APPLICATIONS OF SOLID FREEFORM FABRICATION AT THE NAVAL RESEARCH LABORATORY

J. P. Thomas†, B. A. Bender†, A. Piqué†, K. P. Cooper†, R. J. Rayne†, and A. C. Richardson‡

†: Materials Science and Technology Division, Naval Research Laboratory, Washington, DC 20375
‡: Capt. USN, Department of Radiology, National Naval Medical Center, Bethesda, MD 20889

Abstract

Solid Freeform Fabrication (SFF) and related techniques are used at the Naval Research Laboratory (NRL) for a variety of materials related investigations. Research and applications conducted over the past few years are described including: Helisys Laminated Object Manufacturing System (LOMS) fabrication of: ceramic piezoelectric actuators, tooling for multifunctional materials, and anatomical prototypes for surgical visualization; fabrication of mesoscale electronic and sensor components using a laser forward transfer direct write technique; and visualization of complex, 3-D microstructures using a Stratasys Fused-Deposition Modeler. The paper closes with a brief overview of future SFF related work at the NRL.

Introduction

Solid Freeform Fabrication (SFF) and related techniques are used at the Naval Research Laboratory (NRL) for a variety of materials related investigations. This paper will describe several recent SFF projects conducted using an NRL Helisys Laminated Object Manufacturing System (LOMS Model 2030H) or a custom NRL built laser-based, direct material writing system known as: "Matrix-Assisted-Pulsed-Laser-Evaporation Direct-Write" (MAPLE DW). Use has also been made of the Stratasys Fused-Deposition Modeler (FDM) in some collaborative efforts.

We begin with a description of several LOMS-based applications including: ceramic piezoelectric actuator fabrication, rapid tooling for multifunctional unmanned air-vehicle components, and anatomical prototyping for surgical visualization. Fabrication of mesoscale electronic and sensor components using the MAPLE DW system is described next followed by a description of the use of FDM for creating a physical model for complex, 3-D material microstructures. We conclude with a brief overview of future SFF related work at the NRL.

Laminated Object Manufacturing System Applications

Piezoelectric Actuators

Advancing the development of high authority (i.e., high force and displacement) piezoelectric actuators through the use of innovative designs and advanced fabrication techniques is a critical enabling step for military systems [Wu et al., 1999]. The NRL has been involved in a program to develop the Navy's SFF capability for rapid R&D of novel tailored actuators as a means of accelerating their insertion into fleet applications.

One such novel actuator, the telescoping actuator, patented by Lewis and Kahn [1997] (Figure 1), serves as an active element in machinery mounts for noise (acoustic signature) reduction. The telescoping design provides for displacement amplification with an output force proportional to the cross-section of the smallest element. These actuators are used in constrained spaces of varying size and have varying power/displacement requirements. Another actuator, designed for active payload vibration suppression during spacecraft launch, consists of a thin ceramic piezoelectric ring with small axial holes along the circumference for weight savings.

Actuators can be fabricated using an injection-molding process, but this is too expensive and time consuming for multiple design evaluations. Instead, a modified LOMS process has been used to rapidly fabricate functional components for direct evaluative testing. Griffin et al. [1994] document some of the early efforts to adapt the LOMS technique for fabricating ceramic (alumina) components.

The telescoping actuators are built by integrating the lamination of thin lead-zirconate-titanate (PZT) embedded polymer sheets [Bender et al., 2000] with precise laser cutting by the LOMS. Engineering of the ceramic-polymer sheet stock, referred to as ceramic tape, is critical to the success of the process. The ideal ceramic tape is stiff enough to avoid excessive distortion during handling, amenable to laser cutting, and suitable for lamination via solvent welding, while possessing appropriate firing properties [Cawley and Liu, 1998].

PZT tapes formulated with a polymer binder system optimized for alumina tapes were tried first. These tapes were very flexible due to the large amount of plasticizer that was added to allow mixing with the high specific gravity PZT. Microstructural characterization of the tape using scanning electron microscopy (SEM) showed non-uniform distributions of binder and PZT with PZT-free regions and a vertical density gradient (porous to dense going from top to bottom). Actuators made with these tapes were badly cracked and deformed (Figure 2A). The cracking and deformation were greatly reduced (Figure 2B) using tapes with PZT-optimized binder, which facilitates more uniform PZT powder and binder distributions within the tape.

Selection of an appropriate solvent for lamination welding is vital to achieving a good bond between the tape layers. The solvent must act as a tackifier, enabling bonding between the layers, and it must have a relatively low vapor pressure so that it doesn't evaporate before affecting the lamination process. Also, its action must be limited to the interface region. Otherwise it can diffuse to the laser-cuts and cause partial rebonding, which makes decubing of unwanted material from the build more difficult.

Previous research indicated that a light spray of propanol led to satisfactory lamination [Bender et al., 2000]. On closer examination, however, small interlaminar debonds were observed scattered throughout the actuator. One reason for the presence of these defects was uneven evaporation of the propanol. Longer spray times were tried in an attempt to prevent uneven distribution of the propanol, but the presence of too much solvent created small pockets of liquid that could not be eliminated during lamination leading to even larger interlaminar defects. A low vapor pressure solvent, iso-amyl alcohol, was tried as a laminating solvent. Uniform distribution of the solvent was observed, and after firing, fewer defects were observed. However, the iso-amyl alcohol softened the ceramic tape binder too much making decubing difficult. A solution was found that required adding 10% polyethylene glycol (PEG- MW 200) to the propanol to retard the evaporation, leaving behind a thin tacky interlaminar film. SEM characterization revealed a continuous interlaminar film ~1 μm in width was left behind with no evidence of interlaminar defects. The PEG has time to dissipate away from the interfaces during binder burnout leading to low defect actuators after firing (Figure 2B).

Understanding the important SFF process parameters related to the PZT tapes and solvent lamination has allowed us to develop adequate process control, which leads to dimensional control and property reproducibility. As a result, this LOMS-based SFF process will facilitate more rapid R&D of novel ceramic piezoelectric actuators.

Rapid Tooling for Multifunctional Materials Fabrication

The LOMS machine has also been used to make molds and patterns for use in fabricating multifunctional fuselage prototypes for a micro air vehicle (MAV). We are integrating the MAV's structure and battery functions into one material to reduce weight and increase flight-time [Thomas et al., 2001]. The novel structure-battery materials being developed for this application are comprised of a thin-layer, polymeric lithium-ion battery material with structural additives and a barrier-layer packaging[1]. Molds and patterns are needed to form the composite structure-battery material "package" into the complex, 3-D curved fuselage shell shape.

A LOMS pattern of the MAV fuselage and the corresponding molds for the upper and lower fuselage halves are shown in Figure 3. These "tooling" components are made from standard Helisys paper (LPH 042). After decubing, they are sanded smooth and then epoxy coated for stiffening and strengthening at structure-battery fabrication temperatures ($80°C$ max). The tooling will be used in a vacuum-bag-forming operation to mold the structure-battery materials into the MAV fuselage form. Three types of structural enhancement are being considered. The first involves adding polypropylene (PP) or polyethylene (PE) films internally and bonding with the battery material. The second will increase the thickness of the PP or PE in the barrier-layer packaging to provide the required shape stiffness. The third type uses an epoxy-fiber shell. All three concepts require MAV fuselage molds/patterns for vacuum-forming at elevated temperatures ($80°C$ max) to affect interlayer bonding and shaping of the thermoplastics and curing of the thermosets. LOMS technology allows for rapid creation of complex tooling for this advanced development demonstration of multifunctional structure-power materials concepts.

Anatomical Prototyping for Surgical Visualization

Recently, we used the LOMS to create a very detailed anatomical prototype of a human spine with severe scoliosis from CT-scan digital data (Figure 4). SFF models are routinely used in medicine today for visualization and planning of complex surgical procedures, physician training, and informing/educating the patient, and that is the intended purpose of this model. Several fractional-scale models of the spine were made at the National Naval Medical Center using their Stratasys Fused-Deposition Modeler (FDM). Due to the complexity of the deformed spine structure, a full-scale model was desired, but model sizes are limited to 10 inches for this particular FDM machine. The build envelope for the NRL LOMS was large enough to fabricate the full-scale model of the spine, and it exhibited an added advantage of providing outstanding contrast on the various detailed skeletal features.

The spine prototype, shown in Figure 4, was fabricated as a solid block $18 \times 7 \times 5$ inches in dimension created with approximately 1070 layers of Helisys LPH 042 paper stacked in the 5 inch dimension. The build process took about 70 hours due to the fine-scale features in the model and the small crosshatching size (0.25×0.50 inch). Several days were spent on pre- and post-build tasks and *.StL file manipulations, and decubing took approximately 30 hours spread-out over several weeks.

The software MIMICS[2] was used to create the *.StL file from the CT-scan data. The data was filtered using triangle reduction, but the resulting *.StL file was still too large at 68.8 Mb for

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[1] The battery is ~ 0.5 mm thick in the bicell configuration [Thomas et al., 2001], and was developed in the early 1990's by Telcordia Technologies [Gozdz & Warren, 1997]. The packaging is a multilayer polymer-aluminum heat-sealing laminate (~0.1 to 0.5mm thick) that serves as a chemical/moisture barrier layer.

[2] http://www.materialise.be/mimics/

the LOMSlice software. We used Cyberware's Decimate Polygon Reduction Software[3] to reduce the *.StL file ~50% to 37.7 Mb, which was manageable by LOMSlice. The software works by coalescing polygons of "little importance" for accurate model representation via elimination of select vertices.

Matrix Assisted Pulsed Laser Evaporation Direct Write (MAPLE DW)

A laser-based direct material writing technique known as: "matrix assisted pulsed laser evaporation: direct write" (MAPLE DW) has been developed here at the NRL. This system, which builds on recent developments in materials and laser-based materials processing, provides a radically different method of fabricating mesoscale inorganic structures for electronic and sensor device applications and organic structures for unique biological systems applications [Piqué et al., 1999; Fitz-Gerald et al., 2000; Chrisey et al., 2000a]. An individual electronic component or an array of sensors can be built conformally over the surface of almost any substrate in air and at room temperature using MAPLE DW. This capability opens the door for the rapid prototyping and testing of customized designs.

The material deposition process begins in MAPLE DW when a high-repetition-rate, 355 nm UV laser beam is focused on a material "ribbon." Upon heating from the laser pulse, the build material transfers to the receiving substrate where it forms an adherent coating. The ribbon is a transparent tape that supports a 1-10μm thick layer of build material on one side, analogous to a conventional ink typewriter ribbon. A schematic of the process is shown in Figure 5.

Using MAPLE DW, we can fabricate electronic circuit patterns with feature resolutions on the order of 10μm by synchronously moving the ribbon to a fresh, unexposed region, and the receiving substrate approximately one beam diameter. The individual mesoscopic 3-D pixels or voxels of electronic material, one voxel transferred per laser shot, are assembled into the desired 3-D pattern. Alternating the ribbon material between a metal and a dielectric, for example, allows us to fabricate three-dimensional multilayer structures like parallel-plate capacitors.

The MAPLE DW system can also be operated in a laser micromachining mode or a laser sintering mode by removing the ribbon. This provides the capability for etching grooves or vias in the substrate, or surface annealing, sintering, or etching of individual components to improve their performance or dimensional accuracy. See, for example, Pique et al. [2000] and Chrisey et al. [2000b] for improvements to the electronic properties of oxide ceramics. For infrared (IR) laser wavelengths (1 to 10μm), the penetration depth is on the order of microns for a variety of materials allowing the benefits of higher-temperature processing on thermally sensitive substrates. Ultimately, laser annealing might allow the decomposition and reaction of organometallic precursors for transfers onto substrates that cannot tolerate processing at temperatures above the boiling point of water, (e.g., biomaterials). It might also allow some degree of bulk diffusion and sintering of ceramics for transfers onto substrates that can tolerate heating to a few hundred degrees for a short period of time (e.g., polyimide).

Advances in the research community's understanding of new materials and laser-material interactions have driven the progress evident in direct writing of electronic materials. On the other hand, recent advances in the direct writing of biomaterials have been driven by progress in UV-laser based transfer technology. MAPLE DW in particular can be an extremely gentle process. Using ribbons made of an aqueous composite mixture, we have been able to transfer patterns of viable bacteria such as E. coli onto various substrates [Ringeisen et al., 2001].

[3] http://www.cyberware.com/products/decimate.html

The capabilities offered by the MAPLE DW technique have opened up the possibility of integrating bio-structures with electronic devices on the same substrate for rapidly prototyping unique cell-based biosensors and bio-electronic interfaces. Clearly, the ability to generate components on demand, any place, on any substrate, and in a matter of minutes instead of weeks, provides us with a unique opportunity for bringing new designs to life that can only be dreamed of with today's manufacturing techniques.

Fused Deposition Modeling for Microstructure Visualization

An SFF model for the microstructure of a steel alloy is shown in Figure 6A. This model was fabricated using the Stratasys Fused Deposition Modeling (FDM) process[4]. It depicts a 3-D austenite grain within the alloy where the white solid represents the cementite decorated grain boundary and cementite precipitates and the empty space represents the austenite phase. The material is a Fe-1.3%C-13%Mn model steel alloy that was isothermally heat-treated at 650°C for 50 sec. A series of 128 images of the grain was taken by optical microscopy from serial sections at 0.2µm depth increments (Figure 6B). They were read into a Solid Model Builder program developed by the University of Michigan [Marsan and Dutta, 1996]. Each image was used to generate one slice for the FDM of the solid model.

The microstructures were generated and analyzed by Kral et al. [2000] at the NRL. This work was performed to develop better understanding of the true 3-D morphology and distribution of the solid-state precipitates in structural metal alloys. This understanding is important for the control of microstructure features that have a direct influence on the mechanical properties of components. Microstructural characterization via conventional microscopy provides only 2-D views from which 3-D information can be inferred, often erroneously. Three-dimensional analysis of microstructures gives accurate information on the nature of the grain boundaries, the origin of the precipitates, and the shape, dimensions and distribution of the precipitates. This information makes quantification of microstructure and its relation to material behavior more meaningful.

Three-dimensional microstructures have been mathematically reconstructed using the serial sections and can be viewed in 3D using a Silicon Graphics Imaging system. The image can be rotated and translated as it is studied. However, 3D microstructures are best studied when viewed as solid models. Microstructures inherently have complex geometries and their solid models can only be reproduced by SFF techniques thus highlighting a significant benefit of the technology.

Future Work at the NRL

Continued research on the MAPLE DW process and capabilities and use of the LOMS for rapid fabrication of ceramic-based components is planned. The anticipated addition of a tape-casting machine for creating ceramic-polymer precursor materials for the LOMS will lead to a number of new materials related investigations. There is also potential interest in investigating the use of SFF related techniques for creating hierarchically structured materials with enhanced and multifunctional performance. Examples might include: tailoring the fracture resistance of ceramic-polymer composites and the dielectric properties of capacitor ceramics through hierarchical patterning.

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[4] In collaboration with the University of Michigan-Ann Arbor.

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Figures

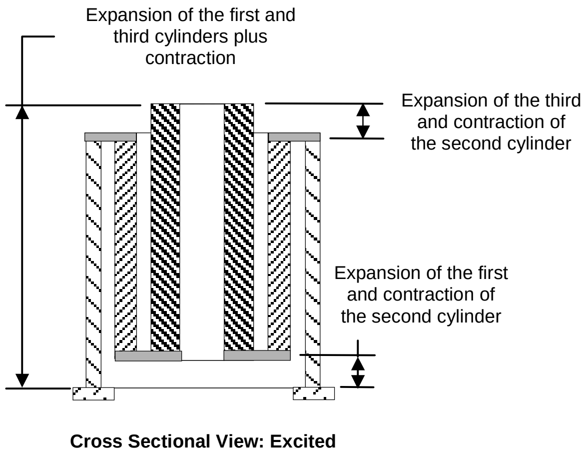


Figure 1: Schematic cross-sectional view of the telescoping actuator.

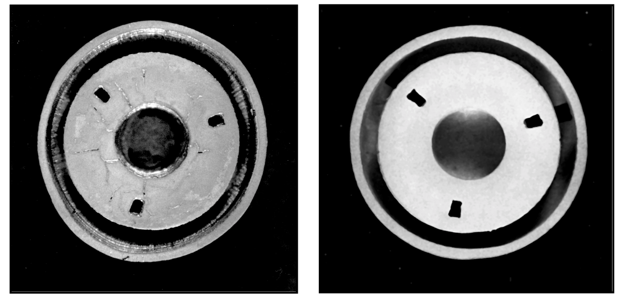


Figure 2A and 2B: Optical micrographs showing a bottom view of the consolidated telescoping actuators made with an unsatisfactory tape formulation (A) and a satisfactory tape formulation (B). Note that the outer cylinder diameter is 2.5 cm.

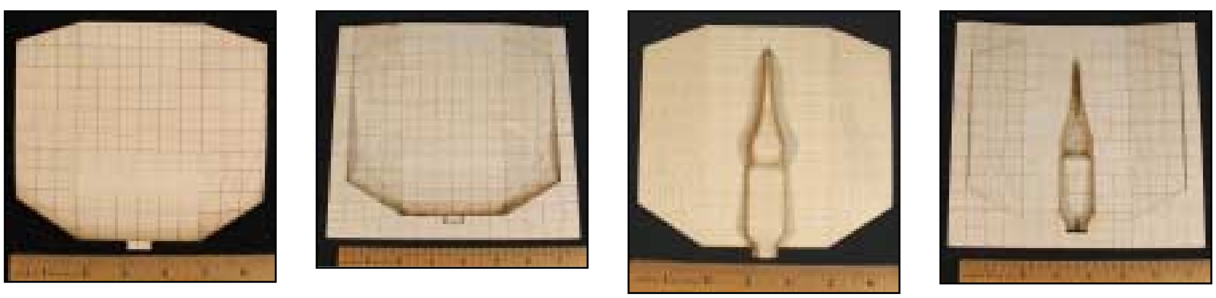


Figure 3. LOMS pattern and molds for a micro-air vehicle fuselage.

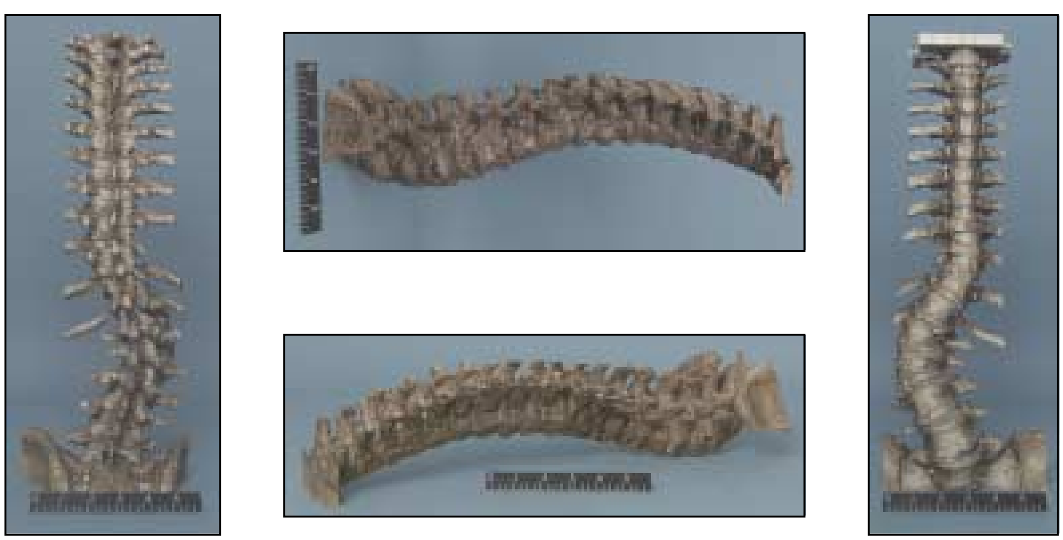


Figure 4. Human spine model created with the LOMS from the CT-scan data.

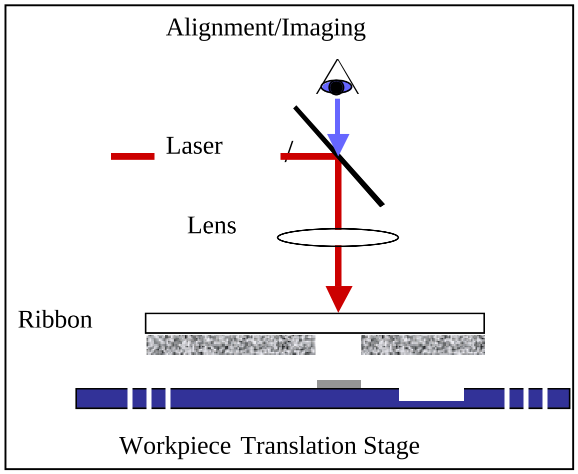
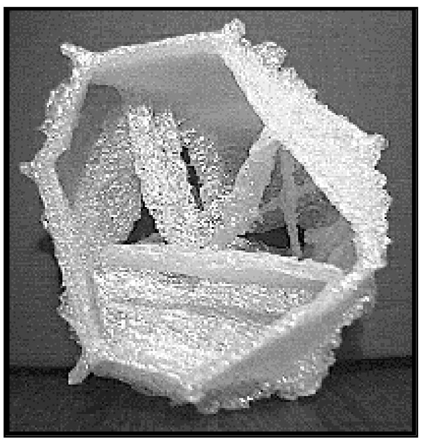


Figure 5: Schematic diagram of the MAPLE DW process.



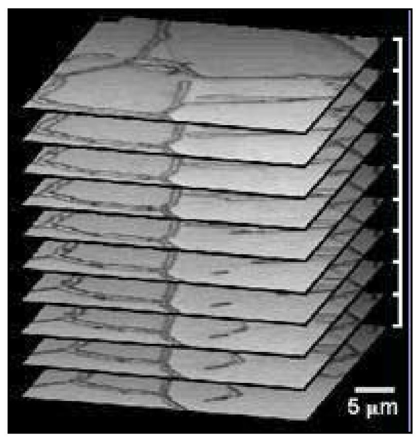


Figure 6A and 6B: (A) FDM model of cementite precipitates and austenite grain in a high carbon steel, and (B) a portion of the stack of 250 images of optical microstructures used as slices for the FDM process.