

Mesoscopic Assemblies with SDM Processing

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Abstract

Shape Deposition Manufacturing (SDM) is a layered manufacturing process capable of building complex 3D parts through the combination of material addition and subtraction. Overhangs can be built with the help of sacrificial support materials. SDM achieves high surface quality by taking advantage of material subtraction by CNC machining. High surface quality in turn enables the fabrication of pre-assembled mechanisms that can be freed to turn or slide after removal of sacrificial support materials. Using SDM, miniature trailing-edge effectors (MiTEs), which are pneumatic actuators with the minimum feature size of about 500 μm , have been fabricated for aeroelastic control of uninhabited air vehicles (UAV's). However, as part size is scaled down, limiting processing constraints were observed. To date clearances of 50 μm could be achieved in MiTEs. Also, this paper will discuss limiting manufacturing constraints and planning issues unique to the size range which is frequently referred to as the 'mesoscopic' regime.

Introduction

Shape Deposition Manufacturing (SDM) is a layered manufacturing process that involves not only additive but also subtractive processes [1] [2]. Through the iterative combination of material addition and removal, complex 3D parts can be built up incrementally layer by layer. One basic major advantage in SDM is high surface quality, which does not require any post-process such as polishing or grinding compared to commercial Solid Freeform Fabrication (SFF) processes. The surface quality difference originates from the material removal process because SDM incorporates CNC machining in the subtractive process. The surface quality is an important issue for functional assemblies.

As part size is scaled down, assembly becomes more difficult and requires special equipment or skilled workers due to smaller allowable tolerances. The alternative solution for the assembling issues is to build parts in an assembled configuration such that no assembly is required. The pre-assembled mechanisms can be built using the SDM process because sacrificial support materials can be completely dissolved or etched away with minimal force from intricate cavities [3]. However, when the part size decreases, there are manufacturing constraints that are unique to the mesoscopic regime in SDM. This paper will discuss manufacturing constraints and planning issues. By considering those constraints, mesoscopic functional mechanisms have been built and evaluated for a real application, which is aeroelastic control of uninhabited air vehicles (UAV's) [4]. The design, fabrication steps and performances of the functional assemblies will also be described in this paper.

Functional Assemblies in SDM

There are several advantages to the SDM process. A variety of part materials (e.g. polymers, metals and ceramics) are available and sacrificial support materials are solvent soluble, which do not require any manual removal process. Easy process interruption enables the fabrication of heterogeneous parts by depositing different materials or embedding sensors and actuators [5].

However, one key advantage is high surface quality, which originates from the material removal process because SDM incorporates CNC machining as a subtractive process, but most commercial SFF processes are based on pure additive processes. The surface quality is directly related to surface smoothness and dimensional accuracy, and becomes more important when it comes to functional parts rather than appearance models. For functional assemblies such as rotating or sliding mechanisms, dimensional accuracy of each component is one of the most important requirements for manufacturing processes. Also mating surfaces between moving components should be as smooth as possible to reduce friction and achieve the required functionality. Due to these criteria, functional assemblies are very difficult to fabricate using commercial SFF processes.

In SDM, assembly can be avoided by building up pre-assembled parts layer by layer so that there is no need to assemble each component manually. In a wide variety of manufacturing industries, assembly accounts for more than 50 % of the total manufacturing cost of a product and more than 40 % of the labor force, which indicates the high impact of assembly on manufacturing productivity [6]. Pre-assembly can reduce the high percentage of assembly costs and improve the manufacturing productivity.

Constraints in the Mesoscopic Regime

Using SDM, functional mechanisms have been built out of polymers, ceramics and metals as shown in Figure 1 [3] [7]. Those functional mechanisms are in the macroscopic scale range and have large clearances. When part size is scaled down, there are manufacturing constraints that are unique to the mesoscopic regime. Due to the constraints, planning algorithms for macroscopic parts, which already have been developed [8], cannot always be valid in the mesoscopic regime so that additional planning algorithms are necessary for mesoscopic assemblies.

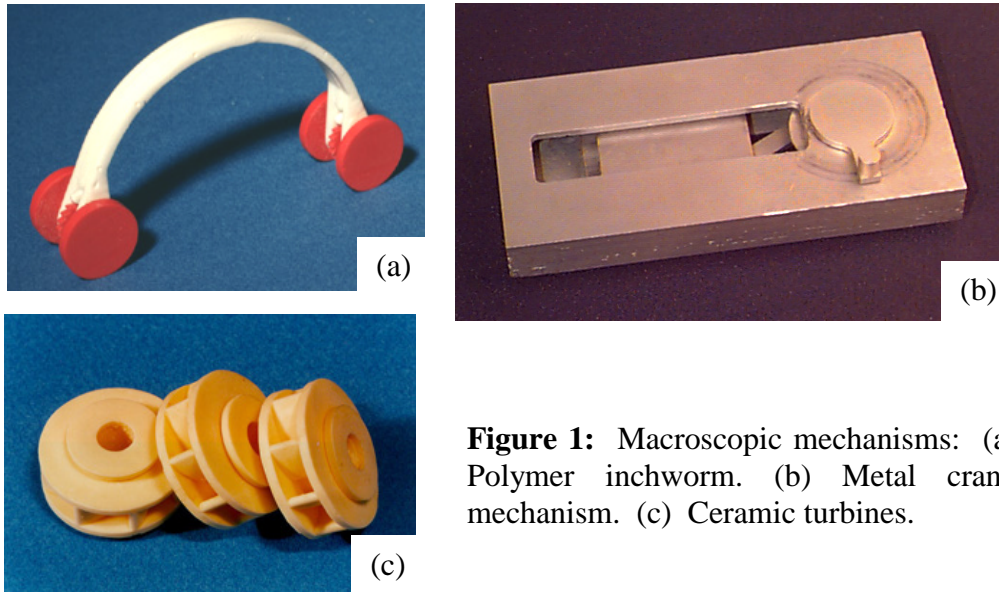


Figure 1: Macroscopic mechanisms: (a) Polymer inchworm. (b) Metal crank mechanism. (c) Ceramic turbines.

In SDM, there are three manufacturing constraints in the fabrication of mesoscopic mechanisms. The first one is viscosity, which is directly related to materials and temperature. Generally, two kinds of materials are involved in SDM: part materials and sacrificial support materials. For the mechanisms, thermoset polymers and machinable waxes have been used as part and support materials respectively [9]. Part materials have low viscosity before curing and vacuum casting is used for good cavity filling and void-free parts. However, sacrificial support materials have higher viscosity and the casting temperature is around 90°C, which is slightly above the material melting temperature. In this case, vacuum casting is not as helpful as for part materials because molten waxes solidify quickly on contact with cooler surfaces through conductive heat transfer in a vacuum chamber. For example, if there is a deep narrow trench, the liquid-state sacrificial materials solidify before filling the cavity completely. As shown in Figure 2, incomplete filling leaves voids in the rotating mechanism, which are filled with part materials later. Through the defects, the shaft and the disc are connected to each other and not free to rotate. Since those small defects directly affect part functionalities, they are critical in functional mechanisms.

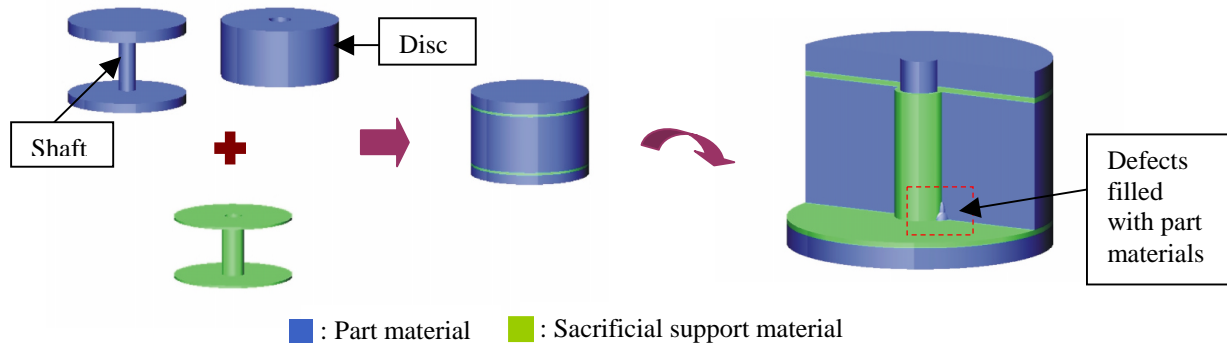


Figure 2: Voids due to incomplete filling and defects filled with part materials.

The second constraint is clearance, which also depends on material properties. For instance, in the rotating mechanism shown in Figure 2, there are two moving parts, the shaft and the disc. There are clearances between the two moving parts to allow this mechanism to rotate freely. In terms of materials, the moving parts are made of part material and the clearances are filled with sacrificial support material. As shown in Figure 3, the clearances are thin-walled cylindrical features between the two cavities for the moving parts. During the CNC machining process, the support material should endure mechanical loads from cutters and cold air, which is blown around the cutting area to remove machined chips and enhance machining quality. If the clearances are smaller than a critical value, the structural strength of the thin-walled features is weak enough to fracture during the CNC machining. However, if one of the parts is built first and a thin layer of clearances is shaped on contact with the previously built part by casting and machining the support material, the thin support structures can endure the mechanical loads during the machining. Following the building steps, clearances of 50 μm have been achieved in functional mechanisms, which will be described in the next section.

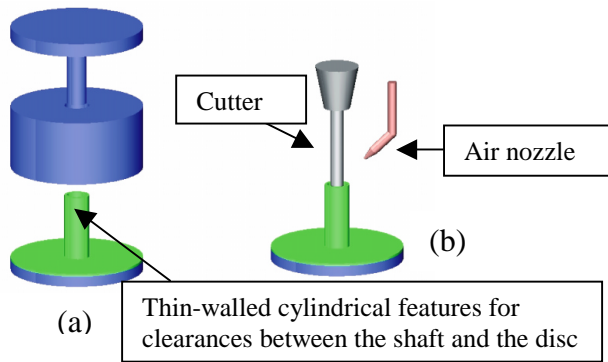


Figure 3: (a) Support structures with moving parts. (b) Mechanical loads from the cutter and air during CNC machining.

The third constraint is cutter, which is related to part feature and available cutter sizes. If a minimum feature size is smaller than a minimum available cutter size, an additional CAD model is necessary to generate machining paths for a minimum feature. As shown in Figure 4, if the shaft is smaller than the minimum cutter, the machining paths for the shaft cannot be directly generated from the original CAD model. For the shaft, an additional CAD model is generated by scaling the original models up to the minimum cutter size so that an oversized shaft is built first using the additional model. Then, additional machining comes after to trim the oversized shaft with respect to the original model.

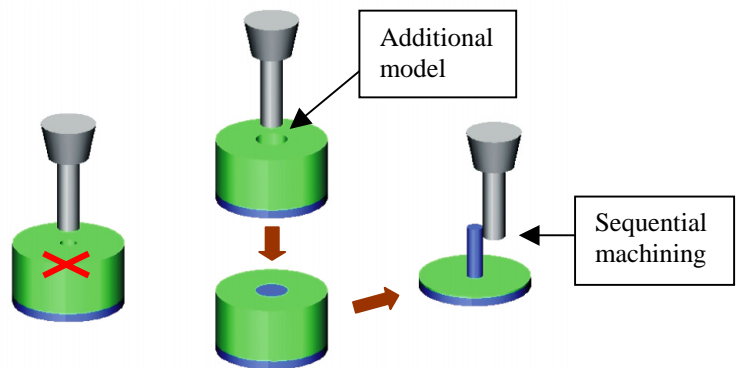


Figure 4: Additional model and sequential machining for the shaft smaller than the minimum available cutter.

Planning Algorithms

There are two kinds of geometric relationships between compacts derived from the constraints: precedence and parallel. A compact is a volume of material that can be manufactured in a single cycle of shaping and deposition [1]. Precedence imposes a restriction on building sequences of compacts in assemblies so that parts can be built only in a certain sequence or order. Unlike precedence, parallel does not constrain compact building sequences, but determines a group of compacts that can be built one by one in any sequence. Among the three constraints, the viscosity and cutter constraints provide information about precedence between compacts. Clearance constraint determines parallel relationships between compacts.

Based on those constraints and geometric relationships, process planning algorithms for functional assemblies have been developed. First, select compacts which are restricted from the given constraints. Second, inspect geometric conflicts between the constrained compacts and adjacent compacts. Third, identify possible compact build sequences satisfying all the geometric restrictions. Using the planning algorithms, the geometric relationships and building sequences can be determined and graphically represented. Figure 5 shows the graphical representation of the geometric relationships for a mesoscopic mechanism, which will be described in the next section.

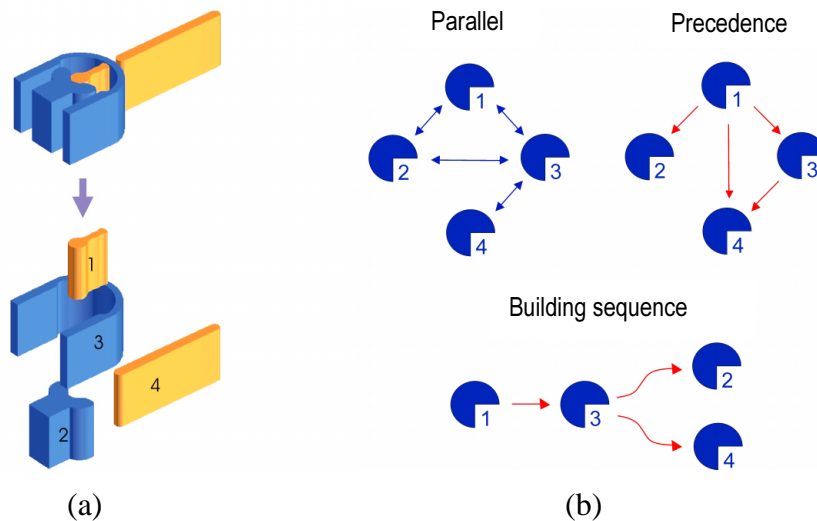


Figure 5: (a) CAD models of compacts. (b) Graphical representation of geometric relationships and building sequences of compacts

Results

Mesoscopic functional assemblies have been fabricated by applying the above planning algorithms in SDM. Figure 6 shows example parts, which are miniature trailing-edge effectors (MiTEs) for aeroelastic control of UAV's. MiTEs are pneumatic actuators with a minimum feature size of about 500 μm . The actuators were manufactured from polyurethane (TDT 205-3,

Ciba Specialty Chemicals) with machinable waxes (Kindt-Collins Master Protowax) as sacrificial support materials. A cutaway view of actuating mechanisms is shown in Figure 6.b. The inlets of the flaps are connected to pneumatic valves through small tubes so that the flaps move up and down by alternating the valves.

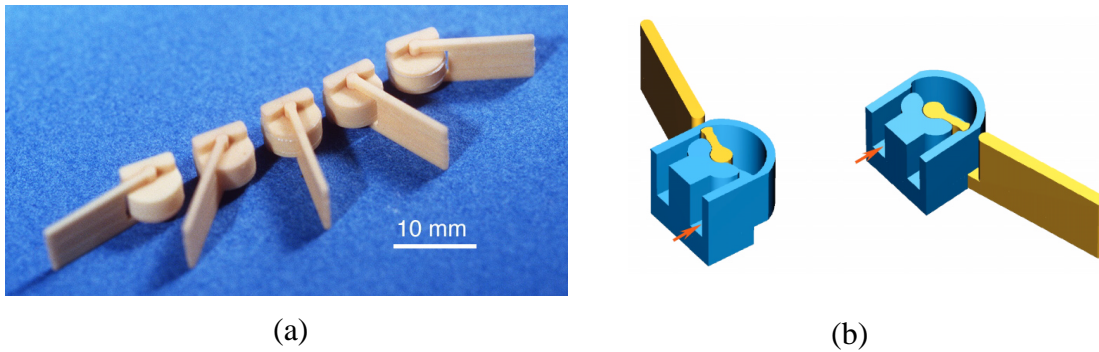


Figure 6: (a) Miniature trailing-edge effectors (MiTEs). (b) Actuating mechanisms.

The mechanism must withstand internal pressure for actuation, and also survive external wind loads applied by an airstream, which requires a moderately strong material. The clearances between moving parts must be minimized to prevent air leaks which would reduce working pressures and achievable control bandwidth. The radial and axial clearances between the flap shafts and their housings were designed to be $50\ \mu\text{m}$ and $150\ \mu\text{m}$ respectively. There is no access to the interior of completed parts to allow either manual support structure removal or finishing operations to smooth interior air passages and bearing surfaces. Those requirements can be satisfied by the SDM process while being challenging for commercial rapid prototyping processes.

The array of sixteen MiTEs shown in Figure 7 was actuated pneumatically at frequencies of up to 20 Hz, using supply pressures of up to 850 kPa. The flap array was attached to a wing section and tested in a wind tunnel at wind velocities up to 20 m/s [4]. All of the MiTEs survived the wind tunnel testing, indicating that SDM is a viable process for the fabrication of functional mechanisms in the mesoscopic regime.

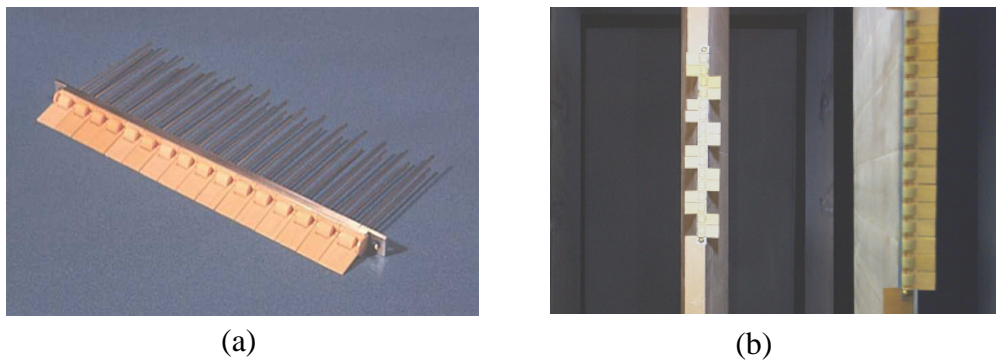


Figure 7: (a) An array of sixteen MiTEs with a manifold and tubes. (b) MiTEs integrated with the airfoil and installed in the wind tunnel.

Discussion

Through experiments, it was found that a minimum clearance of 50 μm could be achieved in MiTEs. The main factor limiting the minimum clearances is the shrinkage of sacrificial support materials. The linear shrinkage of the waxes is about 0.46% [3]. Liquid-state sacrificial materials are deposited around part features, and solidified at room temperature. The process accompanies the volume shrinkage of sacrificial support materials during the phase transformation. As part size is scaled down, the structural stiffness of parts decreases so that the part structures are easy to deform due to the loads from the volume shrinkage of the surrounding support materials.

In planning, the previously described algorithms can be easily applied to 2.5D features by manipulating (e.g. scaling, subtracting, etc) original CAD models while keeping one of the dimensional coordinates constant (e.g. X, Y or Z axis). For 3D features with all the coordinates variable, it will be more complicated to handle the models because the geometric conflicts occur across layers so that the conflicts between layers should be also taken into account.

Conclusion

SDM incorporates CNC machining as a subtractive process which allows functional parts with high surface quality. The surface quality is an important issue for functional assemblies in terms of surface smoothness and dimensional accuracy, which is very difficult to achieve by commercial SFF processes. High surface quality in turn enables the fabrication of pre-assembled mechanisms that can be freed to turn or slide after non-manual removal of sacrificial support materials.

In the mesoscopic regime, the planning algorithms for functional assemblies have been developed from the manufacturing constraints in SDM. Based on the algorithms, mesoscopic functional assemblies have been fabricated and evaluated in a real application such as aeroelastic control of UAV's. From wind tunnel experiments, it has been verified that SDM is a viable process for the fabrication of functional mechanisms in the mesoscopic regime.

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Reference

- [1] R. Merz, F. B. Prinz, K. Ramaswami, M. Terk, and L. E. Weiss, "Shape Deposition Manufacturing," *Proceedings of the 1994 Solid Freeform Fabrication Symposium*, pp. 1-8, The University of Texas at Austin, August 1994.
- [2] F. Prinz and L. Weiss, "Method for Fabrication of Three-Dimensional Articles," U. S. Pat. No. 5,301,415, April 12, 1994.
- [3] A.G. Cooper, S. Kang, J.W. Kietzman, F.B. Prinz, J.L. Lombardi and L.E. Weiss, "Automated fabrication of complex molded parts using Mold Shape Deposition Manufacturing," *Materials and Design*, Vol. 20, No. 2/3, 83-89, June 1999.
- [4] S. A. Solovitz and J. K. Eaton, "Aeroelastic Control Using Redundant Microactuators," *Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference*, San Francisco, California, July 18–23, 1999.
- [5] J. G. Cham, B. L. Pruitt, M. R. Cutkosky, M. Binnard, L. E. Weiss, G. Neplotnik, "Layered Manufacturing With Embedded Components: Process Planning Considerations," *ASME Proceedings, DETC '99*, Las Vegas, Nevada, September 12-15, 1999.
- [6] G. Boothroyd, "Assembly Automation and Product Design," Marcel Dekker, Inc., New York, 1991.
- [7] J. R. Fessler, R. Merz, A. H Nickel, F.B. Prinz, "Laser Deposition of Metals for Shape Deposition Manufacturing," *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, August 1996.
- [8] J. M. Pinilla, J. Kao, and F. B. Prinz, "Process Planning and Automation for Additive-Subtractive Solid Freeform Fabrication," *Proceedings of the Solid Freeform Fabrication Symposium*, pp 245-258, University of Texas at Austin, Austin, Texas, August 1998.
- [9] J. W. Kietzman, A. G. Cooper, L. E. Weiss, L. Schultz, J. L. Lombardi, and F. B. Prinz, "Layered Manufacturing Material Issues for SDM of Polymers and Ceramics," *Proceedings of the Solid Freeform Fabrication Symposium*, The University of Texas at Austin, Austin, Texas, August 1997.