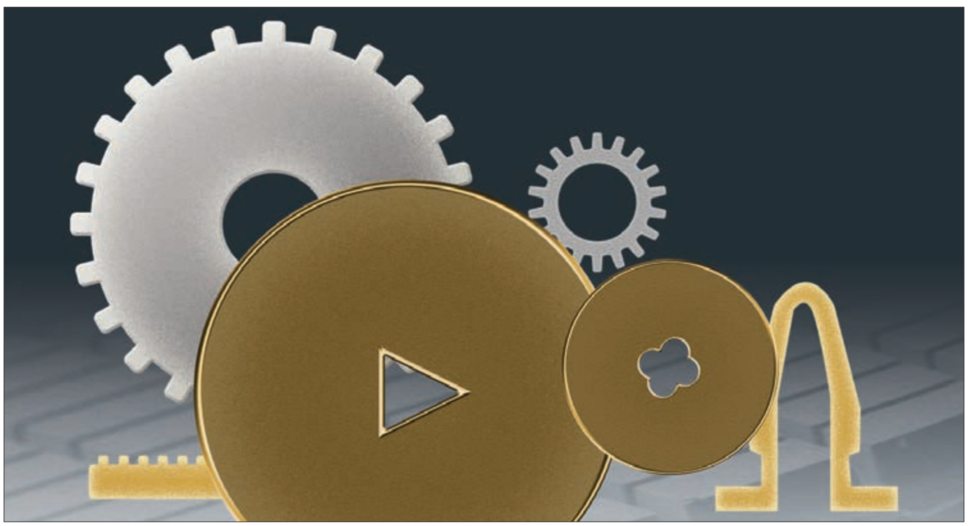
Leveraging the Precision of Electroforming over Alternative Processes When Developing Nano-scale Structures



Electrical and mechanical component and subsystem designers generally have five techniques to consider when deciding how to fabricate their ultra-miniature metallic components: **electroforming, electrochemical machining (ECM), photochemical machining (PCM), laser cutting and drilling, and electrical dischargemachining (EDM)**.

While many factors will enter a decision, on the basis of pure precision, electroforming excels. Additional advantages include layering options (electroformed metal can be molecularly bonded together) and the ability to introduce different substrate materials to produce complex structures. Common components include: nozzles, slits, clips, screen, mesh, embossing tools, and encoder disks, used in medical, ink jet, laboratory, LCD, and fluidics applications.

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Precision at this scale is a science

When manufacturing at nano-scale with extremely close tolerances many factors come into play that are not inherently present at larger scale. And as a component gets smaller the challenges are incremental. The five methods of nano-scale manufacturing can therefore be ranked from top to bottom as a matter related to the tolerances that one can achieve of and between each feature. As seen here, electroforming offers the most desirable tolerance.

Fabrication Technique	Feature Tolerance
Electroforming	**± 2 microns**
Electrochemical Machining (ECM)	± 5 microns
Photochemical Machining (PCM)	± 25 microns
Laser Cutting	± 50 microns
Electrical Discharge Machining (EDM)	± 50 microns

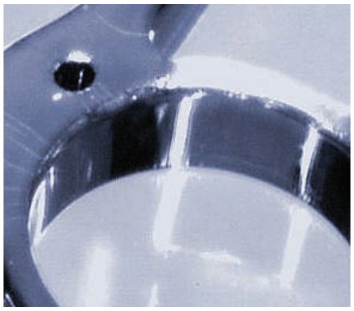
The reason these methods differ in precision is due to the underlying science of how they work — for example, how they either add or subtract very small amounts of material from a surface and the way they are able to contour a shape in three dimensions (if a particular method can at all). Each method therefore "locks in" the manufacturer to a certain level of precision before fabrication even starts.

Let's look at each one of these methods in turn to see why.

Electroforming

Precision electroforming is an additive process in which 2-D and 3-D* microstructures are formed by electrochemically depositing metal onto a precisely patterned photoresist mandrel. Electroforming is ideal for fabricating micron-scale metallic components as well as for making injection molds used for forming nonmetallic microstructures with nano-scale features. Benefits include low-cost, high-quality production plus high repeatability. Such structures may be free-standing or connected together with tabs to facilitate handling or mounting for additional processing. Electroforming is ideal for fabricating complex parts such as micro-nozzles, inject nozzles, orifice plates, nozzle plates, slits, screens, mesh, disks for products like nebulizers, and more.

The process deposits metal onto a (typically glass) mandrel that has been coated with a very thin metal layer covered with photoresist. The photoresist is photo-imaged so that after it is exposed to light a pattern of openings appears in the photoresist, expos-



Electroforming

Compared to other metal forming processes electroforming is very effective when requirements call for extreme tolerances, complexity or light weight. The precision and resolution inherent in the photographically produced conductive patterned substrate, allows finer geometries to be produced to tighter tolerances while maintaining superior edge definition with a straight and smooth finish. Electroformed metal is extremely pure, with superior properties over wrought metal due to its refined crystal structure.

*While electroforming technically produces three dimensional, or 3-D components, for the purpose of this discussion 3-D is limited to singularly formed (if not multi-layer) devices due to the necessity to be able to remove the part from a mandrel..

ing some of the underlying metal — openings that correspond to the features to be fabricated. The pattern is created by UV light shining through a photo-mask that a designer creates on a CAD system. The technology is commonly referred to as photolithography.

The mandrel with the photo-imaged metal layer is immersed in an electrolytic bath containing an ionized solution, and a positively charged cathode made of a metal such as nickel (Ni). The metal from the cathode passes to and bonds with the parts of the metal that are on the mandrel through the action of an electric current. As more and more metal is deposited, a three-dimensional structure rises from the photoresist pattern.

Depending on the resolution of the mask image, electroformed features can be extremely tiny — down to 5 microns (or less) in the Metrigraphics' process. The size of openings, like a nozzle orifice, can be as small as 5 microns and in some cases even smaller.

While electroforming technically produces three dimensional components, it is limited to singularly formed devices with no moving parts. While research and development firms are proving the capability of additive manufacturing techniques to produce sub-micron, micro-electromechanical devices (MEMs) and other submicron features and parts, for the purpose of this brief our discussion is centered single piece designs at 2 microns and above.

Electrochemical Machining (ECM)

ECM can be thought of as reverse electroforming. Like electroforming, both the part to be fabricated and an electrode are immersed in an electrolytic bath. A high electric current passes through an electrolyte between an electrode (called a tool) and the fabricated part, separated by an 80-800 millimeter gap. But unlike electroforming, instead of adding material to the part, ECM removes it. Following a programmed path the tool sculpts the part by essentially pulling off its electrons and turning some of the part's material into a metal hydroxide, which the electrolytic bath carries away.

Although, like electroforming, ECM works at an atomic level, unlike electroforming it relies on the motion of the tool rather than on the much more precise method of photolithography to achieve the desired geometries. So, although results are more precise than the other fabrication methods discussed here, they are less precise than those achieved with electroforming, as shown in Table 1.

Photochemical Machining (PCM)

Also called photo etching, PCM is a subtractive process like ECM but unlike ECM does rely on photolithography. Also, rather than use an electric current to create features in the fabricated part, it instead uses chemical agents. The process essentially consists of three steps: 1) creating a photo tool, 2) using the photo tool to image a photoresist-cov-

Electrochemical Machining (ECM)

Unlike electroforming, instead of adding material to the part, ECM removes it.

ered metal plate; and 3) exposing the metal plate to chemical agents to etch features by removing material from exposed metal.

The photo tool consists of two sheets of film that have been imprinted with an image of the part. Areas containing features are clear; areas not containing features are opaque. The two sheets are then optically and mechanically aligned to form the top and bottom halves of the tool.

The metal plate is formed by cutting a metal sheet to size and laminating it on both sides with a UV-sensitive photoresist. Placing the plate between the two sheets and exposing it to UV light causes the exposed areas of the photoresist (where the film is clear) to be hardened. The photoresist that is not hardened is then washed away from the unexposed areas.

The metal plate is then sprayed on both sides with an etching solution, frequently ferric chloride. The solution corrodes away the unprotected metal, leaving a sheet of fabricated parts, which are then cleaned, dried, and singulated into individual components.

Despite being a photolithographic process, PCM is less precise and harder to control than is electroforming or ECM. A chemical agent's action cannot be as precisely controlled as can electric current or voltage. Features are also less uniform. That's because the action of the chemical agent is more intense the deeper the chemical goes into the metal — so channels are wider (and feature walls thinner) at the bottom than at the top.

Laser Processing

Compared to other "macro scale" fabrication methods like drills, saws, and die cutting, lasers are highly precise, very programmable, and often less expensive. Lasers do not need to be replaced nearly as often as these other tools and setup is generally straight-forward. In addition, setup time may be required, resulting in significant expense before the actual part fabrication even begins. On the other hand, lasers are far less adept at making the types of ultra-miniature components for which the first three methods discussed here are often employed. One reason is that the width of the laser beam is proportional to its power. That means that the beam may be too wide to cut very small features if the material is too hard or too thick. Another issue with lasers is that, although well-suited for creating complex 2-D shapes, they are less well-suited for creating complex shapes in three dimensions.

Editor's Note: Ultra fast, short pulse femtosecond lasers have been demonstrated to be potentially viable in building up nano-structures on silicon carbide, but to the best of our knowledge this is not yet a commercially viable technology.

With a laser, the cutting action occurs when light from a laser (typically a CO^2 laser with an energy of 1500 to 2600 watts) passes through a slit and is directed by mirrors at the material to be cut. Parts are typically cut as two-dimensional designs from sheets of metal, ceramics, and certain plastics held in a fixture beneath a laser moving above the

Laser Processing

Lasers are highly precise, but ultra-small patterns and dimensional shapes are a challenge to achieve with laser cutting and drilling techniques.

sheet in a programed X and Y — but typically not Z or three-dimensional — pattern. As discussed earlier, electroforming and PCM can create complex 3-D shapes by adding layers of material (in electroforming) or subtracting subtracted layers (in PCM).
In ECM and in EDM (to be discussed next) the electrically charged tool these methods employ can sculpt the parts in three dimensions.

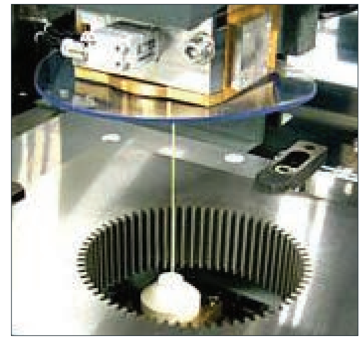
Mechanically aligning the laser (even under computer control) is also inherently less precise than using electric current — as in electroforming, PCM, and ECM — to either add or subtract microscopically thin layers of material.

Electric Discharge Machining (EDM)
This method is somewhat similar to ECM in that a cathode work tool (in this case, a wire tip) comes into near-contact with an oppositely charged fabricated part, both of which are immersed in an electrolytic bath. Two key differences are that: 1) in EDM the bath is non-conductive (i.e., it's a dielectric) and, 2) instead of adding material from the cathode to the part, material is essentially "broken off" the part by sparking. Enough voltage is applied so that the resistance of the dielectric is overcome and current (sparks) flow from the tool to the part, taking away minute bits of material from both — which is flushed away by adding new liquid dielectric to the inter-electrode volume. (Note: Because the cathode is also losing material in the process, it continually needs to be replenished — typically by bringing more cathode wire into the bath.)

Of all the methods discussed, EDM is the least suitable for fabricating very small parts or parts with extreme tolerances. Besides being fairly imprecise compared to these other methods, sparking is also likely to leave a pitted surface along with burrs (bits of excess metal) that must be polished away.

How Important Is Precision To You?

If precision ranks high on your list of priorities, then you may wish to consider fabrication using electroforming. The science of photolithography has proven time and time again that adding and subtracting materials using this method creates parts with the most perfected and repeatable outcomes.



Electric Discharge Machining (EDM)

EDM is the least efficient process when tolerances are critical. Pitting and burrs are common artifacts of the process.

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