# Layered Manufacturing Material Issues for SDM of Polymers and Ceramics

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## Abstract

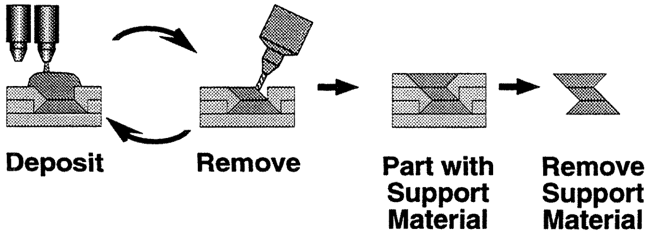
Shape Deposition Manufacturing (SDM) is a solid freeform fabrication process which enables the manufacture of structural parts from engineering materials. This paper discusses the requirements and constraints for SDM part and sacrificial support materials, including chemical and physical compatibility, mutual adhesion, low shrinkage, machinability, and support material removability. Polymers and ceramics processed by SDM include polyurethanes, epoxies, polyurethane foams, photocurable acrylics, and green alumina ceramics. SDM compatible support materials include waxes, water-soluble polyacrylate soldermasks, and water-soluble thermoplastics. This paper details the selection of SDM part and support material combinations for the fabrication of polymer prototypes and polymer molds for ceramic prototypes.

## Introduction: Shape Deposition Manufacturing and Mold SDM

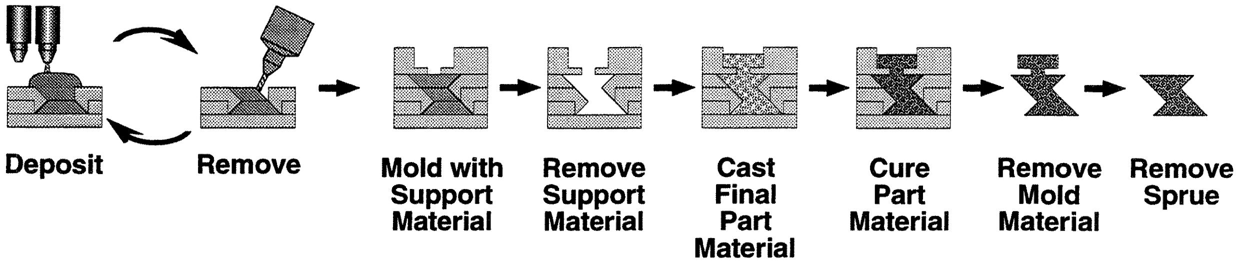
Shape Deposition Manufacturing (SDM) is a layered manufacturing process involving an iterative combination of material addition and material removal [1,2]. A wide range of materials is available, including metals, polymers, and ceramic powders. These materials are deposited using a variety of deposition processes, depending on the materials. Material removal is accomplished with three-axis or five-axis milling, although other processes such as EDM can be used for conductive materials. SDM requires a part material and a sacrificial support material. The final object is made of part material. The sacrificial support material is used to support overhanging features while the object is being built, and is removed when the object is complete. SDM has been used to make metal and polymer parts through direct material deposition and shaping. Current research focuses on expanding the variety of materials processed by SDM.

A variant process called "Mold SDM" uses SDM to build molds for casting resins. In Mold SDM, a layered mold is fabricated. When the mold is complete, the support material is either dissolved or melted, leaving the mold. After casting, the mold is dissolved or melted, leaving the molded object. Postprocessing operations, including sprue removal, binder removal, or sintering, can be subsequently performed on the object. Figure 1 shows the steps required for the construction of simple parts processed by SDM and Mold SDM. Both polymer and green ceramic parts have been cast using polymer molds and the Mold SDM approach.

## Figure 1A. Shape Deposition Manufacturing




## Figure 1B. Mold SDM




### Material Requirements for SDM of Polymers

SDM requires compatible part and support materials, subject to the constraints of the deposition and removal processes. Extrusion and casting are the current polymer deposition methods for SDM. Part and support materials must be physically and chemically compatible. These materials must be deposited or cured at temperatures which do not damage previously shaped features. Part and support materials must have minimal intersolubility, and neither material may inhibit curing processes of the other.

In order to build strong parts using SDM, successive layers of part and support materials must exhibit high degrees of cohesion and adhesion. The part and support materials must solidify without the formation of defects, e.g. internal voids. Layers of cast material have the same intralayer properties as in any conventional casting application. Extruded material, however, may exhibit poorer mechanical properties within a layer due to interbead interfaces. To prevent voids during extrusion, either low viscosity material or high extrusion pressure is required to fill sharp interior corners and interbead gaps. In order to obtain high strength parts, the part material must also have good interlayer adhesion.

Distortion and warpage must be minimized to build accurate parts. Shrinkage is commonly encountered during layer solidification or curing, and it is often nonuniform. This shrinkage must be minimized to reduce residual stresses which can result in warpage or delamination [3]. Choosing amorphous rather than crystalline materials helps minimize shrinkage [4]. Preheating previous layers before depositing new material minimizes temperature differentials between old and new material, reducing differential shrinkage of new material as the layers cool. Coefficients of thermal expansion of part and support materials should be similar and as low as possible to reduce thermal distortion.

Besides the material constraints imposed by deposition processes, there are also constraints associated with support material removal. The support material must be removed carefully to avoid damage to the part material. If solvents are employed, they must induce minimal swelling of the support material before dissolving it, or dissolution stresses may crack the part. It is advantageous to use solvents to remove the support material from internal cavities.

Most of the aforementioned constraints on SDM are shared with the other SFF extrusion or jetting processes, e.g. FDM, BPM, Sanders, Actua, and Genisys. These other SFF processes, however, deposit material to net shape. Therefore, their materials' viscosity and solidification characteristics must be optimized for material to bond to previously deposited material while still maintaining its shape. SDM avoids some of these linked constraints by including a material shaping step. This requires the SDM part and support materials to have sufficient strength and stiffness to enable accurate machining. The support material must exhibit smooth surfaces after machining, since its surfaces will be replicated onto later-deposited part material. The part material must exhibit smooth surfaces after replication or machining.

The Mold SDM process has an additional material restriction. The mold material must also be compatible with the final part material cast into it. In particular, these materials must be chemically compatible, and no solidifying or curing part material may react with the mold material. The final part material is, however, not subject to all restrictions on normal SDM part materials. For example, the cast material need not adhere to itself or to the mold material. After casting is done, the mold material must be separable from the part. The need to have two different removable materials (support material and mold material) limits the possible material combinations for Mold SDM compared to conventional SDM. On the other hand, Mold SDM can make parts from materials which could not be processed directly via SDM.

Similar to other SFF processes, there are several practical manufacturing requirements which affect material selection. Cost, ease of use, and robustness must be considered. Deposition processes must produce well-controlled deposits over a wide range of material and process variations. Part throughput and process speed requirements encourage the use of rapid deposition processes with rapid solidification or curing as well as rapid machining rates. Inexpensive materials and simple deposition methods (with inexpensive deposition equipment) are preferable. SDM materials should have long shelf-lives, long pot-lives, as well as low toxicity. The support material and its removal solvents must have low toxicity.

All of the previous process constraints cannot necessarily be satisfied, and compromises must be made. The next section of this paper describes several complementary SDM material combinations. These material combinations have been used successfully in SDM, but material properties of the resulting parts have not yet been measured.

## Types of Polymer Material Combinations Processable by SDM

Possible part and support material combinations for SDM of polymers can be categorized based on whether materials are thermoplastic or thermoset. As shown by the matrix in Table 1, there are four possible categories of materials for SDM. A discussion of each is presented below.

| | Thermoplastic Support Material | Thermosetting Support Material |
|---|---|---|
| Thermoplastic Part Material | Category A<br>Part: Polycarbonate<br>Support: ACR 200 | Category B<br>Part: Wax<br>Support: Soldermask |
| Thermosetting Part Material | Category C<br>Part: Polyurethane<br>Support: Wax | Category D<br>Part: SLA Resin<br>Support: Soldermask |

**Table 1.** Example SDM Material Combinations

**Category A: Thermoplastic Part Material and Thermoplastic Support Material**

In SDM, heated thermoplastics are deposited by extrusion or casting. For optimal adhesion, surface remelting of previously deposited material is required. If bulk remelting occurs, then previously shaped geometry may be distorted. Materials with compatible melting and softening temperatures must therefore be chosen, and deposition temperatures must be carefully controlled. The support material can be removed by dissolving it or melting it at temperatures below the melting point of the part material.

One SDM material combination entails polycarbonate part material along with ACR 200 support material. ACR 200 is a proprietary non-ionic, water-soluble, machinable thermoplastic obtained from Advanced Ceramics Research in Tucson, AZ. Unfortunately, the high temperatures associated with the extrusion of polycarbonate tend to cause significant softening of ACR 200, producing replicated geometry with poor surface quality. Figure 2 shows an impeller wheel made via SDM using these materials.

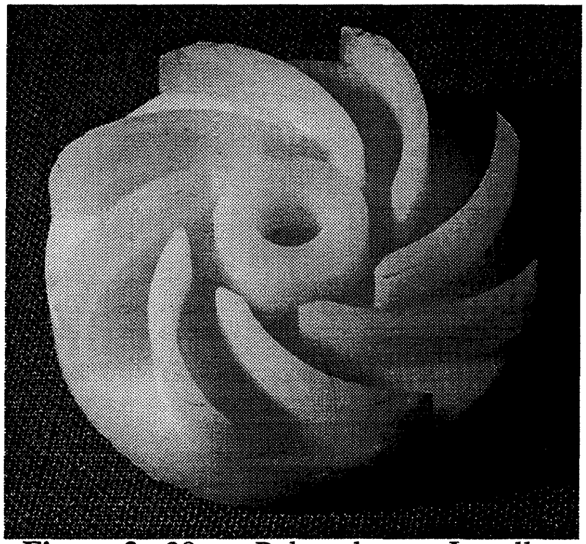


**Figure 2.** 38mm Polycarbonate Impeller

**Category B: Thermoplastic Part Material and Thermosetting Support Material**

In SDM, thermoset support material is deposited as a one-part ultraviolet-curing liquid. In this category, the thermosetting support material must be chosen so that its heat of polymerization does not melt the thermoplastic part material. Since thermoset resin does not melt, solvents are required for its removal.

One possible SDM material combination is wax part material and ultraviolet photo-polymerizable soldermask support material [5]. Soldermask is a commercial product used in the printed-circuit-board industry [6]. It is a highly-branched, lightly-crosslinked polymer which has high-temperature stability for short time periods. This makes it able to withstand deposition of hot thermoplastic. Long ultraviolet exposures are required to cure it sufficiently for machinability. Even when cured, this material is relatively brittle and prone to cracking. It is a water-soluble polymer, allowing easy support material removal. While this combination has been used to make molds for the Mold SDM process, it could also be used for polymer parts, e.g. investment-casting patterns.

In the Mold SDM process, wax molds are built using soldermask support material. When the molds are complete, the soldermask is dissolved in water. Gelcasting ceramic slurries [7] or thermoset resins are cast into the molds; these materials are cured with heat if required. The molds are then melted or dissolved. After mold removal, parts are ready for post-processing, e.g. binder burnout and sintering. This method has been used with alumina gelcasting slurries to make ceramic impeller wheels [Figure 3A]. These alumina parts were sintered to a final density of greater than 99%, measured through Archimedes' method. Polymer turbines have been made using castable polyurethane resins [Figure 3B]. These turbines consist of impellers free to spin on shafts.

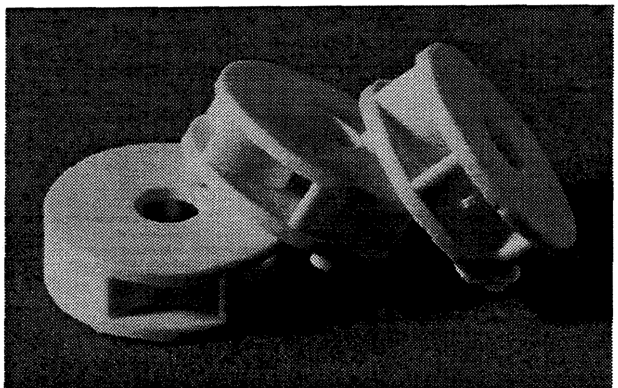


**Figure 3A.** 25mm Sintered Alumina Impellers

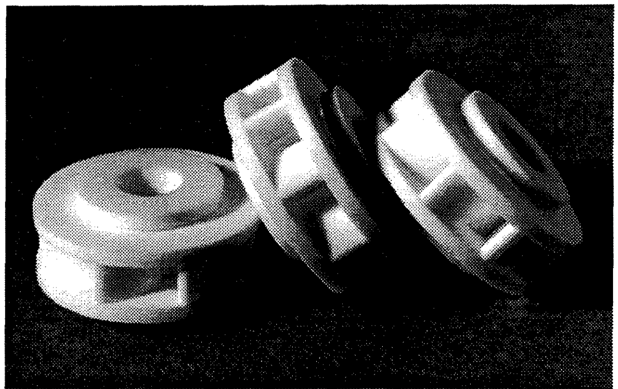


**Figure 3B.** 30mm Polyurethane Turbines

### Category C: Thermosetting Part Material and Thermoplastic Support Material

This material combination has the same properties as the previous one, except that the thermoplastic support material can be removed by melting in lieu of dissolving. SDM materials in this category include two-part castable polyurethane or epoxy part material and wax support material. Either melting or heated solvents are utilized for support material removal. An advantage of this category of materials is the wide variety of castable thermoset resins commercially available for part fabrication. Many different polyurethane and epoxy resins are available, capable of producing parts having a variety of mechanical, chemical, or thermal properties. A limitation of this category of materials is the compromise between process speed and heat generation and shrinkage. Rapidly polymerizing resins are available, but it is difficult to control their polymerization exotherms. These resins exhibit greater shrinkage and severe remelting of the support material. Therefore most SDM parts have been fabricated from resins that polymerize at lower rates.

A series of wearable computers has been made using polyurethane part and wax support materials [8]. One is a waterproof computer which operates while fully immersed [Figure 4A]. Additional work has been done with metal-filled polyurethanes for improved heat transfer and polyurethane foams for improved insulation. Polyurethane and wax materials have been used to make assembled devices with movable parts, like sliding disks restrained by frames [Figure 4B].

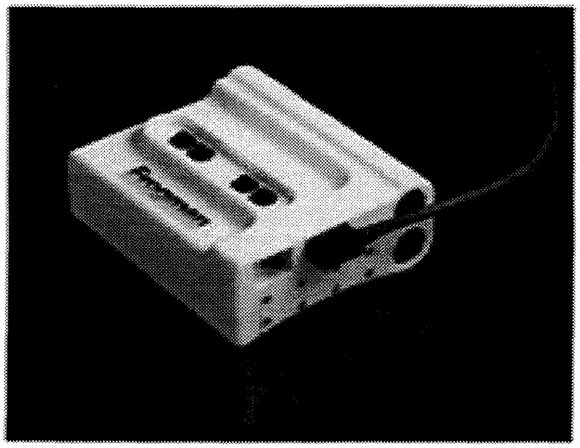


**Figure 4A.** "Frogman" Computer

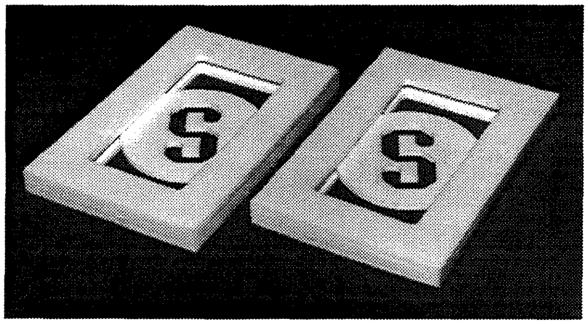


**Figure 4B.** 75 x 50mm Polyurethane Assemblies

**Category D: Thermosetting Part Material and Thermosetting Support Material**

In this category, the thermosetting part material must be more highly crosslinked than the support material so that the support material will be more easily swollen and subsequently removed from the part material. An SDM combination from this category is acrylic stereolithography resin part material with soldermask support material. DuPont SOMOS 2100, the part material, is machinable and somewhat flexible. This resin can be thermally postcured to increase its tensile strength, impact strength, and ductility [9]. While epoxy resins have been tested, epoxy part material is chemically incompatible with the acrylic-based soldermask support material. In the SDM process, part and support materials are both cured using ultraviolet flood lamps rather than lasers or other spot-curing light sources. This simplifies the equipment required, but eliminates the possibility of using different curing patterns to reduce shrinkage or tailor properties. An object made from SOMOS 2100 and soldermask is shown in Figure 5. This part duplicates an injection-molding tool made from stainless steel via SDM. A serpentine cooling channel is located in the middle of the part.

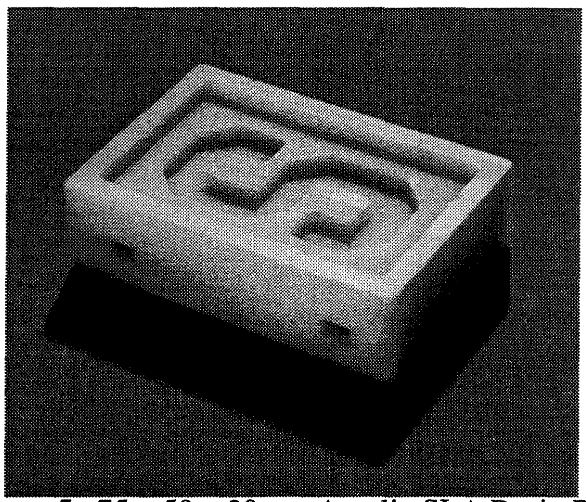


**Figure 5.** 75 x 50 x 20mm Acrylic SLA Resin Part

## Conclusion

Several high quality polymer and ceramic green parts have been fabricated using the SDM and Mold SDM techniques. One successful material combination is castable polyurethane resin with wax support material. Both computer housings and mechanisms with movable parts have been made using these materials. Another successful combination involves wax part material with ultraviolet photo-polymerizable, water-soluble soldermask support material. These materials have been used to make molds for use in the Mold SDM process. Cast polyurethane assemblies and green alumina ceramic parts have been manufactured using this technique.

Current SDM polymer research efforts include both improving materials and interlayer interface quality. Several materials are limited by machinability and shrinkage, especially wax part and support materials. Waxes with good machinability tend to have high solidification shrinkage which causes delamination when building multilayer objects. Waxes with less solidification shrinkage tend to have worse machinability, limiting the achievable feature size. Alternate wax formulations with better compromises between these two properties are being investigated. Soldermask also has machinability limitations due to its brittleness. It often chips during machining unless cutting parameters are chosen carefully. Different curing cycles and improved soldermask formulations are being investigated to resolve this issue. The material combination of polyurethane and wax is also limited by interlayer adhesion; this has led to the use of modified building styles using partial embedding or temporary anchors. We believe that most of these materials issues can be resolved through the identification of improved materials or process steps.

SDM polymer interlayer interface quality is another limitation. For most applications, the issue is not inadequate bonding between layers, but surface finish defects at layer boundaries. Producing smooth surfaces by incrementally depositing and machining successive layers is challenging, especially when the part and support materials exhibit shrinkage upon deposition. Freshly deposited material can cause distortion in previously deposited and shaped material, often producing steps at layer interfaces. Lower-shrinkage materials and additional thermal pre-processing are under investigation in an attempt to alleviate this condition. Another possible solution is characterizing the distortion and modifying shaping processes to correct for it.

Current SDM ceramics research focuses on improving the Mold SDM process and investigating the direct production of green ceramic parts using extrusion processes. Most of the Mold SDM process improvement work revolves around improved materials for polymer molds, as discussed above. Process monitoring and automation are underway so that more repeatable material deposition and greater process throughput can be achieved. The direct deposition and shaping of green ceramic parts is also being investigated to complement the Mold SDM process. Ceramic-filled wax part material and water-soluble support material are being tested.

## Acknowledgments

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## Notes

[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,* The University of Texas at Austin, August 1994, pp. 1-8.

[2] F. Prinz and L. Weiss, "Method for Fabrication of Three-Dimensional Articles," U. S. Pat. No. 5,301,415, April 12, 1994.

[3] For a discussion of residual stresses resulting from solidification of metal droplets in SDM, see F. B. Prinz, L. E. Weiss, C. H. Amon, and J. L. Beuth, "Processing, Thermal and Mechanical Issues in Shape Deposition Manufacturing," *Proceedings of the 1994 Solid Freeform Fabrication Symposium,* The University of Texas at Austin, August 1994.

[4] There is a longer discussion of polymer shrinkage issues in J. J. Beaman, J. W. Barlow, D. L. Bourell, R. H. Crawford, H. L. Marcus, and K. P. McAlea, *Solid Freeform Fabrication: A New Direction in Manufacturing,* Dordrecht: Kluwer Academic Publishers, 1997, p. 94.

[5] We have categorized soldermasks as thermosets because they cure via ultraviolet light. Soldermasks are heavily branched and lightly crosslinked polymers which share characteristics of both thermoplastics and thermosets.

[6] Several ultraviolet-curable, water-soluble soldermasks are made commercially: ElectroLite (Danbury, CT) ELC-4497, Dymax (Torrington, CT) 9-20311F, and Tech Spray (Amarillo, TX) Wondermask W-UVA. The ElectroLite and Tech Spray products cure hard while the Dymax product cures soft; intermediate hardnesses are possible by mixing materials before curing them.

[7] M. A. Janney, "Method for Forming Ceramic Powders into Complex Shapes," U. S. Pat. No. 4,894,194, January 16, 1990.

[8] L. Weiss, F. Prinz, G. Neplotnik, K. Padmanabhan, L. Schultz, and R. Merz, "Shape Deposition Manufacturing of Wearable Computers," *Proceedings of the 1996 Solid Freeform Fabrication Symposium,* The University of Texas at Austin, August 1996, pp. 31-38.

[9] "SOMOS 2100 Family" Product Data, Version 1.26.93, DuPont SOMOS Group.