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# Shape Deposition Manufacturing of Heterogeneous Structures

**L.E. Weiss,** The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania
**R. Merz** and **F.B. Prinz,** Department of Mechanical Engineering, Stanford University, Stanford, California
**G. Neplotnik, P. Padmanabhan,** and **L. Schultz,** The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania
**K. Ramaswami,** Department of Mechanical Engineering, Stanford University, Stanford, California

## Abstract

To date, the most widely recognized advantage of the layered manufacturing methodology is the relative ease of automatically planning and executing the fabrication of complex geometric shapes. But building shapes using selective material-additive processes has a second, far-reaching advantage—the creation of heterogeneous structures composed of multimaterial regions and with prefabricated devices embedded into the structure. The capability to fabricate heterogeneous structures is important because it enables the realization of new, complex designs. Shape deposition manufacturing, a layered manufacturing process described in this paper, addresses how to build multimaterial, embedded structures such as advanced tooling and embedded electronic devices.

***Keywords:*** *Multimaterials, Embedded Structures, Freeform Fabrication*

## 1. Introduction

The methodology underlying the majority of layered manufacturing (LM) processes is to first decompose a 3-D CAD model of the object into cross-sectional layers, and then to use material-additive processes to physically build up these layers to form the object. Sacrificial supporting layers may also be simultaneously built up as required. Layer topology and material composition vary with different LM processes. For example, *Figure 1a* depicts a shape that is first decomposed into 2 1/2-D layer representations (that is, each layer is represented by a planar cross section with an associated uniform thickness). Then each physical layer, which consists of the cross section and a complementary-shaped sacrificial section, is deposited and fused to the previous layer. The sacrificial material has two primary roles. First, it holds the part, analogous to a "fixture" in traditional fabrication techniques. Second, it serves as a substrate on which "unconnected regions" and overhanging features can be deposited. The unconnected regions require this support because they are not joined with the main body until subsequent layers are deposited. Sacrificial material can also be used to form cavities within the part. Several deposition and fusion processes are available to fabricate shapes using this building approach. These processes include: selective laser sintering,[1] 3-D printing,[2] laminated object manufacturing,[3] solid-ground curing,[4] and MD*.[5,6]

Other building approaches, such as stereolithography[7] and fused-deposition modeling,[8] also build with 2 1/2-D layers, but they use explicit support structures where required, that is, for the unconnected regions and steep overhanging features (*Figure 1b*). These explicit support structures are deposited with the same material as the object being formed but are drawn out in a semisolid fashion so that it is easy to remove these supports after the part is completed. For example, they may be deposited as thin-wall structures. The objects in *Figure 1* are "homogeneous" structures in that the final part consists of a single (primary) material.

Freeform fabricated shapes can also be built up with 3-D cross-sectional layers (that is, the outer surface of each layer maintains the 3-D geometry of the original model) as depicted in *Figure 2*. Shape deposition manufacturing (SDM),[9-14] which is discussed in this paper, builds parts using this approach. While the final building plan will be dependent on the part's geometry, as will be discussed in Section 3, proper shape decomposition will ensure that a successful building plan can be automatically synthesized.

To date, the most widely recognized advantage of layered manufacturing methodology is the relative ease of automatically planning and executing the fabrication of complex geometric shapes. Building

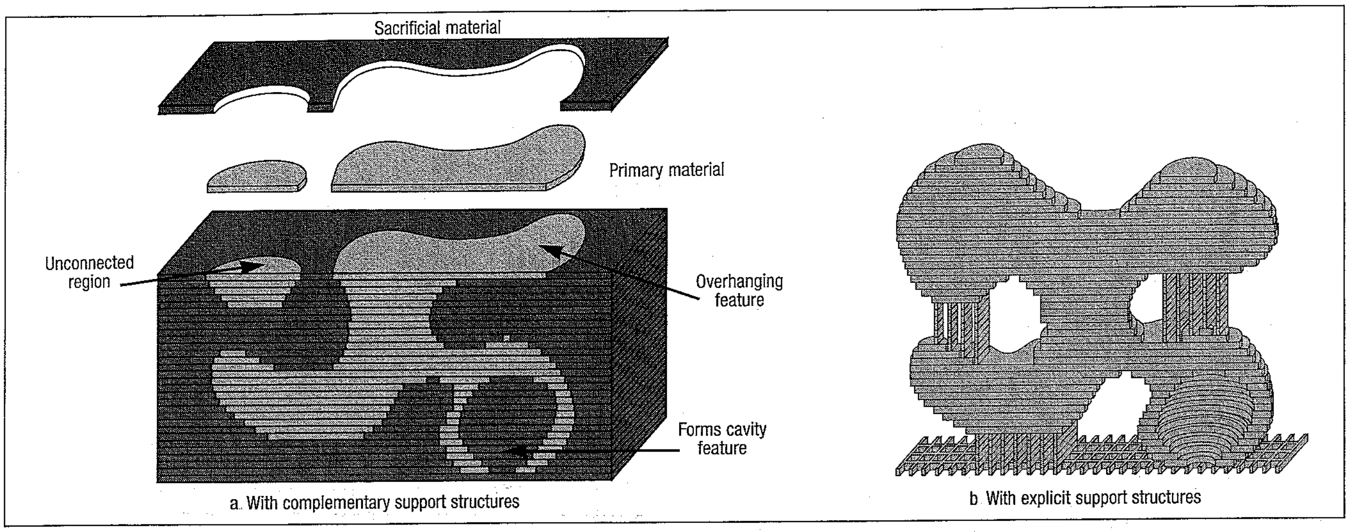



*Figure 1*
**Layered Manufacturing of Homogeneous Structures Using 2 1/2-D Layers**

shapes using selective material deposition/fusion processes, however, has a second, far-reaching advantage—it is also possible to create heterogeneous structures as depicted in *Figure 3*. A heterogeneous structure might include multimaterial regions and/or prefabricated devices embedded into the growing shapes[5] and surfaces with microgeometric textures.[15] These types of designs would not be practical—perhaps might be impossible—to fabricate with conventional forming techniques. SDM addresses how to build multimaterial, embedded structures.

The capability to fabricate heterogeneous structures is important because this capability can make the realization of complex designs both feasible and practical. As one example, consider the design of an autoclave lay-up tool for forming composite structures such as a Kevlar/fiberglass airplane wing. This tool must be preheated prior to the forming process, and the absolute temperature and uniformity of temperature over the surface are critical during the forming process. A conventional tool, as depicted in *Figure 4a*, can take several hours to preheat, thus increasing the manufacturing time; maintaining a uniform surface temperature is also problematic, thus reducing reliability. The heterogeneous tool design in *Figure 4b* addresses these problems in several ways. A heating/cooling channel that conforms to the tool's surface would be used to help preheat the tool. The channel would be formed using sacrificial material. The interior of the tool would be made of copper for fast and uniform heating, while the outside shell would be made of Invar to closely match the thermal

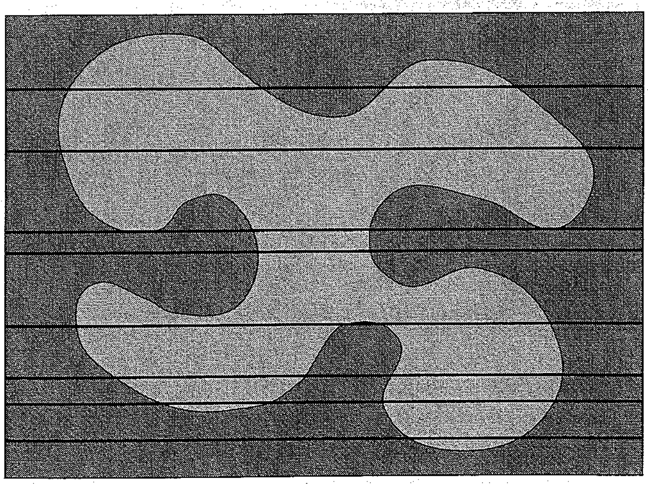


*Figure 2*
**Layered Manufacturing Using 3-D Layers**

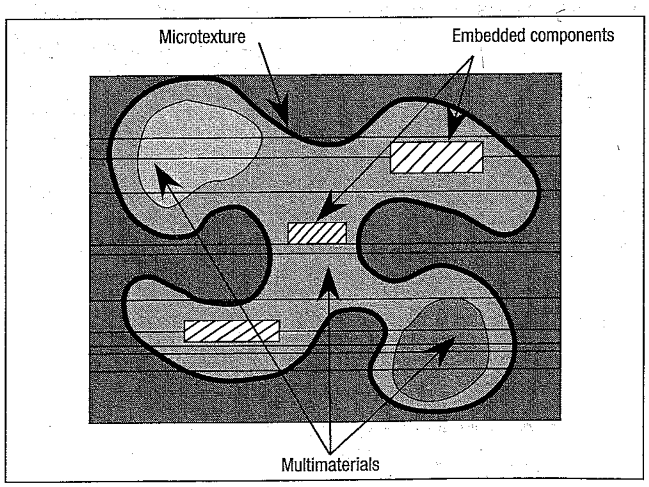



*Figure 3*
**Heterogeneous Structures**

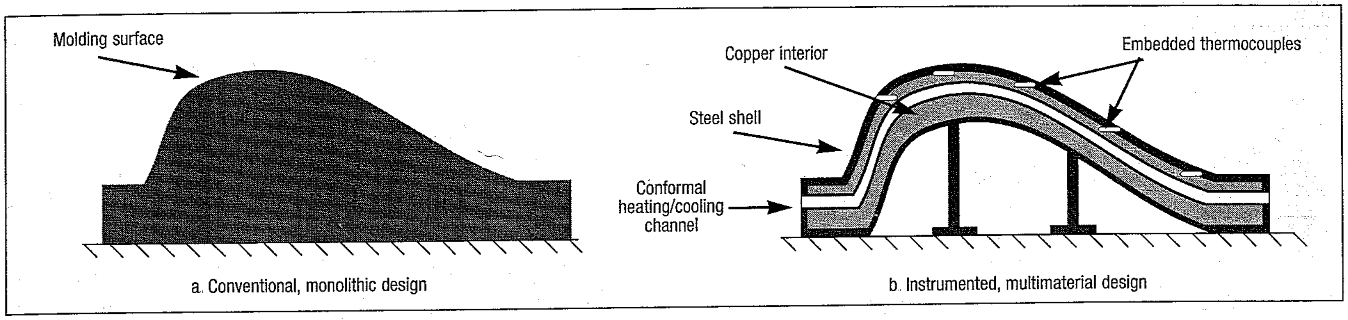



*Figure 4*
**Tooling Dies for Forming Composites (cross-sectional views)**

expansion of the composite. To compensate for thermal expansion mismatches, additional materials might also be required to form a functionally graded layer between the Invar and the copper. The tool's thermal mass would be minimized by a geometry that minimizes tool volume, and arrays of embedded thermocouples would permit the tool's surface temperature to be monitored for process control.

The embedded electronic device represented in *Figure 5* is another example of a heterogeneous structure design. The device is a computer in which the circuitry is integrally housed within a package with a complex-shaped form factor. The housing might be composed of different materials: some for strength, others for lightness, and still others for toughness. The 3-D circuit, which is formed by embedding conventional planar circuits interconnected with embedded vias, is distributed throughout the shape. This structure is compact and is intended to provide ruggedness in extremely harsh environments.

In addition to being able to build complex structures with precision and accuracy, it is equally important that the mechanical properties of the deposited materials are suitable for their intended applications. For example, the metal in production-quality tooling must be fully dense, free from accumulated internal stresses, and with metallurgical bonding between layers. Current LM systems cannot *directly* fabricate metal shapes with these properties. The systems can be used *indirectly* by first quickly creating plastic or wax patterns and ceramic shells from which metal shapes can be cast,[16] or by using powdered metallurgy to create porous metal structures that are subsequently infiltrated.[17,18] One of the goals of SDM is to incorporate a process to directly create dense metal structures. Microcasting, a new process that has been developed for this purpose, is also reviewed in this paper.

This paper is organized as follows. Section 2 describes the basic SDM processing sequence and testbed configuration. Section 3 outlines the decomposition of CAD shapes into 3-D layers and layers into manufacturable sections. Section 4 describes the microcasting process used to deposit metals. Section 5 overviews the SDM planning system that is being developed. Section 6 presents examples of structures built with SDM that demonstrate the designs like those in *Figures 4* and *5*.

## 2. Shape Deposition Manufacturing Process

SDM is a layered manufacturing approach for building heterogeneous structures composed of 3-D layers. SDM integrates material deposition with material removal processes as well as other intermediate processing operations that operate on each layer (see *Figure 6*). Individual layer segments are deposited as near-net shapes and then accurately machined to net shape before depositing additional material. With this approach, structures can be produced that would not be feasible with machining alone.

The basic SDM strategy is to first slice the CAD model of the shape to be fabricated into layers while maintaining the corresponding outer surface 3-D geometry information. The layer thickness will vary depending on the part geometry. Each layer is fur-

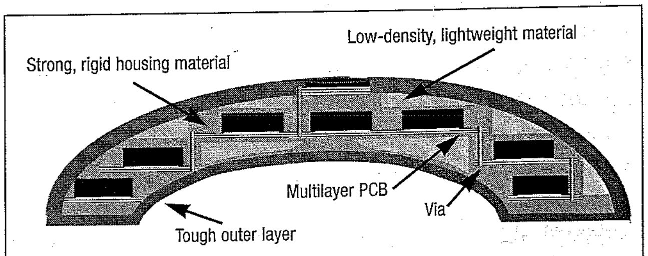



*Figure 5*
**Embedded Electronic Structure (cross-sectional view)**

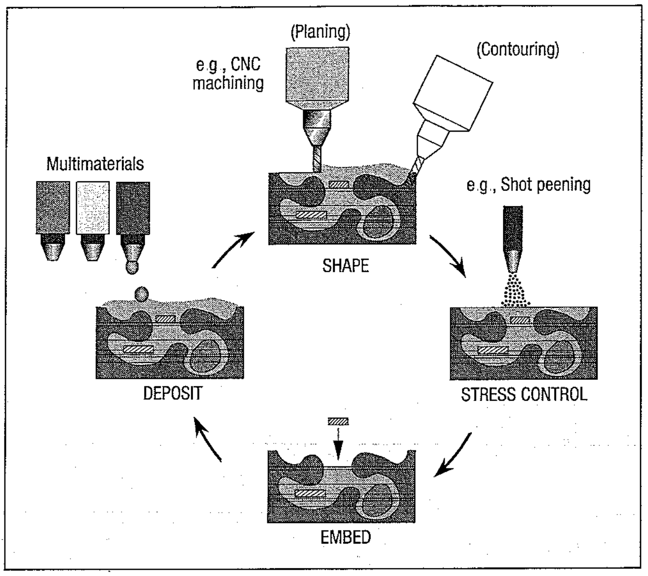



*Figure 6*
**Shape Deposition Manufacturing**

ther decomposed into layer segments, or "compacts," such that undercut features are not machined, but formed by previously shaped segments. Each compact in each layer is then deposited as a near-net shape using one of several available deposition processes. (The sequence for depositing the primary and support compacts is dependent on the local geometry and will be described in more detail in Section 3.) After deposition, each layer segment is then precisely shaped to net shape with a CNC milling machine.

Several deposition processes, including thermal processes such as welding, are currently available for use in the SDM system. With thermal deposition, internal residual stresses build up as each new layer is deposited due to differential contraction caused by thermal gradients between the freshly deposited molten material and the previously solidified layer. Internal stresses can lead to warpage, delamination, and early failure of the material. Shot peening each layer is being investigated as one way to control the buildup of stress. Small round metal spheres (called "shot") are projected at high velocity against the surface in a blasting cabinet. Peening imparts a compressive load in the upper portions of each layer and counteracts the tensile load of the internal stress field of the lower portion of that layer. While this approach does not eliminate the internal stresses, it has the potential to balance the net stress, thus minimizing external effects such as warpage and deformation of the geometry. Individual sections of the material, however, still remain under stress. This is equivalent to a preloaded condition and can contribute to early failure of the material.

Embedding is another intermediate operation that can take place in the SDM cycle. At appropriate layers, discrete components can be placed on top of the current upper surface before subsequent deposition takes place. After deposition, that component becomes permanently embedded within the structure.

To implement the SDM operations, the growing parts are built on pallets that are transferred to individual operating stations using a robotic palletizing system. Robotic manipulation is used to create a flexible system that can be easily modified to investigate alternative deposition, shaping, or other intermediate processing operations. Each processing station has a pallet receiver mechanism. The part-transfer robot places the pallet on the receiver, which locates and clamps the pallet in place. The current shaping processes include computer numerically controlled (CNC) milling and electric discharge machining (EDM). The current deposition sources include arc and plasma spraying, laser welding, MIG welding, "microcasting," extrusion, and a hot wax gun. The wax is used as complementary support material for building polyurethane structures. Polyurethane can be deposited as two-component epoxy mixtures. Intermediate processing operations include a cleaning station and shot-peening station. At the cleaning station, cutting fluids that are used in the milling and EDM operations are removed using a high-pressure water wash. Embedding operations are currently done manually.

## 3. Shape Decomposition

The basic deposition and shaping sequence for building up a structure is described below. The simple shape in *Figure 7* is used to illustrate this sequence. In general, any shape composed of a single primary material can be decomposed into layers that are characterized by one of the following three categories (see *Figure 7a*):

- Category 1: The layer has no undercut features (relative to the building direction).
- Category 2: The layer has only undercut features.
- Category 3: The layer has both undercut and non-undercut features.

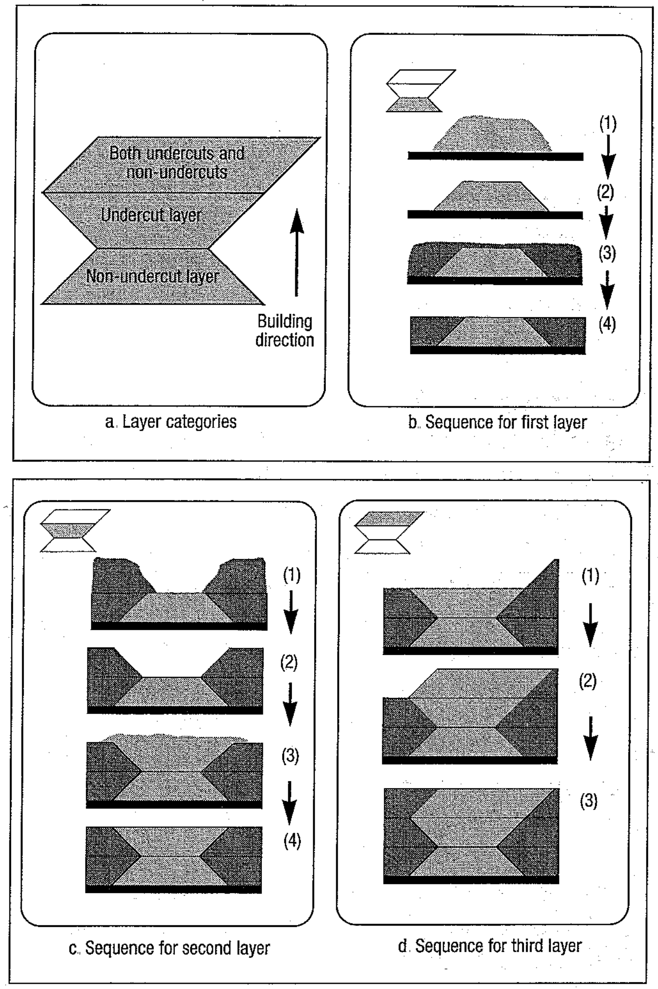



*Figure 7*
**Basic Sequence for Depositing and Shaping Layers**

Straight-wall features are considered to be either undercut or non-undercut features, depending on subtle processing steps.

The thickness of each layer and the sequence for depositing and shaping the primary and support materials in each layer will vary based on part geometry. For layers in the first category, the primary material is deposited first (*Figure 7b*, step 1) and then machined (step 2). The support material is then deposited (step 3); then the entire layer surface is planed (step 4). For layers in the second category, the support material is deposited and machined first (*Figure 7c*, steps 1 and 2); then the cavity created by the support structure forms the undercut features of the part (steps 3 and 4). Layers in the third category containing both types of surfaces must be further decomposed into layer segments, or "compacts," which are deposited and shaped in a sequence such that all undercut features (of either the primary or support materials) are formed by the previously shaped non-undercut feature. For example, in *Figure 7d*, step 1, a support compact is first deposited and shaped. Then in step 2, the primary material is deposited; its undercut feature is formed by the preceding support structure compact, and its non-undercut feature is shaped by machining. In step 3, the final support material compact is deposited and similarly shaped.

For more complex geometry, a Category 3 layer may have to be decomposed into even more compacts to satisfy the requirement that undercuts be formed from previously shaped material. Similarly, each layer of a multimaterial structure must be decomposed into a number of compacts equal to or greater than the number of materials in that layer.

Building structures using the strategy outlined above requires complementary primary/sacrificial material combinations such that freshly deposited materials do not destroy or distort previously shaped materials. A thermal deposition process called "microcasting," which satisfies this requirement for building metal structures, is described in the next section.

## 4. Microcasting

One goal for SDM is to be able to *directly* create fully dense, metallurgically bonded structures with controlled microstructures. Microcasting,[19,20] a nontransferred welding process that is being developed for this purpose, creates discrete, superheated molten droplets. One implementation, depicted in *Figure 8*, establishes an arc between a tungsten electrode and feedstock wire that is fed from a charged contact tip. The wire melts in the arc, forming a molten droplet at the end of the wire. When the droplet has accumulated enough molten material, its weight overcomes the surface tension by which it adheres to the wire. The droplet falls from the wire, is accelerated to the underlying substrate by gravity, and flattens on impact. In contrast to the small droplets created with thermal spraying, microcast droplets are much larger (that is, on the order of 1 mm diam). The larger microcast droplets remain in the arc for a longer period of time, allowing for a significant amount of superheat. Due to a large volume-to-surface ratio, they remain superheated in flight and contain sufficient energy to *locally* remelt the underlying substrate to form metallurgical bonding upon solidifica-

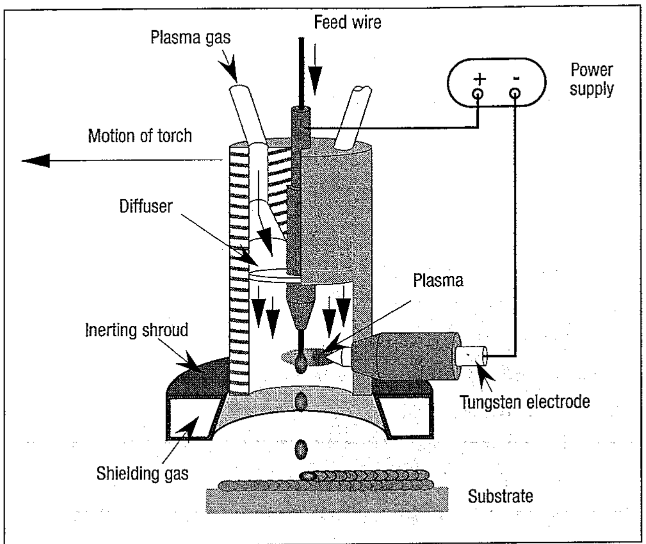



*Figure 8*
**Microcasting (cutaway view)**

tion.[21] The substrate may be preheated to facilitate remelting and reduce stress buildup.

To control oxidation, it is critical to shield the droplets and substrate with inert gas. Placing the microcaster in an environmental chamber is feasible but costly. Alternatively, a straightforward process is to locally shroud the droplets and working area with a laminar curtain of shielding gas. For this purpose, a commercially available shrouding device from Praxair, Inc. (Tarrytown, NY) was used.

The rapid solidification of molten droplets onto colder substrates allows for fusion bonding of dissimilar materials even for cases where a higher melting material is fused on top of a material with a lower melting point temperature. This is required for building multimaterial metal structures with high-strength bonding between sections of dissimilar materials and with a very limited alloying zone (that is, in the μm range). In contrast, the support/primary material interface requires a bond that is strong enough to withstand cutting forces only, but not a full-strength metallurgical (alloy) bond between dissimilar materials. To create acceptable support/primary material interfaces, it is necessary that the materials have different melting temperatures and different thermal conductivities. The material with the higher melting temperature must have a lower thermal conductivity, and vice versa. For material combinations that experience a small difference in melting temperatures and a relatively large difference in thermal conductivities, microcasting conditions can be found such that each material will remelt only sections composed of the same material, but not sections of the dissimilar material.[19] For example, parts can be built out of 308 stainless steel ($T_{melt}$ = 1410°C, $\lambda$ = 14 W/mK) with copper ($T_{melt}$ = 1083°C, $\lambda$ = 401 W/mK) support material that is sacrificed using nitric acid. Steel droplets can remelt the previously solidified steel, but not the higher thermal conductivity copper, as is required to build overhang features.[19,22]

## 5. Planning SDM

An SDM planner has been developed to automatically produce manufacturing plans, including shape decomposition, sequence of operations, trajectories for deposition and machining, and instructions to control the individual SDM cells. Nonlinear CAD model representations are used to obtain the accuracy and surface quality required by many applications. For heterogeneous structures, the CAD model comprises separate individual solids representing regions of a different material. Each of the solids is augmented with a set of attributes containing material and surface specifications.

Several issues, which are briefly outlined below, have to be addressed for automatic planning. First, the CAD model is decomposed into compacts, which are further decomposed into layers to resolve manufacturing constraints on part geometry (see Section 3), tool interference, and the capabilities of material deposition processes. A geometric algorithm has been implemented to automatically decompose the individual solids of the CAD model into manufacturable compacts.[23] The algorithm identifies the silhouette curves that separate the undercut and non-undercut regions on the surfaces of each individual solid of the part. To avoid manufacturing conflicts, the surfaces must be separated along convex silhouette curves, that is, the transition lines where undercut surfaces are higher than the non-undercut regions with respect to the build direction. Partition surfaces to split the inside of each solid into compacts are obtained as ruled surfaces by sweeping relevant portions of the silhouette edges along the build direction. Partitions are further required where projections of silhouette loops are self-intersecting or where cyclic ordering of the manufacturing sequence occurs. To satisfy process constraints, such as limited cutting tool length or the inability of certain deposition technologies to reliably fill the edges along larger vertical steps in the substrate, the compacts might be further split into layers of limited thickness. Because all geometric interference problems have been resolved, layering is accomplished by simply splitting along planes perpendicular to the build direction. The typical layer thickness ranges up to approximately 0.060″ (1.52 mm) for microcasting, depending on material selection and tool availability.

Once the part and support models are divided into layers and compacts, a generic planning strategy is used to describe the sequence of operations required to manufacture an individual compact. In general, the strategy contains a deposition and a shaping step. Other intermediate processing steps, such as shot peening, embedding, or heat treatment, can be added. Each of the steps can be executed depending on certain conditions (such as material, thickness of layer, type of compact, and so on). Different strategies have been developed for different species of parts and are available in a strategy database. Future developments will include a simple command syntax to express and easily create SDM strategies, and a mechanism to automatically choose a strategy for each compact from the database depending on optimization criteria.

Deposition trajectories are derived from the geometry of each compact, the material specification attributes, and various material and process-dependent parameters that are chosen from a process database. Depending on material availability and processing requirements, an optimal deposition process can be selected or a specific process will be used. Deposition path shape and the order and direction in which the segments are traversed during deposition greatly affect the properties of the deposit. Simple, raster-scanning trajectories with parallel line segments, as well as various spiral-based approaches to optimize the quality of the deposits, are available for deposition. For minimization of stress effects, deposition patterns with different fill and hatch styles are also being explored.

After each compact is deposited as a near-net shape, it is machined to its net shape. The machining operations are separated into several steps: planing the top surface, 2-D contouring, and 3-D shaping of the side surfaces. Offsetting operations of nonlinear geometries are required to derive trajectories for cutting tools with finite dimensions and are robust for 2-D contouring operations. For 3-D shaping, three different approaches (face or side cutting with cylindrical cutting tools, or tracing the surface with a spherical tool with slightly different surface offsetting methods) are available. While algorithms have been developed to handle each case individually, the offsetting methods are not advanced enough to reliably handle the areas near boundaries between surface regions where different approaches are used for 3-D shaping. Tool interference due to incorrect offsetting at boundaries can potentially damage the neighboring surfaces. Further developments of offsetting algorithms, interference detection, and tool path correction are currently being addressed.

One of the biggest challenges in the development of an automated process planning system for SDM is to overcome problems with the stability of existing CAD kernels. Intensive geometric manipulations, which are required to decompose heterogeneous models while preserving the 3-D geometry, result in shapes containing nonmanifold features. These features have triggered inconsistencies in CAD systems and have led to unpredictable and faulty operation of the planning software. Currently, manual checking of the calculated trajectories must be performed to ensure reliable fabrication. To improve the performance and to develop a fully automated planning system, a variety of CAD kernels (for example, SHAPES, ACIS, and Parasolids) providing different levels of support are still being tested.

## 6. Examples of Heterogeneous Structures

To demonstrate the feasibility of using SDM to manufacture heterogeneous structures like the tool represented in *Figure 4b*, the artifacts shown in *Figures 9* and *10* have been built. The part in *Figure 9a* is a hemispherical-shaped structure with a 308 stainless steel outer shell, a permanent copper interior, and conformable channels as depicted in the CAD drawing in *Figure 9b*. Other examples of artifacts created with a combination of laser welding and microcasting can be found in Fessler et al.[24]

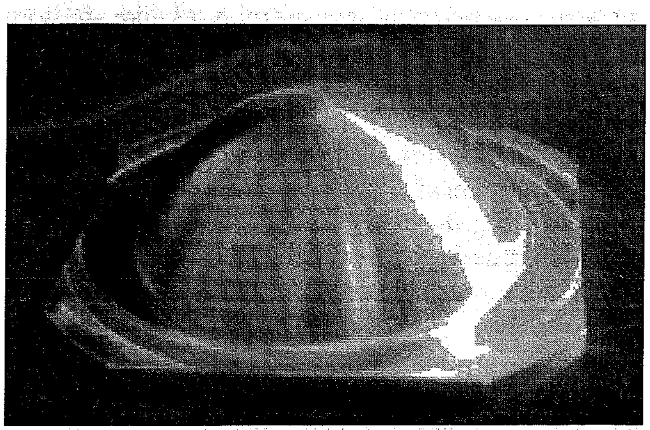
The artifact in *Figure 10* demonstrates embedding of sensors. The sensor is a K-type thermocouple that was embedded in stainless steel. The active part of the sensor was exposed during the embedding process; the junction was created during deposition and remained functional thereafter. The insulation to the sensor was not damaged because of the relatively low heat transfer achieved with microcasting. The issue of getting wiring to this type of sensor in an actual tool is currently under investigation and might involve the use of vapor deposition and laser-based processes to selectively deposit insulating materials around conductive metals.

In another design domain, *Figure 11a* shows an example of an embedded electronic assembly, like that shown in *Figure 5*, built with SDM. This device, the "VuMan-SDM," is a personalized wearable computer that can store maps for navigational aids, or detailed assembly drawings for service or maintenance applications. The graphical information is displayed on a commercially available heads-up display. While the original VuMan series computers were built using conventional packaging processes,[25] investigations are under way on the use of SDM to build these types of computers for underwater applications where compactness and ruggedness are critical.[26]

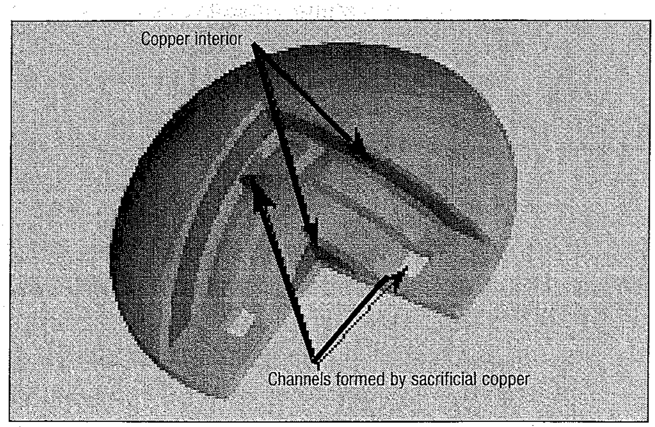
A cutaway CAD rendering of VuMan-SDM is shown in *Figure 11b*. The unit is a three-layer polyurethane (PU) structure. The two-component PU mixture (resin/activator) used for this experiment was deposited manually. Each layer took approximately one hour to partially cure before it could be machined. A support structure made of wax was deposited with a hot-wax gun. VuMan-SDM contains two layers of printed circuit boards (PCBs); the first PCB is located on top of the first PU layer, and the second PCB is located on top of the second PU layer. The two PCBs are electrically interconnected using pin receptacles, which are more commonly used to make conventional IC sockets. The steps for making embedded interconnects and other components are described in detail in Weiss et al.[26] While only two layers of PCBs had to be connected in VuMan-SDM, the interconnect system is designed so that each via can be extended upward to an arbitrary number of layers. Component parts that are not fully embedded, such as switch buttons, the opening to the PCMCIA card slot, and the battery caps, were protected during deposition with plastic covers that were machined away during the final shaping operation. Embedded indicating lights (LEDs) were attached to light-transmitting pipes that extended past the outer surface of the structure. The pipes were then embedded in a layer of polyurethane, and both the plastic pipes and the polyurethane were machined to form a blended surface.

## 7. Discussion

Shape deposition manufacturing is a layered manufacturing methodology that uses alternating steps of selective material deposition and shaping to create heterogeneous structures from a wide range of materials. SDM has been implemented at two research facilities: in the Shape Deposition Laboratory at Carnegie Mellon University and, more recently, in the Rapid Prototyping Laboratory at Stanford University. These robotic, cell-based implementations of SDM allow for easy expansion of the process capabilities and the introduction of different subprocesses. In addition to welding, thermal spraying, microcasting, dispensing two-component mixtures, and CNC milling, new processes that are currently being added or investigated include



a. Completed steel/copper structure




b. CAD rendering, cutaway view

*Figure 9*
**Multimaterial, Copper/Stainless Steel Structure Built with SDM**

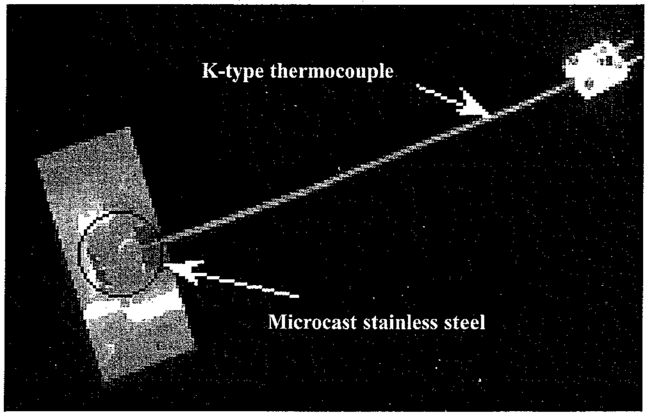



*Figure 10*
**Thermocouple Embedded in Stainless Steel**

laser welding, extrusion, vapor deposition, electroplating, and CNC EDM. To implement the extrusion-based SDM process, stand-alone SDM machines are currently being built by mounting the extrusion heads directly on the *z*-axis housing of conventional CNC milling machines. This integrated CNC shaping/deposition machine can demonstrate how existing, commercially available CNC milling machines can be relatively inexpensively modified to serve as high-performance solid freeform fabrication machines.

Several artifacts have been constructed to demonstrate the feasibility of both the process and the concept of heterogeneous structure manufacturing. While the manufacturing issues and process development have been the main focus of this research, current research efforts concentrate on the materials aspects of the process. Thermal and mechanical models are used to understand important deposition mechanisms and the effects on interlayer bonding, warpage, and internal stress buildup. Additional combinations of primary/support materials have to be identified and incorporated into the SDM process. Effects related to dissimilar material properties, especially to differences in coefficients of thermal expansion, have to be addressed for multimaterial structures. Research toward the creation of smart materials and structures will focus on methods to embed or manufacture electronic sensors and actuators directly inside of plastic and possibly metal structures. Further development on the automated planning system focuses on advances in the geometric decomposition of the CAD model into manufacturable subsections ("compacts") and improved functionality and optimization of manufacturing and deposition strategies. For modeling heterogeneous structures, linking mechanical and electronic CAD packages will become necessary to enable concurrent design of functional and structural components of the desired prototype.

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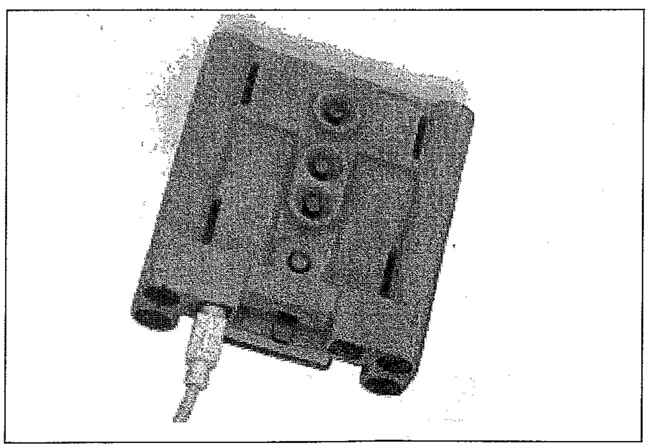
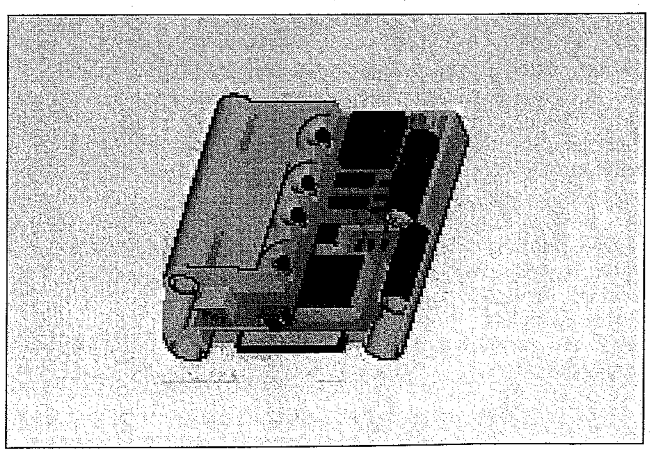


a. Vu-Man SDM



b. CAD model of Vu-Man (cutaway view)

*Figure 11*
**Embedded Electronic Structure**

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## Authors' Biographies

Lee E. Weiss is a principal research scientist at The Robotics Institute, Carnegie Mellon University, where he directs the Shape Deposition Manufacturing Laboratory. He received his PhD in electrical and computer engineering from Carnegie Mellon in 1984.

Robert Merz is an engineering research associate with the Department of Mechanical Engineering at Stanford University. His research interests focus on expanding shape deposition manufacturing capabilities; embedding of sensors, circuits, and optical components; and the fabrication of mesoscopic devices. He received a PhD in electrical engineering from the Technical University of Vienna (Austria) in 1994.

Fritz B. Prinz is the first holder of the Rodney H. Adams professorship in the School of Engineering at Stanford University. Prior to joining Stanford in 1994, he taught mechanical engineering at Carnegie Mellon University for 14 years. He obtained his PhD in physics and mathematics from the University of Vienna (Austria).

Gennady Neplotnik is a research engineer in the Engineering Design Research Center of Carnegie Mellon University. He is responsible for both mechanical design and manufacturing of embedded wearable computers. He received his PhD in mechanical engineering from the Civil Engineering Institute of Moscow in 1967.

Prakash Padmanabhan is a postdoctoral research associate in mechanical engineering at Carnegie Mellon University, from where he received his PhD in 1996. His research focuses on planning and optimization of the shape-deposition processes.

Larry Schultz is a senior research engineer in The Robotics Institute of Carnegie Mellon University. He has more than 15 years of R&D experience with welding systems and metallurgy.

Krishnan Ramaswami is a postdoctoral research associate in mechanical engineering at Stanford University, from where he obtained his PhD in 1997. His areas of interest include solid modeling, geometric reasoning, physically based modeling, process planning, finite element mesh generation, and computer graphics.