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Additive/Subtractive Material Processing for Mesoscopic Parts

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Abstract

Mesoscopic additive/subtractive material processing (Meso A/SMP) is a solid freeform fabrication technique capable of producing engineering parts in mesoscopic (100 micron to several millimeters) scales. This process integrates silicon processing, electroplating, hot pressing, casting, and traditional machining methods to provide opportunities for 3D layer fabrication and parallel production, and opportunity to build small dimension parts. The proposed approach overcomes material constraints in MEMS fabrication and current layered manufacturing processes. In this paper, various manufacturing strategies are discussed for generating engineering parts with mesoscopic dimensions. In particular, processes to build components of magnetic field based micro motors and 3D thin airfoils are described.

Introduction

Most of the current solid freeform fabrication techniques are restricted to a small range of materials. Shape Deposition Manufacturing (SDM) [1] and Mold Shape Deposition Manufacturing (Mold SDM) [2] are capable of building objects of various engineering materials, but with a lower limit part size of several millimeters. The development of Micro-Electro-Mechanical Systems (MEMS) has enabled designers to conceive applications for smaller scale parts. However, the processes involved in MEMS have material and geometric limitations.

Mesoscopic additive/subtractive material processing (Meso A/SMP) expands solid freeform fabrication into the mesoscopic scale, which is defined as 100 microns to several millimeters. Meso A/SMP integrates silicon processing, electroplating, hot pressing, casting, and traditional machining methods to provide opportunities for 3D layer fabrication and the possibility of parallel production for mesoscopic parts. It allows a wide range of engineering materials to be used in this range, so that the material constraints in MEMS fabrication and current layered manufacturing processes can be overcome.

In this paper, manufacturing strategies and fabrication techniques in Meso A/SMP are discussed. Also, its application to build components of a magnetic field based micro-motor and a small flying vehicle, “mesicopter,” are illustrated.

Meso A/SMP Approach

For large-scale parts, additive/subtractive SFF techniques typically employ traditional machining methods and novel deposition methods for material addition and removal. In order to reach smaller dimensions, Very Large Scale Integration (VLSI) techniques have been used. Meso A/SMP integrates the processes innovatively by combining processes from traditional and VLSI regimes, and can be treated as a 2-stage process— planning and fabrication. Planning involves three main issues: 1. material selection, 2. decision of shaping strategies, and 3. determination of supporting operations for shaping strategies. Integrated in this approach are considerations for CAD modeling and checking of manufacturability. Once the fabrication strategies are determined, parts will be built according to the processes selected. Processes involved in material addition are electroplating, hot pressing, gelcasting, polymer casting, and casting of powder filled polymers. Likewise, EDM, CNC machining, and plasma etching are employed in material subtraction.

Planning

In the planning stage, the part's function and material requirements are considered. Under these constraints, materials for building the parts are selected first. Once the part material is selected and its characteristics are assessed, shaping techniques are chosen. Analysis is then performed on the selected shaping strategy to determine if support operations are required and how to coordinate them accordingly. Before starting the fabrication, one should also complete manufacturability checks and any necessary post-processing of CAD modeling.

Five groups of materials are considered in the material selection phase of planning—ceramics, polymers, magnetic materials, electroplated materials, and other conductive materials. The shaping strategies for different materials are summarized in the following table.

Material	**Example**	**Shaping Strategy**
Ceramics	Silicon Nitride	Gelcasting
Polymer	Epoxy, Polyurethane	Casting
Magnetic materials	Amorphous metal, Nd-Fe-B	EDM, Casting of powder
Electroplated metals	Cu, Ni	Electroplating
Other conductive materials	Alloys	EDM

For ceramics and polymers, the shaping strategies mainly rely on gelcasting and polymer casting. The supporting operation for these two fabrication techniques is to build molds. Molds can be made of wax or silicon. The molds may be generated by CNC machining and plasma etching, respectively. Wax, compared to aluminum, is easier to machine in the mesoscopic scale, and easier to remove by melting out. Wax allows for less tool wear and less machining time when working with high spindle speeds which is required for miniature end mills. Commercial miniature end mills have a size limitation of 0.01 inch (0.254mm) in diameter. Features smaller than this will require modifying machining sequences or using silicon molds. Part of the manufacturability analysis would determine if smaller dimensions exist on the potential part and modify the fabrication strategy. Silicon molds can be obtained by stacking thin etched silicon wafers.

Hard magnetic and soft magnetic materials are hard to machine and deposit. Most micro machining techniques cannot directly shape magnetic materials, whereas most large-scale material subtraction techniques for these materials cannot be used easily for micro and mesoscopic scale. Moreover, their crystalline structure has a strong impact on their performance, and deposition techniques in micro fabrication, such as electroplating or physical vapor deposition (PVD), do not allow enough control over the resulting microstructure. Complicated heat treatment cycles are involved to develop good magnetic properties. Parts in the mesoscopic scale have high surface to volume ratios, making them difficult to be heat-treated. Therefore, shaping stock materials is a better option. Two possible shaping techniques are proposed here—EDM and casting of powder in polymer binders. The supporting operations are building electrodes for EDM and molds for casting, respectively. EDM electrodes are made either by electroplating copper or by hot pressing silver-tungsten into silicon cavities, while casting of powder in polymer binder uses silicon or wax as molds.

Materials that can be electroplated, such as copper and nickel, are widely used in micro fabrication. LIGA ("LIthographie, Galvanoformung Abformung") is a well-known process using deep X-ray lithography to create electroplating masks out of PMMA (plexiglass), and is capable of making high aspect ratio structures. However, the cost of LIGA setup is very high. In our approach, we chose plasma-etched silicon wafers as electroplating masks, which is a more economical technique. Photolithography and plasma etching are the necessary supporting operations. Stacking of wafers may be employed if the part geometry is complex and needs more than one layer to build up. Through electroplating, parts can be obtained which closely resemble parts fabricated with LIGA.

EDM technology can be applied to most conductive materials. In order to reach a satisfying surface finish, several experiments need to be conducted to find out the optimal operating conditions for the selected material. Electrodes needed for EDM can be made by the same methods as mentioned before, electroplating or hot pressing.

Once fabrication strategies and related supporting operations are decided, the examination of part features for manufacturability is important, especially in small scale. In addition, certain post-processing of CAD models is required. For example, machining code needs to be generated for CNC milling. Moreover, most of the strategies mentioned above need patterned silicon wafers for molding or pattern transfer. Therefore, it is necessary to determine how to slice the 3D CAD model and translate layer information into standard format for mask making. A software package that converts STL files to CIF format, a standard commonly used by semiconductor mask makers, was developed in the Rapid Prototyping Lab at Stanford. If the part is prismatic, the bottom surface will be exported as an STL file. If the part is non-prismatic, it has to be approximated by a stair-step profile and a patterned wafer has to be fabricated for every step. Once the slice heights are determined, the surfaces at different heights can be exported as STL files and then converted to CIF format. Since an individual part is usually much smaller than the wafer size, several patterns can be put onto one photolithography mask, allowing parallel fabrication of parts.

Fabrication

The fabrication step implements the strategies decided in the planning stage to build the parts. Patterning silicon for molding or masking is a common supporting operation in the shaping strategies. Silicon wafers are coated with a layer of liquid photoresist and selectively exposed to UV light through photomasks. After the unexposed section of photoresist is chemically removed, the wafers are patterned by plasma etching. The resulting wafers have prismatic patterns etched into them or etched all the way through, depending on their application. Silicon molds and masks can be removed later by etching in boiling KOH solution.

Three major shaping techniques are described and discussed—casting, electroplating, and EDM.

Casting: *Molding -> Casting -> Mold Removal*

Consider building polymer thin 3D airfoils for a small flying vehicle, "the mesicopter," (Figure 1). The shaping strategy selected to build the part is casting. Molds can provide either complete geometry or only bottom geometry that will require further machining after casting. Silicon is a good mold material because it is hard, insensitive to most solvents and common acids, and has a high melting point. Several patterned wafers can be stacked to form a more complex mold. The individual wafer pieces can have different thickness, allowing variable height steps to approximate the desired geometry. Wax molds are currently used in Mold SDM [2]. For the dimension that miniature end mills can achieve, wax mold would still be a good option, since it provides the opportunity to build full 3D objects and to build functional prototypes with short lead-time.

Casting can be used for thermosetting polymers or ceramics and metals mixed with a gel. These materials can be cast into cavities and then solidified either through cooling or chemical reaction. For polymer thin airfoils, casting of thermosetting polymer, such as epoxy and polyurethane, was used. Polymers that cure at room temperature and require short curing time are preferred. For the ceramics blades, gelcasting was used. Gelcasting is a casting process in which a high ratio of ceramic or metal powders is mixed into the uncured slurry, polymers and solvent. Parts with these filled polymers would be sintered after mold removal. During the sintering process, the polymer binder burns out with little or no residue and the ceramic or metal powder particles bond together strongly. Gelcasting is well suited for ceramic or metal parts with very fine features. Figure 2 shows a thin 3D airfoil made by wax mold, epoxy casting, and CNC machining with miniature end mills. Figure 3 shows silicon nitride blades made by gelcasting into a silicon mold.

In addition to the two casting processes discussed above, casting of powder filled polymer may be used. It is similar to gelcasting but the polymer binder is used as structural material for the final part, and the part is not sintered after casting. For those magnetic materials that are hard to deposit and cannot tolerate high temperature processing, casting of powders filled with polymer is a technique that is able to process the material. Although the resulting structures are weaker magnets than the pure magnets, this method is highly parallelizable and thus much more suitable for mass production.

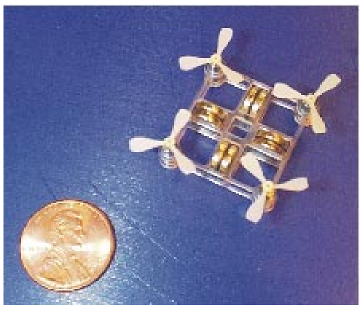

Figure 1 Prototype of 16mm x 16mm Mesicopter.

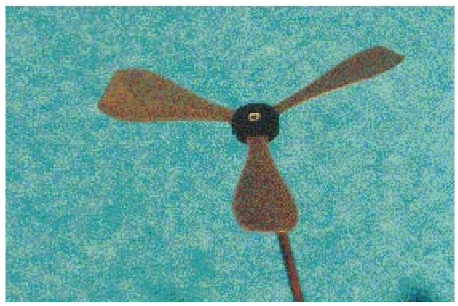

Figure 2 True 3D epoxy rotors for the mesicopter. The rotor (right) is 80 µm thin and 15 mm in diameter.

Figure 3 SEM of gelcasted Si_3N_4 blades (500µm high and <150µm thick).

Electroplating: *Patterning silicon wafers-> masking-> electroplating-> silicon removal*

Figure 4 shows a copper structure, which is used as one turn armature coil for a four-phase miniature stepper motor. Highly conductive bulk structures are required; therefore, copper is selected as the structural material and electroplating is the shaping strategy. Another example part that can be built by electroplating is a micro propeller with small uniform thickness.

Electroplating has been used for decades in metal finishing. In micro fabrication, electroplating is used to build up thicker layers than PVD can do at a faster deposition rate. In Meso A/SMP, electroplating is used to make bulk structures of pure metals, thin uniform thickness objects, and, moreover, EDM electrodes. A supporting operation for electroplating is the development of masks or molds.

Depending on the application, "non-through plating " and "through plating" are two different electroplating approaches. Non-through plating is to electroplate metal onto the silicon. Highly doped silicon with a copper seed layer on the surface is used in this process. On the other hand, through plating uses silicon as a mask, hence nonconductive silicon is preferred. In the latter case, the nonconductive silicon wafers can be further passivated by creating a silicon dioxide layer on their surface. After attaching the silicon mask to the substrate and covering the area that is not to be electroplated, the part is placed in the electroplating bath.

For copper electroplating a commercial acid copper-electroplating bath containing copper sulfate and sulfuric acid is used. For mesoscopic structures with high aspect ratio cavities, a periodic-pulse-reverse (PPR) [4] current source is recommended. The PPR output waveform is a forward cathodic current interrupted by specific short anodic pulses to ensure dense and even electroplating through the deep cavities. The current density used is about 30 mA/cm^2. Figure 4 and 5 show copper structures for the DC micro motor. High aspect ratio structures are achieved by this silicon-masking approach. Layers with different geometries can be electroplated one after another. Once the first layer of the cavities is filled, the second layer mask can be stacked on to the previous one by precision alignment system. Then the deposition process is repeated. Figure 6 shows the copper coils on a circular base, which was done by two layers of through plating. Objects with thin uniform thickness can be built through electroplating as well. True 3D geometry can be approximated by stacking sufficiently thin 2D layers. A copper micro-propeller approximated by two-layer silicon mold is shown in Figure 7.

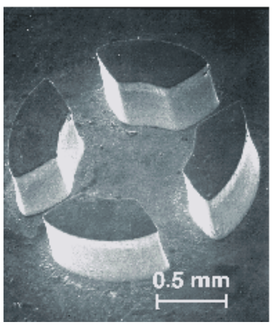

Figure 4 SEM image of electroplated Cu structure. It is 500 μm high and 1.6 mm in diameter.

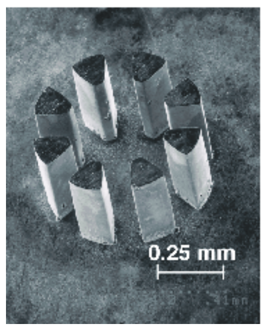

Figure 5 SEM image of electroplated Cu structure. It is 500 μm high and 800 μm in diameter.

Figure 6 Electroplated Cu structure on a circular base. It is 500 μm high and 1.6 mm in diameter.

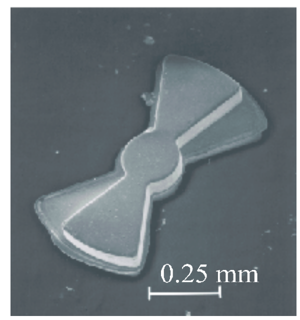

Figure 7 SEM image of electroplated Cu propeller. The structure is 200 μm high and 1 mm in diameter.

Electric-Discharge-Machining: *Patterning Silicon wafers-> making electrodes-> EDM*

Casting of powder filled polymers provided a way of mass producing soft and hard magnetic components. However, their magnetic properties were weak compared to pure stock materials. Most magnetic materials are electrically conductive and can therefore be shaped by EDM. Since EDM does not attempt to cut materials but, instead, removes materials with electrical discharge, it can be used to shape hard and brittle materials. EDM transfers patterns from the electrode to work piece by controlled spark erosion. Most popular materials for EDM electrodes are graphite and copper. However, graphite is mainly shaped by conventional machining techniques like milling or turning, and therefore is not a suitable electrode material for mesoscopic scale. Here we propose two ways to obtain EDM electrodes—electroplating and hot pressing of metal powder into the silicon mold. Electroplated copper electrodes can be obtained with the method described in the previous section. Figure 8 shows a copper electrode made by electroplating.

Besides copper, other high melting-point materials like graphite or tungsten are ideal for EDM electrodes. However, their processing temperatures are above the melting point of silicon that is used as molds. Therefore, the combination of tungsten with highly thermal conductive materials, such as silver and copper, is used through hot pressing blended powders. Copper forms alloys with silicon at low temperatures and would destroy the mold during hot pressing. Silver, on the other hand, can be easily hot pressed into silicon, since its melting point is closer to the hot pressing temperature and it does not form alloys with silicon. All hot pressing experiments are done at 750°C and 30 MPa for one hour. This temperature and pressure setting was low enough to avoid plastic deformation of the silicon. The final AgW part has around 93% of the theoretical full density, and replicates the mold sufficiently well (Figure 9).

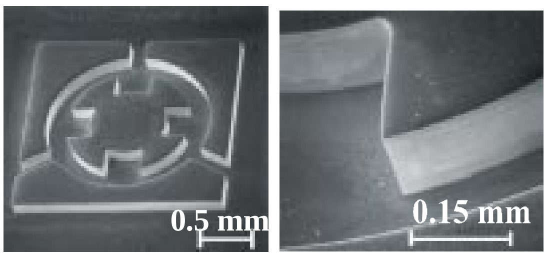

Figure 8 SEM images (full and detailed view) of electroplated Cu electrode.

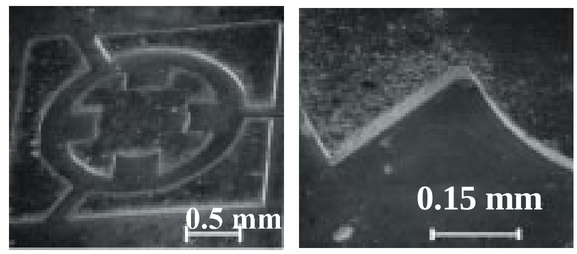

Figure 9 SEM images (full and detailed view) of hot pressed AgW electrode.

Once the EDM electrodes with fine features are fabricated, we can transfer the patterns to conductive work pieces through EDM process. The energy and shape of the individual electric discharge pulses control the resulting surface finish. The lower the energy of the pulses, the smoother the surface that can be achieved; yet this increases machining time and tool wear. From experiments, pulses with sufficiently low energy, 40 μJ/spark, can produce a surface finish (2-5 μm) which is acceptable for our application. Finer surface finish can be achieved with special micro EDM machines. Figure 10 shows amorphous Fe-Co sheets shaped by EDM with electroplated and hot pressed electrodes.

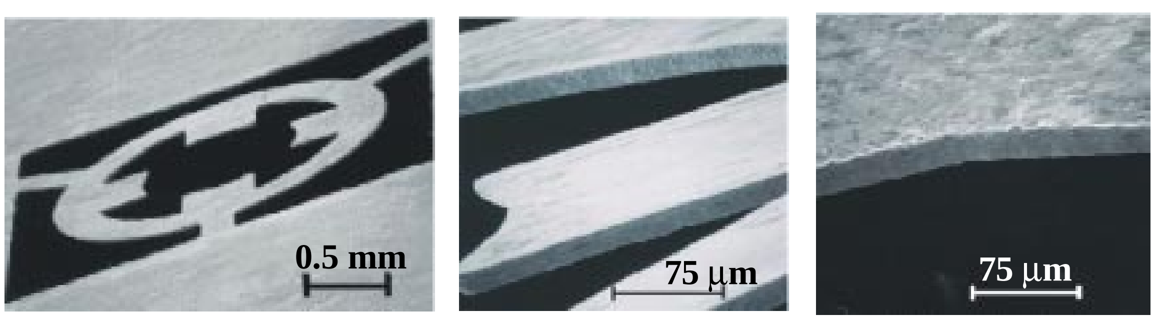

Figure 10 SEM images (full and detailed view) of amorphous metal sheet shaped by EDM with electroplated Cu electrode (left and middle) and with hot pressed AgW electrode (right).

Advantages of Meso A/SMP

1. Meso A/SMP suggests various fabrication strategies for different types of engineering materials, therefore overcomes material constraints in 3D layered fabrication and in micro fabrication.

2. Most of the process steps (silicon process, electroplating, hot pressing, and casting) are parallelizable, allowing mass production and group assembly of mesoscopic parts.
3. With the integration of VLSI techniques and conventional fabrication processes, parts can be built within 100 μm range and potentially even smaller.

Conclusion

A planning and fabrication approach for mesoscopic parts has been suggested which uses fabrication processes from VLSI and traditional machining. The planning stage includes material selection and coordinating fabrication techniques and support operations. The research presented here discusses five groups of engineering materials (ceramics, polymer, magnetic materials, electroplated metals, and other conductive materials) and their corresponding fabrication strategies. Casting, electroplating and EDM are the main shaping techniques. Meso A/SMP overcomes the material constraints in the current layered manufacturing processes and MEMS, and provides opportunities for mesoscopic 3D layer fabrication and parallel production. The ability to produce mesoscopic parts in a variety of engineering materials has now been attained.

Acknowledgements

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Keywords

- additive/subtractive material processing
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- mesoscopic
- casting
- electroplating
- Electric-Discharge-Machining
- silicon processing

Note: The title of this paper has been changed from "Mesoscopic Shape Deposition Manufacturing" to "Additive/Subtractive Material Processing for Mesoscopic Parts".