Novel Applications and Implementations of Shape Deposition Manufacturing

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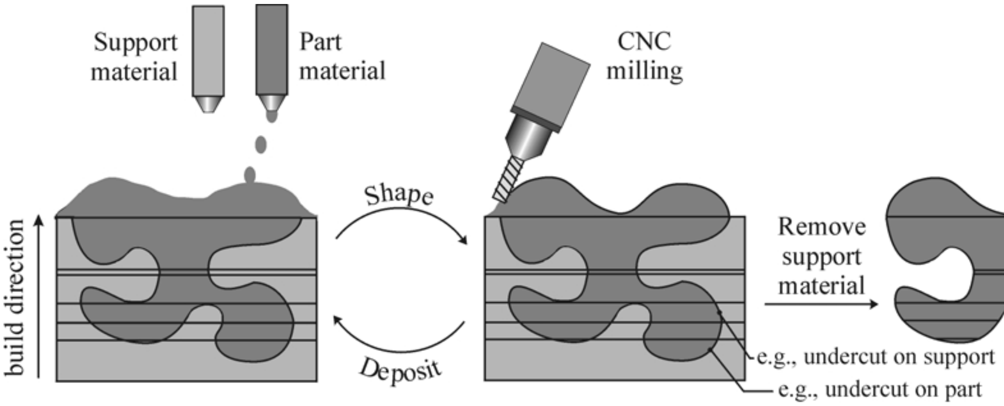
Abstract

Shape Deposition Manufacturing (SDM) is a solid freeform fabrication (SFF) process that incrementally builds up complex parts by systematically combining material additive processes with material removal processes. The advantages of each type of process are thus combined such that novel structures can be fabricated with SDM that could not be practically fabricated with either material additive or material removal processes alone. Examples of such structures, which are relevant to Navy/DOD applications, are described in this paper including a waterproof wearable computer with embedded electronics, a composite steel/copper injection mold tool, and a miniature turbine wheel assembly. In addition, this article presents a novel implementation of a SDM system based upon the integration of deposition apparatus (i.e., material additive process) with an existing computer-numerically-controlled (CNC) milling machine (i.e., a material removal process). Such an implementation is a cost-effective way to create high-quality SFF machines.

1. Introduction

Most solid freeform fabrication (SFF) systems are based upon a material additive, layered manufacturing method. Computer-aided-design (CAD) models are first decomposed into thin cross-sectional layer representations, then physical parts are built up in custom automated fabrication machines, layer-by-layer, using material additive processes (1). Layers of sacrificial structures are simultaneously built up to fixture and support the growing shapes. While layered manufacturing facilitates rapid prototyping (e.g., quickly fabricating “models”, as opposed to production parts) of arbitrarily complex shapes, the resulting surface finish and accuracy, which are critical factors for being able to fabricate functional parts, are compromised by the “stair-steps”

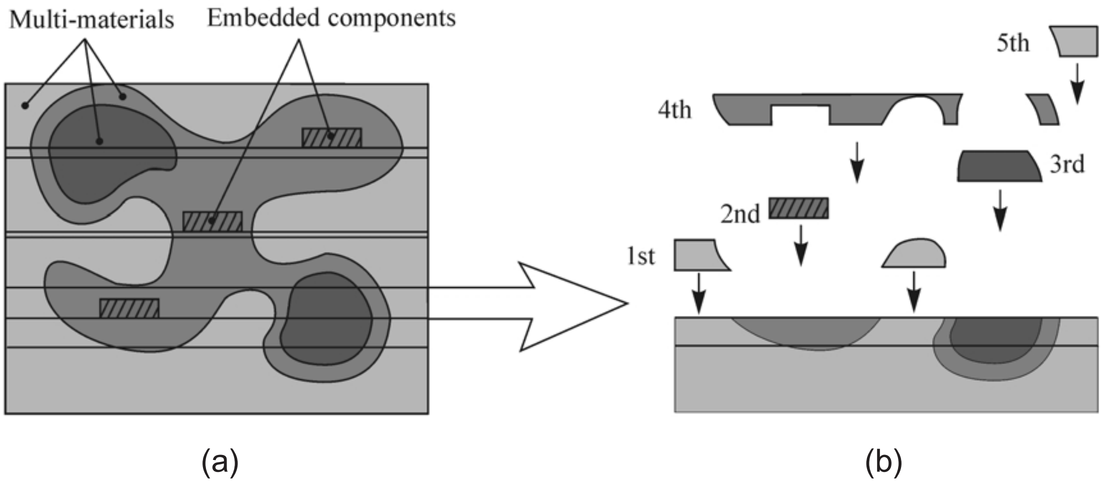
Figure 1
Shape Deposition Manufacturing.



from layer-to-layer. High accuracy and quality surface finishes, required for such applications as custom tooling, precision assemblies, and structural ceramics, are best achieved with material removal processes such as 3- and 5-axis computer-numerically-controlled (CNC) milling and electrical discharge machining (EDM) machines.

Shape Deposition Manufacturing (SDM) is a SFF process for which the original goal was to combine the advantages of geometry decomposition and material addition with the advantages of material removal processes (Figure 1). The basic SDM fabrication methodology is to deposit individual segments of a part, and of support material structure, as near net shapes, then machine each to net-shape before depositing and shaping additional material (2). This method takes advantage of the basic SDM decomposition strategy which is to decompose shapes into segments or 'compacts', such that undercut features need not be machined, but are formed by depositing onto previously deposited and shaped segments. For example, undercut part features are formed by depositing onto shaped support material compacts, and vice-versa. In addition, the decomposition plan preserves the 3D-geometry information of the outer surface of each compact so that the desired shape of the CAD model can be accurately replicated when 5-axis machining is available. Each compact in each layer is deposited as a near-net shape using one of several available deposition processes that are described in subsequent sections. The thickness of each compact depends not only on the local part geometry, but also on

Figure 2
Multi-material structures with embedded components. (a) Example of a heterogeneous structure. (b) Sequence for depositing and shaping; each compact is deposited, then shaped before proceeding to next compact.



deposition process constraints. After the entire part is built up, the sacrificial support material is removed to reveal the final part.

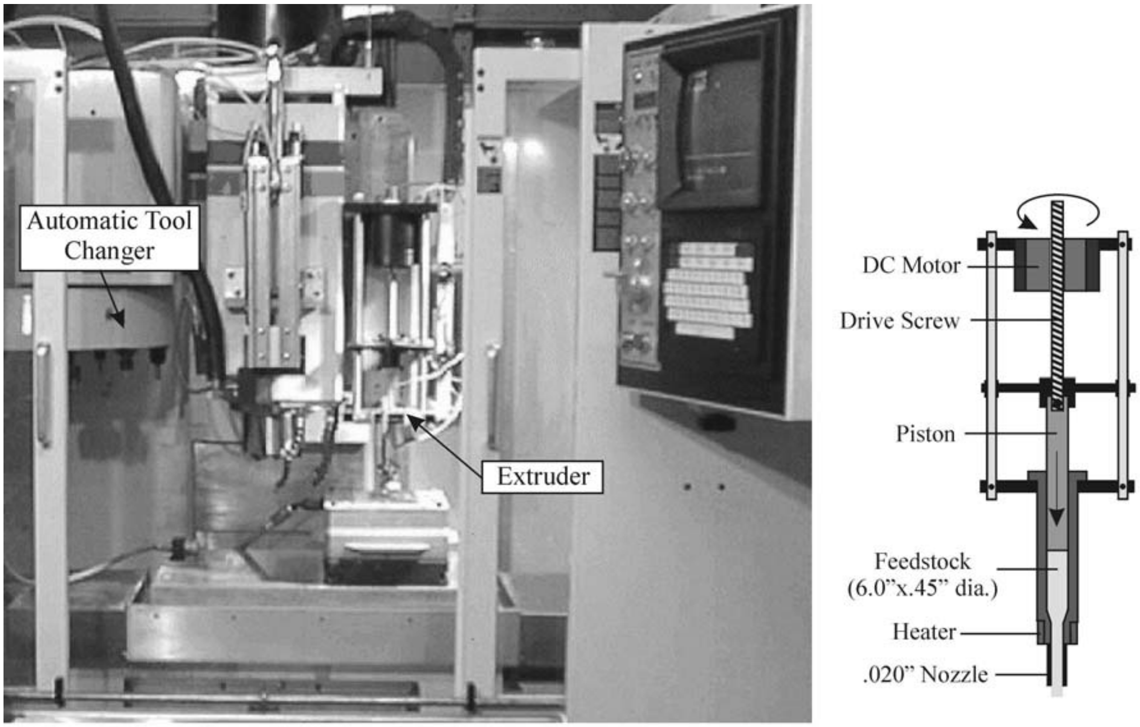
In addition to the rapid prototyping of complex shapes, selective additive material processing enables the fabrication of multi-material structures and it also permits prefabricated components to be embedded within the growing shapes as depicted in Figure 2a. Another goal of SDM research is to investigate how the capability to fabricate such heterogeneous structures enables the manufacture of novel product designs (3). An example of the compact splitting strategy and sequence for depositing and shaping materials for a typical layer of a heterogeneous structure is depicted in Figure 2b. Note how depositing onto the machined surface of one compact forms the undercut surface of another compact on top of the first compact. Several examples of heterogeneous designs are described in subsequent sections including a waterproof wearable computer with embedded electronics, and a composite steel/copper injection molding tool. In addition to heterogeneous designs, novel assemblies of parts can also be directly built up with SDM by using sacrificial material to separate the individual parts. An example of a miniature metal turbine assembly is described in this paper.

Another key issue for our research is how to implement SDM in a cost-effective fashion. Until recently, SDM operations have been executed by building up the parts on pallets and transferring them to individual operating stations using a robotic palletizing system (4). Robotic manipulation was used in order to create a flexible system, for an R&D environment, which could be easily modified in order to investigate alternative deposition, shaping or other intermediate processing operations. Such a system, however, is too expensive and large for general dissemination of this technology. The next section describes a novel, cost effective and compact implementation of SDM.

2. Integrated CNC Shaping and Deposition Machine

Commercialized SFF systems are customized machines, and high performance SFF apparatus can be relatively expensive. As an alternative to customization, or to robotic automation, we are exploring implementing SDM by simply adding deposition apparatus directly to existing CNC milling machines such as are typically found in machine shops throughout the world. In addition to shaping operations, the CNC milling machine provides the precision

Figure 3
Integrated CNC shaping/deposition machine for SDM. (a) Fadal VMC-15 CNC milling machine with integral extruder. (b) ACR extruder.



(a) (b)

motion control required for deposition. When not being used for SDM, such an integrated CNC deposition and shaping machine can still be used as a conventional milling machine.

For one example, the integrated CNC deposition/shaping machine shown in Figure 3a is being used to investigate the fabrication of 'green' ceramic parts using an extrusion deposition process (5). Green materials, which are deposited by the extruder, are composed of ceramic powders densely bound in polymeric binders. After the green part is built up and removed from the machine, the binder is burned out in a furnace. Then, the part is sintered to fuse the powder to form the final ceramic part. The CNC machine is based upon a commercially available Fadal VMC-15 3-axis mill with an automatic tool changer carousel[1]. An Advanced Ceramics Research extruder[2] is mounted on a pneumatically actuated slide that is attached to the Z-axis spindle housing of the CNC machine. The slide is retracted when the extruder is not in use (e.g., during machining operations) and lowers the extruder into the workspace during deposition operations. The extruder is used to deposit both support and part materials; currently, we manually switch extrusion tubes/nozzles preloaded with the different materials. Being able to quickly build complex ceramic parts is important for many military applications such as components for high-performance miniature turbine engines for drone aircraft.

An example of a 'green' ceramic part built on the integrated SDM machine is shown in Figure 4. The part material is silicon nitride, and the support material is ACR 200, a proprietary non-ionic, water-soluble, machinable thermoplastic. While this particular shape could have been cut directly from a block of 'green' ceramic stock, such conventional machining would require re-orienting, re-fixturing, and registering the part after the top-side has been cut in order to cut the bottom-side. Another advantage of SDM over conventional machining is that first depositing shapes in near-net, before machining, reduces the waste of costly materials.

We have also explored the use of an integrated SDM machine that incorporated conventional welding to directly deposit steel and copper parts (6). We are currently creating an SDM machine for fabricating wax molds for molding gelcast or thermoset materials (5).

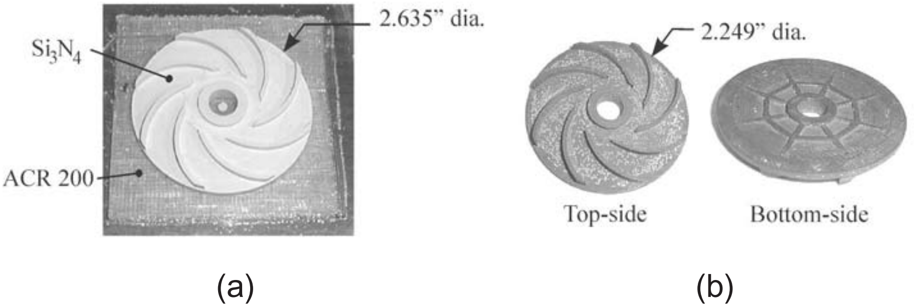
3. Multi-Material (Heterogeneous) Structures

We believe that one of the most important roles for SFF in the future will be to help manufacture heterogeneous product designs. Several of these novel products that have been built with SDM are described below. While conventional manufacturing methods could have been used to fabricate these products, these methods would have required additional time-consuming operations, including the need for custom fixturing and tooling, complex assembly operations, and high-strength material joining processes.

3.1. Steel/Copper Tooling

Injection molding is the process of forming plastic parts by first flowing heated plastic into the cavity of a custom tool (i.e., the cavity is in the shape of the part), then allowing the plastic to cool down and solidify, and finally opening the tool to remove the part. Injection molding is used to mass-produce plastic parts in quantities from hundreds to millions of parts. SFF has been widely investigated for fabricating injection mold tools with complex molding surfaces, as well as with conformal internal cooling channels for thermal management. With SDM, even more advanced tools can be fabricated composed of multi-materials such as steel/copper composites. While steel provides strength and wear-resistance, copper's superior heat transfer properties provide quick heat up and cool down of the tool as well as uniform heat-

Figure 4
Example of a part built with an integrated SDM CNC shaping/deposition machine. (a) Green Si_3N_4 part. (b) Part after pressureless sintering in N_2 at 1750°C.



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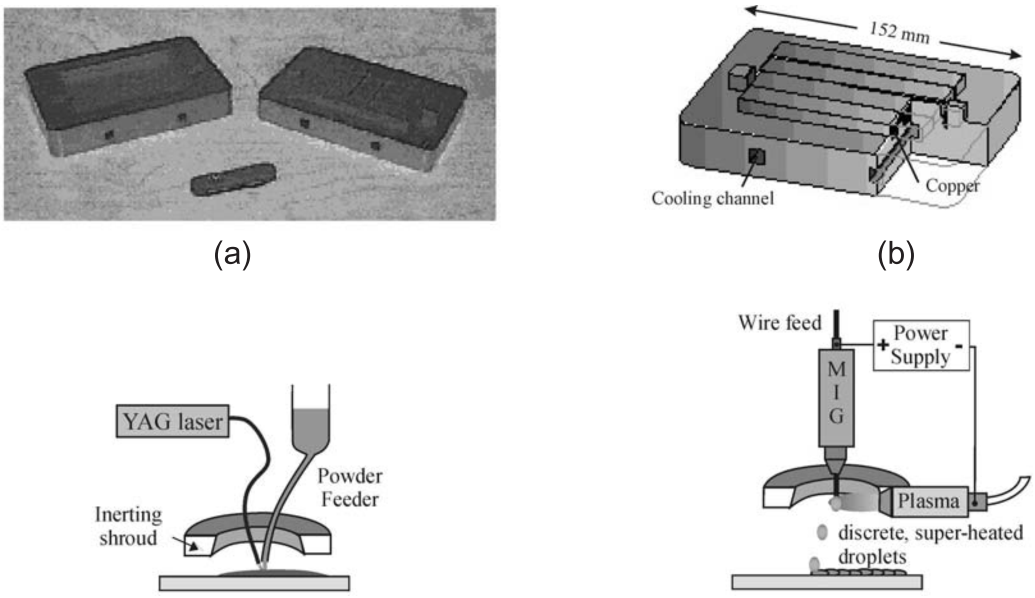
[1] Fadal Engineering, Chatsworth, CA.

[2] The extruder and the feedstock materials are manufactured by Advanced Ceramics Research Corporation, Tucson, AZ.

Figure 5
Multi-material metal structures built with SDM. (a) Multi-material injection mold tool. (b) Schematic of one half of tool. (c) Laser welding process. (d) Microcasting apparatus.



(a) (b) (c) (d)

ing. For example, Figure 5a shows a composite 316L stainless steel injection molding tool produced by SDM using robotic-controlled laser welding and microcasting deposition processes (7). One half of the tool, which is shown schematically in Figure 5b, has four internal copper deposits for temperature equilibration. Both halves of the tool have a "U"-shaped channel for water cooling during the molding process. The channels were formed by sacrificial copper, which was removed by etching in nitric acid. Portions of the cavities contained small features that could not be cut with end mills and these were finished with EDM.

In this tool, the steel was deposited with a laser welding process (Figure 5c). A 2.4 kW CW Nd:YAG laser scans over the substrate and a melt pool forms into which metal powder is injected (Figure 5c). The injected powder fuses onto the substrate, leaving a bead of deposited material in its wake. While this laser welding process is very precise, in comparison with conventional welding methods, it cannot effectively deposit copper due to copper's high reflectively. Therefore, microcasting was used to deposit the copper (Figure 5d). Microcasting is a non-transferred welding process that deposits discrete droplets of super-heated molten metal (6).

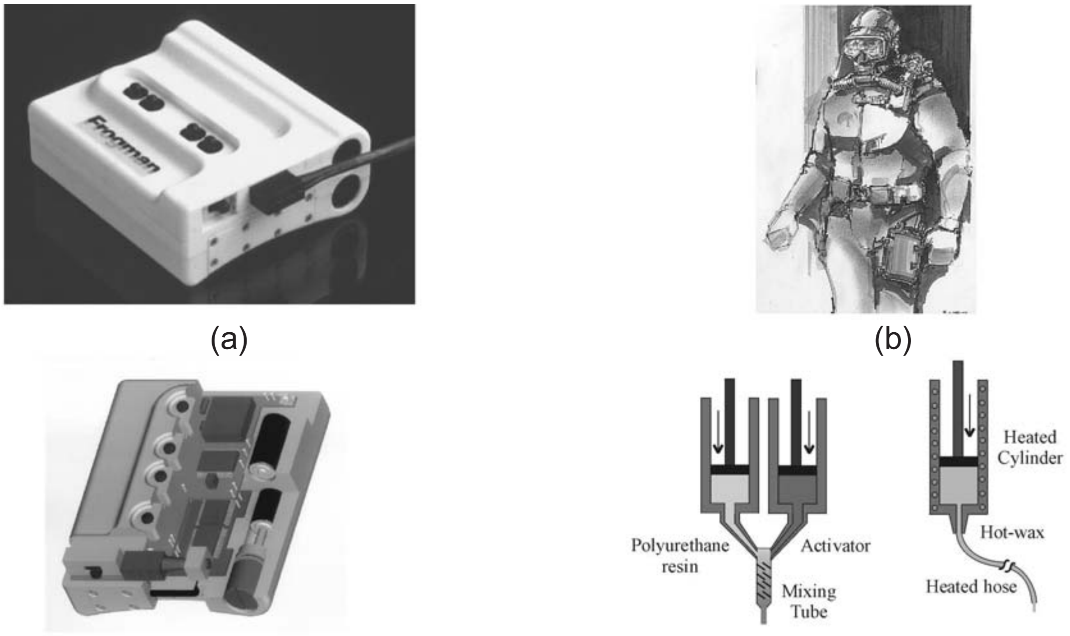
In addition to creating steel/copper structures, the laser system has also been used to deposit INVARTM, a low coefficient-of-thermal-expansion (CTE) nickel alloy, onto copper that was previously deposited onto steel. Such multi-material structures will have significant advantages in a wide variety of military applications. For example, in dies used for forming composite airfoils (e.g., for airplane and boat bodies), INVAR provides a closer match to the CTE of composite materials, thus resisting deforming the material during molding operations.

Ideally, the transition between different materials should be functionally graded, e.g., having a gradual change in material composition from one material to the next material. The laser system is particularly suitable for producing functional-gradient, multi-material parts because different materials can be continuously alloyed during the build process by simply mixing the powders which are fed to the melt pool.

3.2. Embedded Electronics

Another example of a heterogeneous design is an embedded electronic device fabricated by building up a non-conductive housing package and simultaneously embedding and interconnecting electronic components within the housing. With this approach it is feasible to relatively quickly fabricate compact, rugged, customized computer modules in small lot sizes. This capability is particularly well suited for military applications, to manufacture mission-specific, conformal shaped 'smart' devices such as wearable computers tailored for an individual soldier or a small military unit.

Figure 6
Embedded Electronics. (a) 'Frogman' computer. (b) Waterproof application. (c) CAD model of 'Frogman'. (b) Deposition apparatus.



(a) (b)

(c) (d)

These computers might store maps, equipment descriptions, help to log data, or provide communication links.

For one example, the ‘Frogman’ shown in Figure 6a and 6b is a waterproof computer that can store maps for navigational aids, or detailed assembly drawings for service, maintenance, or field operations. The graphical information, which is stored on Personal Computer Memory Card International Association (PCMCIA) cards, is displayed on a heads-up display (Figure 6c). A conformal shaped rear surface was also required so that the unit could be comfortably strapped to a diver’s leg. The device is built up in layers of polyurethane (PU) and sacrificial wax. The PU is deposited as a 2-part thermoset (left side of Figure 6d). The wax can be extruded with a conventional hot-glue gun (right side of Figure 6d), or thick layers can be poured from a hot-melt pot. The fabrication details, including component embedding and interconnection are described in detail in (8). The important points are that custom tooling was not required to manufacture the Frogman and that embedding facilitates waterproofing.

4. Integrated Assemblies

SDM has also been used to build up simple assemblies in a single operation. As an assembly is being built up, its individual components are separated by and encased within sacrificial support material. After the assembly structure has been completely built up, the sacrificial material is removed, freeing the components to move with respect to each other. For example, SDM was used to create the steel crank mechanism shown in Figure 7. In this mechanism, a piston is connected to a crankshaft with a connecting rod. Turning the crank causes the piston to move back and forth in its chamber. The mechanism components are 316L stainless steel, deposited with laser welding, and the sacrificial support material was microcast copper.

The capability to create such integrated assemblies may be particularly useful for producing miniature mechanisms where discrete assembly is difficult, i.e., similar to the micro-electro-mechanical systems (MEMS) methodology. To demonstrate the feasibility of SDM for the fabrication of structures with feature sizes in the range of tens to hundreds of and thousands of microns, several simple artifacts have been built (9). This regime has been recently referred to as the ‘mesoscopic regime’ which means that characteristic feature dimensions are bigger that those typically achieved using very large scale integration (VLSI) fabrication methods (e.g., used to make integrated circuit chips), yet smaller than parts produced using conventional processing techniques. We believe that mesoscopic assemblies will be particularly important for enabling future DOD applications such as autonomous micro-vehicles and micro-flying machines.

In SDM, mesoscopic structures are built up using sputtering and electro-plating deposition processes, and shaped

Figure 7
Complete assemblies and mechanisms directly built up with SDM. (a) Steel crank and piston mechanism. (b) Schematic of mechanism.

(a) (b)

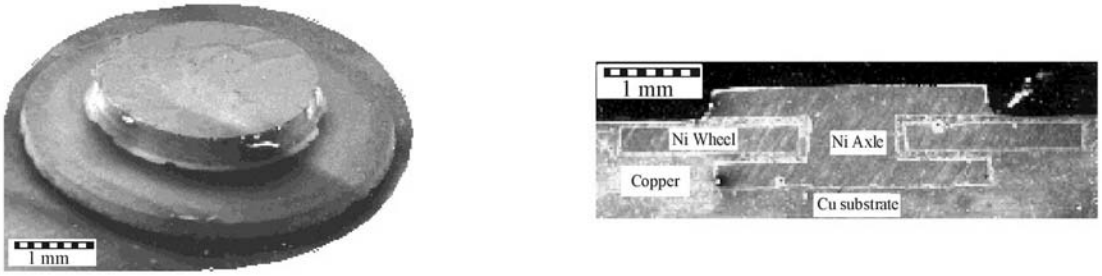
with micro CNC or EDM machining. For one example, the 1.1mm high nickel structure shown in Figure 8a consists of a wheel (5mm dia., 0.3mm thick) which is permanently mounted on a nickel axle (1mm dia.). The scanning electron microscopy (SEM) photograph in Figure 8b shows a cross-section of the wheel and axle before removal of the copper support structure.

Additional examples of novel SDM mesoscopic integrated assembles are shown in Figure 9. Figure 9a is a nickel substrate carrying nine mesoscopic wheels. This structure suggests the possibility for building massively parallel miniature machinery. Figure 9b shows a 130mm thick microturbine impeller that rotates at high speeds when air is passed through the gas jets. This structure establishes the feasibility of building assembled devices with clearances on the order of less than 20 microns.

5. Discussion

SFF has been successfully used within the limited realm of Rapid Prototyping. However, as SFF processes improve and are able to build functional, engineering models, SFF will be used for mass customization, i.e., customers able to order products in small-lots (as small as one) customized for their specific needs. Such ‘mass-customization’ will be attractive for not only consumer and commercial markets, but also for defense industries as a “dual-use” technology for creating products tailored to individual soldiers needs, as well as for cost effective tooling for manufacturing defense systems. In addition, by opening up the design space, novel designs, inaccessible with conventional manufacturing techniques, will be possible. One class of such novel designs is heterogeneous structures, such as embedded electronics, and another class is integrated assemblies as described in this article. For heterogeneous structures to be practical, however, streamlined CAD systems will be required which enable concurrent representation and manipulation of geometry, material and embedded components. Other possible novel designs will involve functional gradient structures such as ceramic to metal parts or graded metal to metal structures allowing the transition from highly thermally conductive regions, inside, to tough surfaces on the outside of a part. Beyond these novel applications of SFF, it is hard to predict where exactly this will lead to when creative people have access to SFF technology. Undoubtedly, the creation

Figure 8
Mesoscopic nickel wheel on axle built with SDM. (a) Mesoscopic Ni wheel. (b) Cross-section of wheel and support.



(a) (b)

Figure 9
Examples of mesoscopic assemblies. (a) Assembly of nine mesoscopic wheels. (b) Miniature turbine impeller.

(a) (b)

of products that no one has even conceived of as yet will be one of the likely outcomes.

Acknowledgments

This work has been supported by the ONR, DARPA, and NSF. The authors acknowledge the following individuals for their contributions in creating the systems and the parts built with the systems described in this article: Gennady Neplotnik, Larry Schultz, Robert Merz, Alexander Cooper, John Fessler, JohnKeitzman, and John Lombardi.

Bibliographies

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