STEREOLITHOGRAPHY: A BASIS FOR INTEGRATED MESO MANUFACTURING

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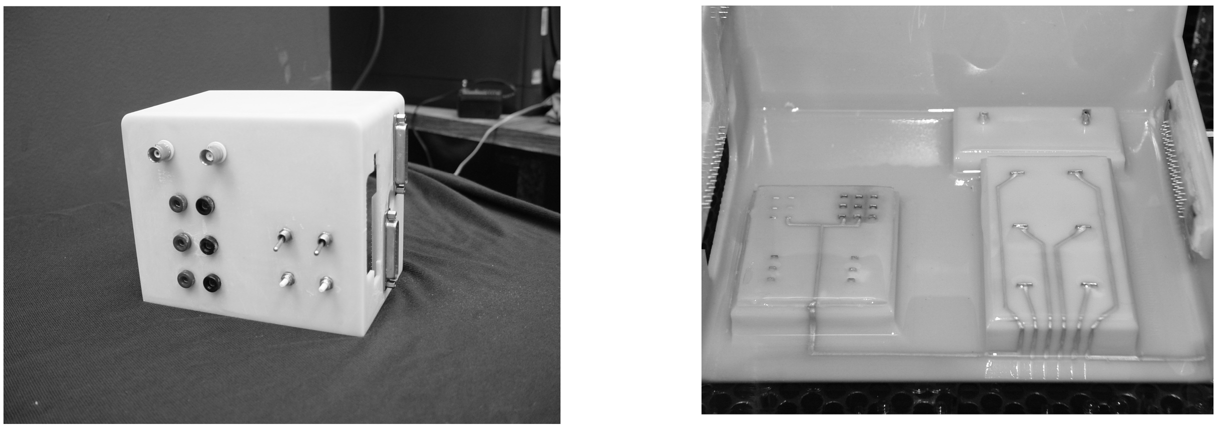
The maturation of stereolithography (SL) technology, particularly high-resolution micro stereolithography (MSL), has created opportunities for practical meso scale products (with millimeter and sub-millimeter features) that integrate MSL and other novel value-added processes. This study presents examples of MSL as a basis or foundation in meso products manufactured with several technologies utilized in a complimentary fashion. Specific examples include a meso relay with MSL and micro wire EDM components, and electrical distribution products that combine SL and Direct Write (DW) material dispensing. Results emphasize niche product solutions that may not be achievable with the state-of-the-art in any single process.

Introduction

The expansion of three-dimensional layer additive manufacturing and Rapid Prototyping (RP) has spawned a vision of a far-reaching technology whereby complex products from kitchen appliances to fighter jets are printed automatically in a single operation in the home or in automated industrial facilities (Clough, 2005) [1]. While the cost and cycle time advantages of this idealized approach are obvious, many technical and economic obstacles prevent its implementation in the foreseeable future. In the near term, some groups have realized advanced products based upon what is perhaps a more pragmatic integration of stereolithography (SL) and micro stereolithography (MSL) with other micro technologies (Varadan, Jiang and Varadan, 2001) [2]. Han *et al.* fabricated microfluidic systems using electroforming and hot embossing of plastics to make high aspect ratio channels quickly and inexpensively (Han, Graff, Wang, Mohanty, Han and Frazier, 2003) [3]. MSL was chosen to construct micro scale couplings directly on the surface of the fluidic ports without adhesives or fasteners [3]. Luharuka, Wu and Hesketh devised a fuel delivery system for miniature fuel cells with exclusive use of SL for pump housings and other critical components (Luharuka, Wu and Hasketh, 2004) [4]. Gong *et al.* demonstrated evanescent-mode filters based on both silicon bulk micro machining and MSL (Gong, Margomenos, Liu, Chappell and Katechi, 2004) [5]. In many of the examples cited from the literature, stereolithography materials and technology are utilized in the final version of the product. The trend toward extension of SL and MSL beyond traditional prototyping is apparent in micro and meso devices, where use of polymers is common. Moreover, researchers may utilize commercial MSL equipment to fabricate miniature three-dimensional components rapidly with minimal investment of time and money. This paper describes three new products created by engineers at Sandia National Laboratories and the University of Texas at El Paso (UTEP) whose manufacturing is based upon SL and MSL integrated with the following mirco fabrication technologies: direct write material dispensing (DW), micro wire electro discharge machining (μEDM), and LIGA (a process that encompasses lithography, electroplating and forming) [2]. Discussion focuses on the benefits and liabilities of integrated manufacturing in achieving functional objectives. Specific results relating product performance are out of the scope of this paper, and the reader is directed to corresponding references for complete details.

Stereolithography and Direct Write Material Dispensing

Rapid Prototyping of High Density Circuitry (RPHDC) is the result of recent Sandia/UTEP research that merges Direct Write material dispensing (DW) and MSL to rapidly fabricate cost effective smart products that incorporate low voltage (less than 240 volts) electrical distribution systems and electronic networks within application specific structural members (Palmer, Yang, Davis, Chavez, Gallegos, Wicker and Medina) [6]. Encapsulated circuitry is three-dimensional and features solderless interconnect [6]. Fig. 1 is an example of a junction box that distributes signals ranging from 6 to 28 volts from encapsulated pilot devices on the "dead front" panel to connectors on either side [6]. This example emphasizes cost savings incurred by eliminating manual wiring and solder joints in favor of solderless three-dimensional DW circuitry [6]. RPHDC is enabled by the next generation of three-dimensional DW machines. The nScrypt 3De™ system used in this program consists of a multi-axis robotic nozzle that deposits metallic, ceramic, polymer or biological liquid phase suspensions on a variety of curved, three-dimensional surfaces with precise control of flow and stopping point (Church, Fore, and Feeley, 2000) [7]. More importantly, many modern DW machines routinely create features on the order of 50 micrometers [7]. During a typical DW operation, surface contours are laser scanned and the data subsequently stored for write path planning. Conductivity of the silver-filled inks (Heraeus PC 5915, and Parelec Parmod® SDA-301) used in this program is suitable for electronic applications following a post-process anneal at approximately 120 ºC [6]. This exceeds the glass transition temperature of many commercial SL resins. Consequently, a glass-filled composite SL resin, ProtoTool™ 20L, was used (DSM Somos Corp., 2005) [8]. ProtoTool™ has a nominal glass transition temperature of 100 ºC following UV curing [8]. Although performance of the RPHDC junction box was acceptable relative to the conventionally fabricated counterpart, additional work is necessary to reduce the resistance of DW circuitry and the susceptibility of the composite structure to brittle failure.



(a) **(b)**

Fig. 1. Electrical junction box fabricated by integrating SL and DW: a) Front view, b) Encapsulated pilot devices and DW circuitry [#].

Fig. 2 depicts a prototype multi-functional electronic module with three-dimensional DW interconnect for a satellite application (Palmer, Summers, Davis, Gallegos, Chavez, Yang, Medina and Wicker, 2005) [9]. Encapsulated commercial electronics on the lower level

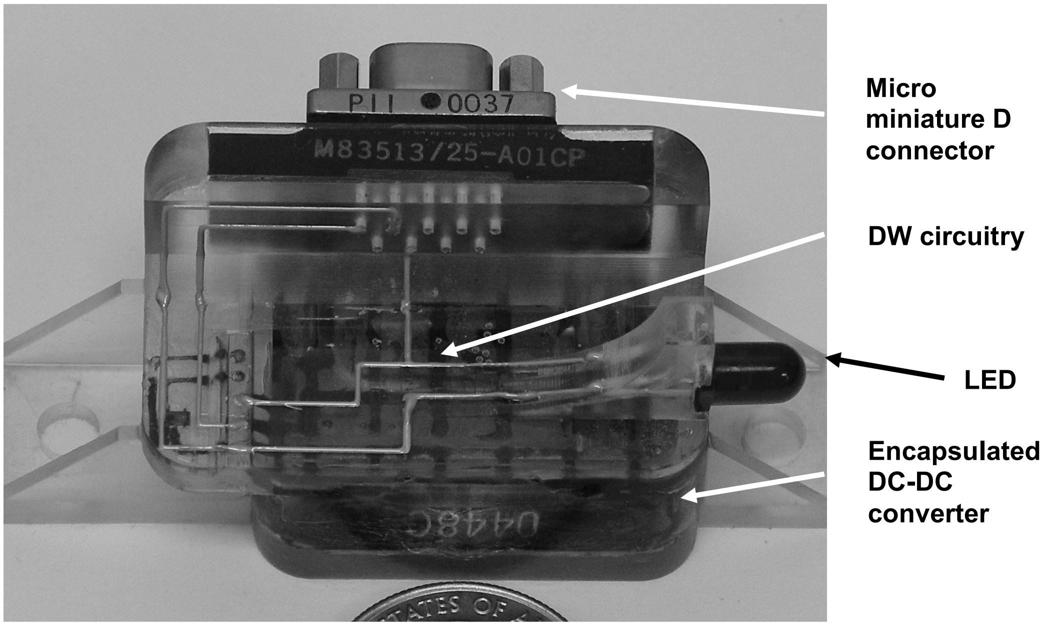


Fig. 2. RPHDC prototype multi-functional module.

convert a 28 VDC signal input to the micro miniature "D" connector on the upper level to 5 VDC. The 5 VDC output powers a simple circuit containing a light emitting diode (see Fig. 2). In three independent trials, the prototype was subject to the typical launch acceleration profile shown in Fig. 3. A random vibration spectrum with 2 kHz maximum frequency and maximum

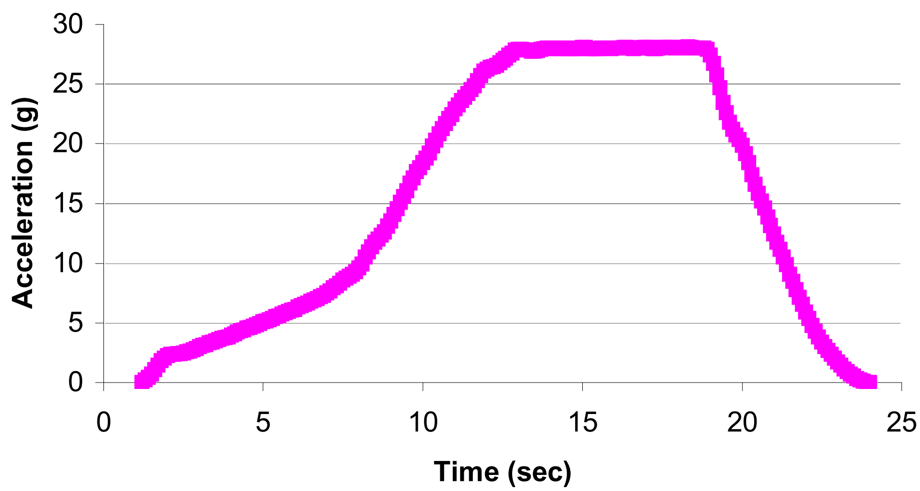


Fig. 3. Multifunctional-module launch acceleration profile.

amplitude 2 g^2/Hz (where *g* is one times the force of gravity) was imposed with the acceleration field. Operation of the circuit and output signal was successfully verified following each trial.

Undoubtedly, there are many approaches to fabricating smart structures with encapsulated electronics. Using SL and MSL in RPHDC is practical for two reasons. First, as a basis for fabricating the structural portion of the smart product, the commercial SL and MSL platforms were versatile in that they facilitate frequent design changes without hardware modification (within the limits of the process and materials) and process interrupts for device encapsulation.

These advantages are part of what the authors refer to as *bounded customization*. Furthermore, SL and MSL operations were largely autonomous which conserved human resources. Lastly, complimenting SL and MSL with high resolution DW in the near term opens the possibility of three-dimensional MEMS with inexpensive maskless interconnect. One disadvantage of the serial SL and DW systems in this case is the low throughput relative to lithographic techniques.

Micro Stereolithography and Micro Wire Electro Discharge Machining

Research was undertaken to create a novel meso scale radio frequency (mRF) relay with circuit component dimensions on the order of millimeters. The mRF relay depicted in Fig. 4 is designed to switch signals with higher power relative to RF MEMS while maintaining

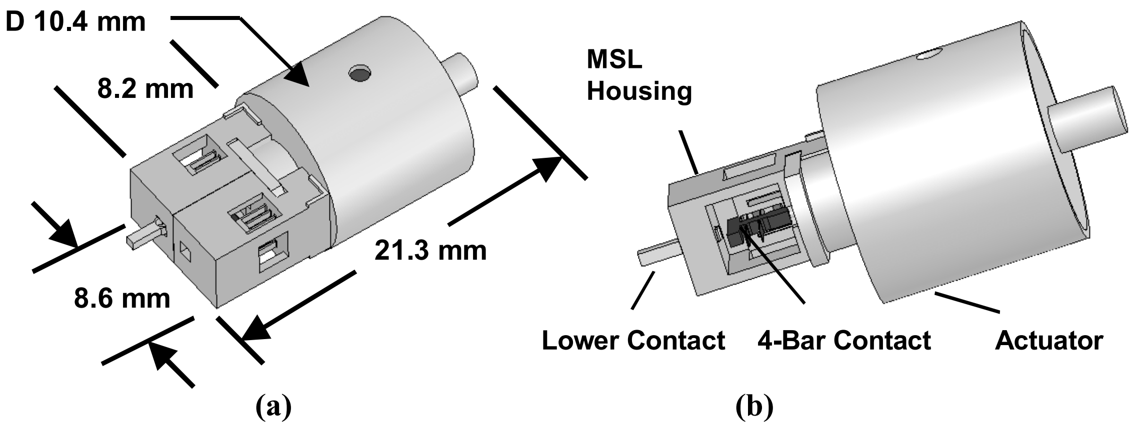


Fig. 4. mRF relay: (a) iso view (lower contact removed for clarity), (b) partial section view.

compactness. It incorporates a complex load-bearing switch mechanism driven by a miniature "pusher" solenoid actuator (see Fig. 4). Considering the meso scale dimensions of the individual components, the most desirable approach is to fabricate the complete relay in a rapid, cost-saving self assembly or non-assembly operation without adhesives or fasteners in a manner similar to MEMS microfabrication (De Laurentis, Kong and Mavroidis, 2002) [10]. This suggests a layer additive process. However (to our knowledge), commercial MSL equipment is not able to switch from one material to another during the build cycle. Consequently, MSL was selected to fabricate the switch housing with suspended contact box shown in Fig. 5. Note the orientation of

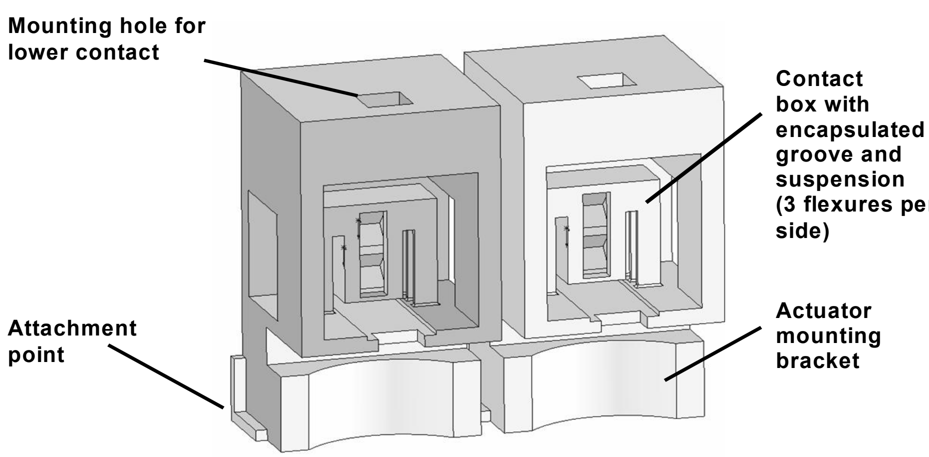


Fig. 5. mRF relay housing.

the contact box and suspension precluded the use of subtractive machining methods. Micro wire electro discharge machining was utilized to fabricate the aluminum 4-bar and lower contacts, and other components (see Fig. 4). The 4-bar contact was nominally 500 micrometers deep with 50-micrometer thick flexures. Micro wire EDM was regarded as faster and more cost-effective relative to alternative resources such as LIGA for fabricating metallic components with these dimensions. High dimensional accuracy was achieved in the housing by starting the MSL build on a Mylar sheet instead of using the traditional SL base support structure (Wicker, Ranade, Medina and Palmer) [14]. Teflon spacers were inserted during MSL and removed subsequent to fabrication in order to successfully block resin from filling critical sub- millimeter gaps between the fixed and movable structures of the housing. Grooves that captured the 4-bar contact flexures were defined by encapsulating (during the MSL process) an aluminum insert fabricated accurately by µEDM. Actuator components were manufactured with conventional resources. A novel micro telerobotic apparatus was applied to assemble the parts and fasten the two halves of the housing together with two-part epoxy. This research resulted in fully functional and robust mRF prototypes. The reader is referred to [11] for complete characterization results (Palmer, Jokiel, Nordquist, Kast, Atwood, Grant, Livingston, Medina and Wicker, 2005) [11]. Additional work is necessary to reduce contact resistance and the high variation observed in the displacement (stroke) of the contact mechanism. It is noteworthy that much of the variation occurred in the epoxy joint attaching the 4-bar contact to the solenoid output link. A multi-material non-assembly technology may reduce or eliminate this variation.

Micro Stereolithography and LIGA

Many of the widely employed techniques for fabricating micro electromechanical systems (MEMS) rely on photolithography to perform surface and bulk micro machining of various materials including semiconductors, polymers and metals [2]. Photolithography excels in quickly turning out large volumes of a specific micro device with high accuracy and precision [2]. Similarly, the LIGA process illustrated in Fig. 6a utilizes X-ray lithography to define high-aspect ratio (i.e. high depth versus width) MEMS components *or* micro molds of MEMS components in PMMA material [2]. The exposed PMMA (attached to a metallized substrate)

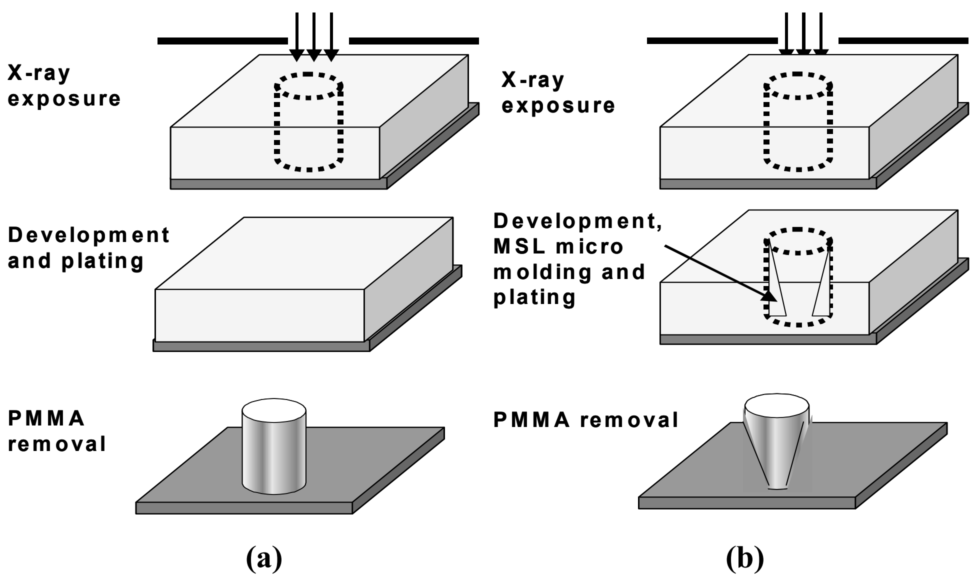


Fig. 6. a) LIGA process (simplified) showing metal MEMS component fabrication [2], b) Three-dimensional LIGA complimented by MSL

may then be electroplated to create either metal MEMS components or a permanent metal mold to reproduce the components in other materials [2]. In addition to high throughput, LIGA components exhibit straight sidewall profiles and low surface roughness [2]. Performance trade offs exist, however. Because lithography involves projection through an X-ray mask, LIGA is limited to extruded two-dimensional forms. In addition, modifying the mask may be difficult and costly. The process proposed in Fig. 6b involves in situ construction of three-dimensional MSL micro molds directly adjacent to pre-existing features formed by X-ray lithography. This work builds on the so-called IH process of micro molding and electroplating with MSL introduced by Ikuta and Hirowatari in the early 90's (Ikuta and Hirowatari, 1993) [12, 2]. MSL construction on silicon substrates was successfully undertaken by Tse, Hesketh, Rosen and Gole (Tse, Hesketh, Rosen and Gole, 2003) [13]. A copper meso part created by MSL micro molding on silicon is depicted in Fig. 7. This approach (to our knowledge) is the first attempt to

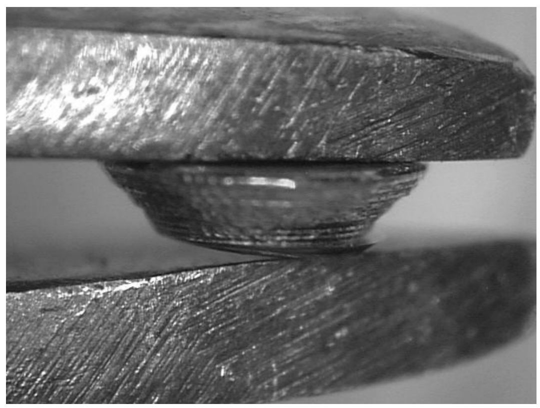


Fig. 7. Copper meso part created by MSL micro molding.

compliment LIGA with MSL micro molding and yields practical, cost-effective 3-D MEMS with the surface finish and throughput advantages of X-ray lithography. At the time of this writing, the technology is in the early stages of research and challenges remain in the areas of MSL resin recoating and process planning.

Conclusions And Future Work

This work presented examples where stereolithography was integrated with advanced micro technologies to realize novel products and processes. Here, design objectives were achieved when material and geometry limitations of individual technologies were overcome through process integration. Commercial high-resolution MSL has proven to be a versatile and cost-effective basis for integrated meso and micro manufacturing, particularly in products where polymer materials are pervasive. Future work focuses on establishing multi-material and multi-process platforms to advance the vision of meso and micro manufacturing characterized by automated non-assembly operations.

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