. This Gap is defined by at least four conditions:

1. Size
2. Complexity
3. Number of materials
4. Cost

Engineers have devised ingenious methods to produce a host of amazing devices. However, sometimes the design that would give a competitive advantage cannot be realized, since there are no cost-effective methods to produce it. In some cases, the only alternative is to use micro-assembly. A good example of this is the vibration motor hidden away in almost all cell phones. Other methods of vibration have been tried for cell phones, but the motor and weight assembly shown in Figure 1 is still the preferred method. Unfortunately, these motors must still be made by micro-assembly in low-cost regions.

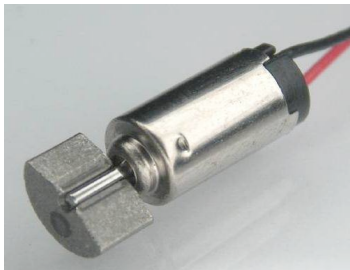


Figure 1: Cell Phone Vibration Motor Manufactured By Precision Microdrives

While this method is satisfactory for some parts that are not too small, it becomes increasingly difficult as the part size decreases and as the number of materials increases. In addition, some 3-D designs are technically impossible to produce with assembly.

Many other manufacturing techniques are used for small complex devices, especially where the number of materials can be limited. A representative list would include: electroforming, micro-molding, LIGA, lamination, MEMs, EFAB and others. Some of these techniques can utilize different materials, but it is usually expensive and difficult to use more than two materials in the same device. For example, with micro-molding, it is possible to design a mold with movable internal baffles so that two different

materials can be injected into the mold in their proper location. With MEMs (micro electro mechanical systems) it is also sometimes possible to work with a few materials and to use both a metal and the oxide of the metal in the same part. While this is technically feasible, the majority of MEMs parts are still based primarily on silicon and silicon dioxide and these are processed by semiconductor methods.

All of these methods still leave a Gap that is illustrated in Figure 2. The X-axis represents feature size and the Y-axis represents the number of materials in the device. The X-axis starts on the left with micro-assembly and moves to the right through molding and MEMs and all the way to the world of nanotechnology, where devices assemble themselves. The Gap illustrated below is for methods in the mass production of low-cost, small, complex devices that require multiple materials.

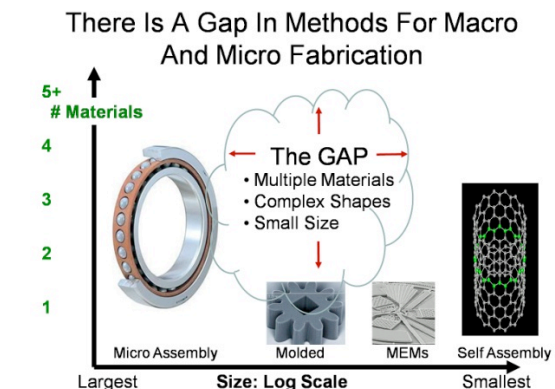


Figure 2

High Volume Print Forming

In the 1990s, engineers working to develop a medical catheter were struggling to create a design that fell within the Gap area of Figure 2. This led to the invention of technology that became known as High Volume Print Forming™ (HVPF™) [1].

HVPF™[2] uses a combination of processes and materials from ceramics, metallurgy and polymers along with proprietary printing techniques to produce parts in the Gap where the parameters include:

- Typical device size: 1mm-10 cm
- Number of materials: 1-7
- Minimum feature size: 50μ-200 μ
- Maximum number of layers: 100s, limited only by cost
- Features include: channels, conductors, capacitors, open spaces, sealed cavities, piezoelectric elements, heaters and catalysts

HVPF™ can best be illustrated by considering the manufacture of a part that appears simple, but which offers several challenges. This part, shown in Figure 3, is composed of two conductors separated by a ceramic dielectric. It has hollow vias at each end and a portion that is suspended without direct support. Assume that this part is needed in high volumes, such as millions per week, and that it must sell for less than 10 cents/part. There are not many techniques that would be able to produce this part. Techniques like brazing and LTCC (low temperature cofired ceramics) have some potential, but costs would be high and processing difficult.

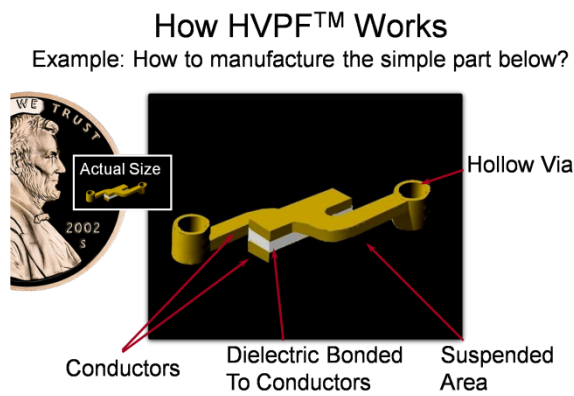


Figure 3

HVPF™ would manufacture this part with an additive approach. Proprietary “inks”, usually called printing pastes, would be used to build the part in layers. As shown in Figure 4, the first layer is a print of the bottom metal conductor. In production, it may take several layers to create the proper thickness of this feature. After each print, the image is cured to a temporary “B” stage to allow additional layers to be added. Various cure methods are utilized including: UV radiation, other radiation and heat. All of the layers will bond chemically as the process continues. As the bottom conductor is built, the area around it is printed with a negative image (shown in orange) to give a flat surface and to support the prior features.

The remaining features are built in a similar fashion with the ceramic parts added next. The upper conductors are then deposited on top of the negative structure, so that they are supported to create the overhanging portion. The finished part is a block of three different materials: metal, ceramic and fugitive (orange). The fugitive will be driven off in special heat treating processes and the parts are all fired together, leaving four completely finished parts ready for inspection, test and shipment.

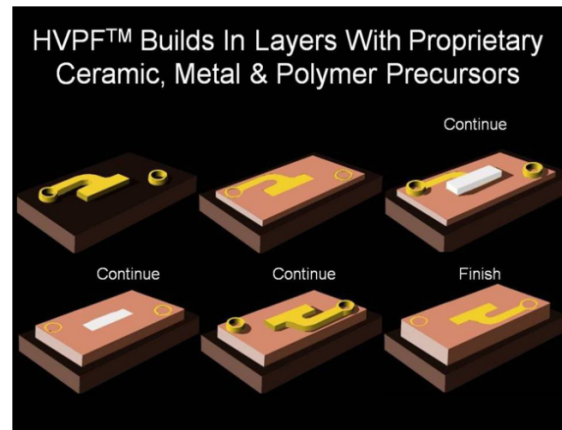


Figure 4

HVPF™ can manufacture large panels of devices simultaneously. Panel-processing is one of the ways that HVPF™ keeps costs low even for complex devices. Figure 5 illustrates a small panel before and after heat treating.

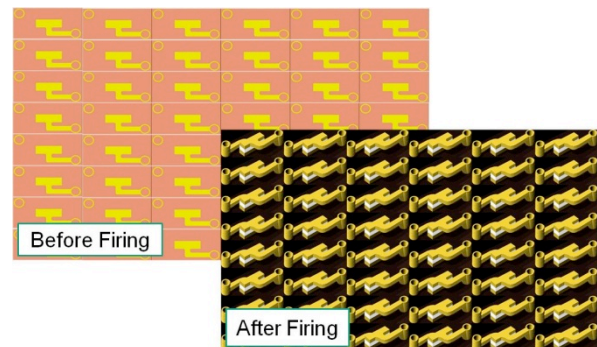


Figure 5

The simple part in Figure 3 was used to illustrate how HVPF™ works. Actual parts are usually more complex and contain more materials. Figure 6 shows samples of more complex parts that were prepared for demonstration. The package on the left is a section of a large panel and contains four parts built with 200 layers and 60 different features. On the right, the finished parts are shown after the red, fugitive material has been removed.

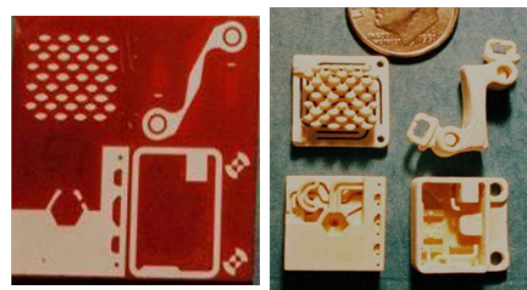


Figure 6

The demo-parts in Figure 6 are not customer devices and were prepared to illustrate capabilities of the process. The part in the upper left quadrant demonstrates structures that may be valuable for heat management, upper right demonstrates a device with moving parts, lower left is a fluidic part shown with half of the top removed to reveal some of the inner structure and lower right is a package with undercut and cantilever elements. These parts help demonstrate the advantages of the HVPF™ method including:

- Low cost
- Enables designs not possible by other techniques
- Multiple materials are allowed
- 3-D designs are cost effective
- Design changes are fast - similar to editing
- Components are built into devices during production
- Existing designs improved and costs reduced
- Provides new design rules for customers to take full advantage of the technology and develop new devices superior to competitors

An additional advantage is that the HVPF™ fabrication facility (FAB) is relatively small and low cost. This allows the FAB to be located anywhere within the customer supply chain: including sites nearby, across the “fence” and even within the customer’s factory. A local plant is not always necessary, but it can provide the lowest total cost of ownership, the highest level of supply chain integrity and minimizes risks from disruptions due to weather, terrorist activities, fuel shortages, strikes, etc. A typical HVPF™ FAB line is shown in Figure 7.

FAB Is Small, Inexpensive & Can Be Located Anywhere In The Supply Chain



Figure 7: Typical EoPlex FAB

Applications:

HVPF™ is a platform technology that can be used successfully in many applications. Working with customers in many markets, we have identified two applications where this technology offers many advantages. These markets are: 1. Ceramic chip antennas and 2. Micro lead frame packages. These applications are discussed next. We are also working at a lower level on a few other markets including: Sensors, Energy Harvesters and Fluidic Devices for fuel cells and other applications.

Ceramic Antennas: Modern cell phones contain many more antennas than might be expected. In the early days, cell phones were large “bricks” and as the technology advanced they began to shrink in size and weight. Recently this trend has stabilized and even reversed as more features are added to phones, including large displays, cameras, GPS, TV, etc. Today, a typical smart phone may contain several primary antennas to connect to different types of voice networks and a handful of secondary antennas, or ancillary antennas, to connect to wireless headsets, WiFi, MIMO, GPS, laptops and new services, which are added constantly. As the number of services goes up, the space within the cell phone becomes more of a premium and everything possible is done to reduce the number and size of the components. Ceramic antennas were developed for just this reason. They typically perform better, where size must be limited, compared to the older metal wires or trace antennas. Most importantly, they are small and can be handled with SMT equipment like any other circuit component.

Figure 8 shows some ceramic antennas made by EoPlex using HVPF™. Several of these samples contain hidden internal features, multiple dielectrics, or other unique features. These antennas are demonstration samples and not customer proprietary designs. The smallest samples shown in this package are 2X6X1 mm and are intended for cell phone use. In production, about 2,000 to 10,000 of these parts are made at once on a single substrate.

Ceramic antennas are a good example of how a technology like HVPF™ can free engineers from the limitations of older design rules. With HVPF™ designers can integrate multiple dielectrics, complex metal layers and structures, as well as open spaces, to create totally new antennas. These new design rules are already showing the way to wider bandwidth, smaller sizes, lower cost, better efficiency and multiple antennas on the same chip

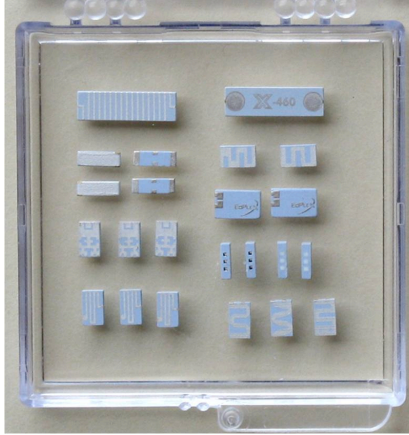


Figure 8: EoPlex Cell Phone Antennas

An exciting recent development with HVPF™ is its use to create parts with metamaterial-like structures. Conventional printing can print 2-D images from thousands of pixels in different colors. In a direct analogy, HVPF™ “prints” parts from thousands of 3-D pixels, known as voxels, in different materials. This gives engineers the freedom to create new metamaterials. Metamaterials are materials that get their properties primarily from microstructure rather than from just their chemistry. Metamaterials have been in the news recently since Dr. David R. Smith^[3] and his team at Duke University demonstrated the first successful “cloaking device.” Using metamaterials, the Duke scientists were able to create a device which bent microwaves around an object. As a result, if you were scanning this object with microwaves you would “see” what was behind it, but not the object itself. The object would be invisible or cloaked in the best tradition of Star Trek.

Definitions of metamaterials often include the statement that they are artificial structures not found in nature. However, a material that is a lot like a metamaterial and which does occur in nature is mother of pearl or nacre. Nacre occurs in sea shells like those of abalone or oysters. It is very strong and shows beautiful iridescent patterns on the inside of the shell, yet it is made from the same stuff as the piece of chalk which breaks when it falls from the blackboard. Anyone who has tried to open an oyster or pried an abalone off a rock will have firsthand experience of just how strong these shells are. Both the strength and the iridescence is a direct result of structure of the “chalk” in these shells, which is in the form of tiny micro plates or voxels bonded together with a second phase. These plates give the shell its strength and are small enough to create an interference pattern with light and the beautiful colors.

HVPF™ can produce new metamaterial structures from different materials at low cost, offering the potential for totally unique antennas and other devices in the future. The work being done by Dr. John Halloran at the University of Michigan indicates that ultra-wide-band antennas may be possible by the use of metamaterials and that new methods are needed for their production^[4]. Figure 9 shows some models of EoPlex metamaterial structures and Figure 10 shows some early EoPlex laboratory prototypes.

Voxel Deposition Allows Creation of New Meta Materials

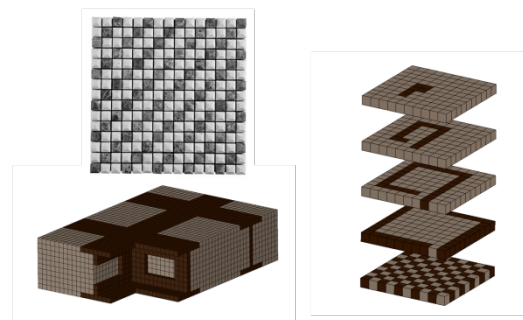


Figure 9: Metamaterial designs

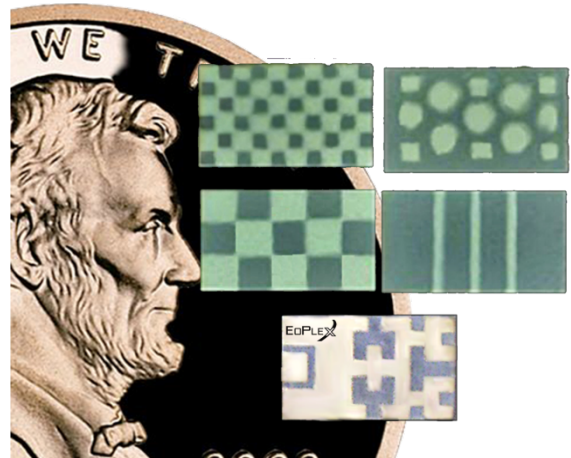


Figure 10: Typical types of metamaterial layers under study shown with a finished antenna (bottom)

Quad Flat No Leads Package (QFN): A QFN is a micro-lead frame package that is widely used in portable and low-power electronics. These were patented in 1999 and their use has grown each year. QFNs are successful, but there is still need for lower cost versions and to eliminate the plating processes and other steps that create environmental problems. A basic QFN is shown in Figure 11. EoPlex engineers are currently developing a novel QFN with

HVPF™ that would eliminate plating and reduce both size and cost. “Clean-tech” QFNs are scheduled for commercial launch in late 2009.

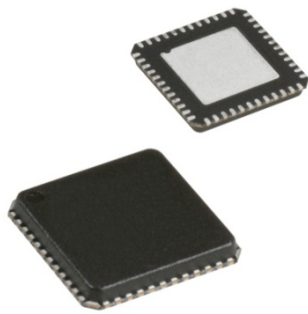


Figure 11: Top and bottom views of a typical QFN

Energy Harvesters: Energy harvesters, also called energy scavengers, are devices which capture free energy from the environment and store it to power certain types of circuits. The military has been funding research in energy harvesters to convert the motion of soldiers into electrical power. This application is difficult, but harvesting mechanical energy from other sources looks very promising.

One of the best sources of energy to harvest is vibration from machinery, motors or vehicles. Energy harvesting has received a lot of interest since the passage of the TREAD act of 2000, which mandated tire pressure sensors on new cars and light trucks in the USA. This legislation was enacted in response to a cluster of fatal accidents linked to under-inflated tires on SUVs. The law requires sensors on all wheels for new cars sold in the United States starting in 2007.

Tire sensors are not new. Some high-end vehicles, like the Corvette sports car, have had them since the late 1980s. However, requiring them on all new cars meant that the sensors had to be very low cost and highly reliable. New tire pressure sensors were developed to meet this requirement. Today's sensors are small, sealed units that mount on the wheel or valve stem inside a tire and send a wireless signal to warn the driver of under inflation. A typical sensor is shown in Figure 12.

These sensors work well and are relatively low cost, but there are two problems with them. First, they are battery powered and, although batteries will work well in many climates, they may not last as long in the parts of the country where weather and temperatures are extreme and where roads are rough. Second, the units must be sealed to protect against water, road chemicals and other hazards. As a result, the batteries in them are not replaceable and the

entire unit must be replaced and recycled properly when the battery fails.



Figure 12: Left, sensor showing wheel mount location. Right, back of sensor with potting compound removed

A spinning and vibrating tire represents a good source of energy for several harvesting schemes. Unfortunately, most of these add more costs than automotive OEMs can tolerate. The one method that has looked promising is the piezoelectric (PZT) harvester. A schematic of the PZT energy harvesting concept is shown in Figure 13.

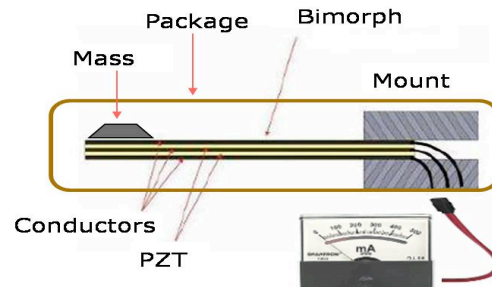


Figure 13: PZT Energy Harvester

A PZT energy harvester is essentially a cantilevered beam made up of layers of conductor and PZT ceramic with a mass attached to one end. Vibration of the beam generates a charge in the PZT, which is collected by the conductors and accumulated in a capacitor in the circuit. In the case of a tire pressure application, the requirement is for a new signal every 20 seconds and the harvester must be designed to produce enough energy to meet this specification. Tire vibration rather than tire rotation is the best source of energy to harvest for this application and can provide all the energy required.

The problem with energy harvesters is that manufacturing processes previously available could not produce a rugged device at a competitive cost. HVPF™ allows for production of the PZT bimorph, vibration mass, mount, conductors and parts of the package all in one step as shown in Figure 14 (top). This creates a rugged package at a price that is competitive with batteries. Two different

configurations of EoPlex harvesters are shown in Figure 14 (bottom).

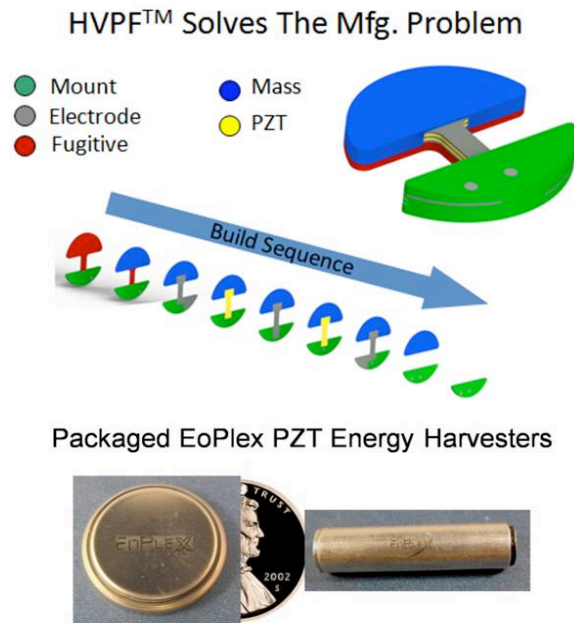


Figure 14: Top diagram showing how HVPF™ is used to construct an energy harvester. Bottom Left: coin cell harvester; Bottom Right: cylindrical cell harvester

The advantages of replacing batteries with these types of energy harvesters include:

- Potential energy source for the life of vehicle
- Eliminates dead batteries and replacement costs
- Greener - no battery disposal
- Not degraded in use

Energy harvesters can now be modeled and designed to provide the output required by a number of different applications. Figure 15 shows the output of one typical EoPlex energy harvester designed to operate in an environment where vibrations generate a few Gs. Other designs have been produced for vibration forces in fractional Gs and for G-forces that are much higher.

Parts such as these have been running in our vibration simulator for over a billion cycles with no statistical drop in output. We expect energy harvesters to be adopted in tire sensors and other applications, such as monitoring motors and other parts of vehicles, within the next few years.

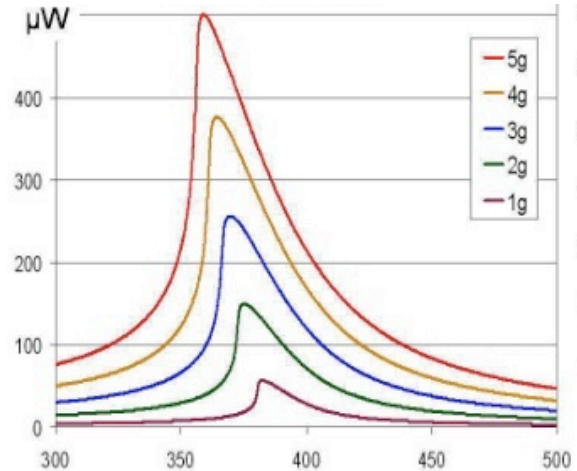


Figure 15: Energy harvester output: Y-axis power in micro watts, X-axis vibration frequency in hertz

Fluidic Devices: The part shown in lower left quadrant of Figure 6 is a demonstration of a fluidic device made with HVPF™. This device includes complex internal channels, chambers, pipes and cavities. To build devices such as this, EoPlex had to develop a family of printing inks that are called “fugitive” or “negative” inks. These formulations had to meet very demanding criteria. They had to deposit features with great accuracy and precision and then disappear at the proper time to leave behind the fluidic pathways. When these materials disappear, they must do so at a controlled rate. This is critical, since the rest of the structure is in what is known as the “green state” and very weak. The negative inks must depart without creating any excess pressure on the rest of the structure. In some designs, the cavity or chamber defined by the fugitive material will have only a small opening to the outside or even be completely closed. In these cases, the fugitive must defuse through the pores in the walls of the structure, otherwise the device may literally be blown apart.

The ability of HVPF™ to allow designers to form internal open structures at low cost and insitu is extremely valuable with many types of fluidic devices. An excellent example is the work EoPlex did on a miniature hydrogen reformer for portable fuel cells. There are many types of fuel cells under development and some are already in use for limited applications. One particular application that has received a lot of attention, is the use of fuel cells to replace the large weight of batteries carried by soldiers, firefighters, police, emergency and other first responders.

These applications require a fuel-cell system that can deliver significant power. One of the best systems in this class is the type of fuel cell that works with hydrogen gas. Unfortunately, hydrogen is difficult and dangerous to carry and it is hard to resupply in the field. As a result, there is a need for a fuel cell plus a miniature hydrogen reformer that can extract hydrogen from an alcohol-water mixture. Alcohol is easily and safely carried, is widely available and can be resupplied in the field. A reformer-fuel cell system could provide all the power required at 50 percent of the weight of batteries.

Reforming is the process by which hydrocarbons, such as alcohol, natural gas or gasoline, are converted to hydrogen. The plant required for this process is known as a reformer. A typical full scale reformer plant is shown in Figure 16.



Figure 16: Typical reformer plant; The Linde Group

In a reformer that converts methanol (CH_3OH) to hydrogen, the reactions are as follows:

1. $\text{CH}_3\text{OH} + \text{heat} + \text{catalyst} \rightarrow \text{CO} + 2\text{H}_2$
2. $\text{H}_2\text{O} + \text{CO} + \text{catalyst} \rightarrow \text{CO}_2 + \text{H}_2$

For a portable fuel cell, the reformer must be miniaturized to the size of a stack of US quarters, as shown in Figure 17. The original design for this reformer was brought to EoPlex by our customer who was not yet familiar with all the options presented by the EoPlex technology. Working together, we were able to improve the design, lower cost to them and take advantage of true 3-D design rules. The result was a miniature device with over 30 different internal design features including: a heater, catalyst beds, ports, channels, chambers and electrical connections. The entire device was created in one package that required over 300 layers and 5 different materials. All of the internal structure was formed during the heat treating cycle and no machining or other forming was

required. These devices were tested successfully and one sample is shown in Figure 17.

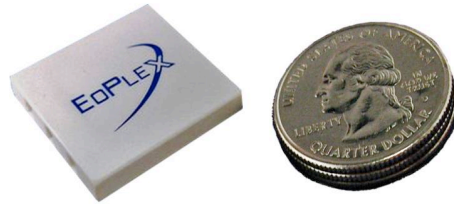


Figure 17: Miniature Fuel Cell Reformer

Conclusion

Many manufacturing methods exist that can produce a variety of complex parts. However, a significant need is still unmet and a “Gap” exists in techniques that allow the design and high-volume production of small, complex, 3-D parts which contain several different materials. High Volume Print Forming (HVPF™) is a new technology that helps fill a critical portion of this Gap. HVPF™ provides engineers with new design rules that allow unique designs to be made at low cost from a variety of materials. The technology is a clean-tech process, and is able to replace older methods that require etching, machining and other processes that can have negative environmental impacts. EoPlex Technologies, Inc. is a private company that is using this technology to commercialize new designs for products like miniature antennas, semiconductor packages, fluidic devices and energy harvesters.

References

- [1] Charles S. Taylor, et al, “Spatial Forming” A Three Dimensional Printing Process”; 29 January – 2 Feb, 1995; IEEE Publication
- [1] US Patent number 5,348,693; Taylor et al.
- [2] Arthur L. Chait, “High-Volume Print Forming, HVPF™ - A New Method for Manufacturing Large Volumes of Complex Metal-Ceramic and Hybrid Components”; IMAPS etc.....
- [3] Justin Mullins, “Working invisibility cloak created at last”; New Scientist, October 19, 2006
- [4] Dr. John Halloran, University of Michigan
<http://www.mse.engin.umich.edu/research/projects/72>