“SPATIAL FORMING”
A THREE DIMENSIONAL PRINTING PROCESS©

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Abstract

A three-dimensional printing process which we call “spatial forming” has been conceived and demonstrated as a method of manufacturing parts for cardiac catheter systems.[2] This work extends the range of particulate forming techniques into the micro-structure area; brings to bear on the manufacture of three-dimensional structures the high production capabilities of offset lithography; and allows us to visualize a complete process for the volume production of objects and assemblies of a geometric complexity hitherto found only in nature.

This process combines several technologies to generate solid metallic microstructures from fine powder. Cross section data from computer solid models are used for patterning of a chrome mask which images a lithographic printing plate like those used in the publishing industry. A custom built offset printing press prints “negative” material (the space around the parts) on a ceramic substrate in multiple registered layers of ceramic pigmented organic ink averaging 0.5 µm thick; each layer is cured with UV light. Periodically an ink heavily loaded with finely powdered metal is knifed onto the substrate, filling the non-image voids with “positive” part material. This material is also UV cured, the surface planarized, and the entire printing process repeated in proper register until the desired thickness (e.g. 500 µm) is reached. The semi-finished parts are then debinderized to remove organic ink components, and sintered in controlled atmosphere furnaces in processes similar to those used in the metal injection molding industry. The negative material crumbles away and the finished parts separate from the substrate.

Demonstration parts have been realized in 17-4 PH stainless steel in lots of several thousand, having overall dimensions of 0.1 to 20 mm and minimum feature sizes of 10 µm, with negligible registration errors. These structures are “2 1/2 D” or “extruded” shapes, i.e. the same image was printed on itself to a thickness of 300 µm, with the negative material in about 600 layers and the positive material in about 20 layers.

By varying the pattern of the printed images as the layering process progresses, one could change the cross sectional geometry of the structures to form more complex shapes or assemblies. A “progressive wedge” imaging and printing technique has been invented which will enable the continuous production, from a single printing plate, of structures having fully three-dimensional shapes of practically arbitrary geometry, including fully assembled interlinked mechanisms. Since this process generates structures from polymers and particulates, numerous other materials should be adaptable to it, including many metals, ceramics, piezo-ceramics, plastics, and combinations thereof.

Introduction

Biological shapes are commonly more complex than anything humans make. They are often interwoven in complex structures of multiple materials with a “fractal” diminishing of size that extends to the cellular level, less than 10 µm. Below this size the dramatic complexity continues into the molecular, nanometer range, but is perhaps better thought of as chemistry rather than physical shape, at least for the purposes of this project.

We assume that the ability to mass produce structures that are a little closer in form to those routinely found in nature will be advantageous to the development of more effective medical devices. Producing the sophisticated miniature devices that work inside human coronary arteries constantly presents new challenges to manufacturing technology. These catheter devices are typically about 1.3 meters long, with diameters ranging from 0.3 mm to 3 mm.

In the metal injection molding process, plastics are mixed with fine metal powder (ceramics are also commonly used), in ratios of about 50% by volume. This mixture is injection molded in regular plastic molding equipment. These “green” parts are debinderized, i.e. the plastic is dissolved and cooked away, which leaves a brittle, porous part consisting of lightly bound particles. This structure is sintered at near the melting point of the powder, which consolidates it into its final form. In this investigation the goal was to generate “green” structures, similar to those created by metal injection molding, via a printing process adaptable to three-dimensional layered object formation. This layering, or "spatial forming", has several interesting capabilities.

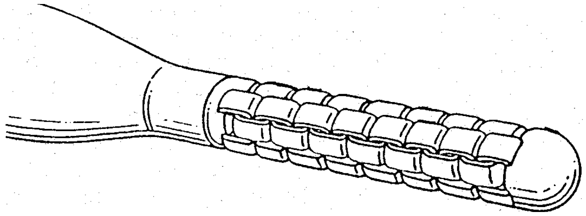


Figure 1. Target structure: pre-assembled chain type catheter tip.

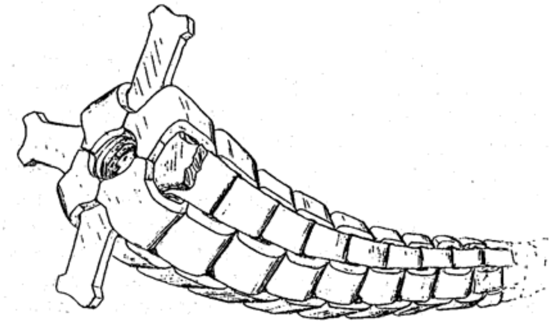


Figure 2. Form of prototypes

The "link tip" structure

The target structure of the investigation was a tip assembly, Figure 1,[3] for a guidewire, the component that leads the catheter system down the correct branches of the arterial tree. For coronary procedures guidewire tips are made in diameters of 250 µm, 350 µm, and 450 µm, with a typical length of 20 mm. Figure 2 shows how the prototype "link tip" structures were made: Over a hundred cross-shaped parts, etched in conventional fashion from an alloy of equal parts of molybdenum and rhenium, were individually folded, one around the next, to create the chain structure. This process was tedious and difficult, with custom automated assembly equipment being imaginable, but expensive and inflexible. Thus we were motivated to develop a process that would allow the mass production of various pre-assembled three-dimensional micro-structures directly from computer models. It was clear that if such a process could generate these link tips, it would have broad applications in the production of other complex small devices.

"Spatial Forming"

Our name "spatial forming" was chosen to denote the lack of restrictions on the possible geometries that can be created. Objects are generated by combining thin layers of material in shapes defined by cross section data from computer models. The negative space around the parts is filled concurrently with solid material, leaving a planar supporting surface for the next layer. Our definition of the term states that the material of which a "spatially formed" object is made can exist, or not exist, at any point within the space the object occupies, at the will of the designer. Thus assemblies, parts within parts, three-dimensional grids, totally enclosed voids, multiple material structures, and complex shapes are possible. The size and definition of the objects are limited by the capacity and resolution of the specific process. The minimum clearance between separate parts is roughly equal to the width of the minimum line that can be formed or the depth of the thinnest possible layer.

Related Forming Processes

Several processes have been developed that utilize the principles of layered object formation to generate parts in a similar physical fashion, utilizing a variety of forming technologies. As a group, these technologies have come to be called "rapid prototyping". One of the first of these to be commercialized, and currently the most widespread, is called "Stereolithography", developed by 3D Systems of Valencia, California. In this process, a beam of laser light selectively cures liquid photopolymer in thin layers adjacent to the liquid surface, according to cross section data from a sliced computer model. The solidified prototype is then removed from the liquid tank for further processing. There are a variety of other ingenious rapid prototyping processes.[4]

We are aware of several processes in the micromechanical realm that create structures that are thick relative to their planar size via layering techniques:

- The stereolithography process has been miniaturized, and the resulting parts used as electroforming mandrels.[5]
- A scanned laser erosion and deposition process has been developed.[6]
- The LIGA process, while not exactly layering, stands out for the exquisite detail and perfection of the structures created.[7]
- Thin film magnetic heads for disk drive applications are layered in a complex, customized, 200 step process pioneered by IBM. The working part of the head is less than 50 µm thick, and contains within that film magnetic pole pieces, conductive coils, insulating encapsulant, and electrical connection points. This process includes electroforming in addition to other technologies more commonly used in chip manufacture.

Spatial Forming Investigation and Results

Initially, the overall objectives of the investigation were as follows:

Develop and demonstrate a process suitable for economical mass production on the order of 30,000 structures per month, made of useful materials, including metals, and meeting the following criteria:

- Size envelope of finished structures: 2 x2 x 300 mm.
- Minimum feature size: 8 µm.
- Tolerance: plus or minus 3 µm.

Computer models were generated for the demonstration parts using a commercial solid modeling system. Customized programs were written to slice the models into numerous sections and transfer the cross-section data to an E-beam pattern generator to image a chrome mask, like those used in microcircuit production. The mask pattern was then imaged onto a lithographic printing plate, similar to those commonly used in a dry offset printing press. Such plates are coated with a silicone that is not wetted by the ink. The photo-patterning removed this coating in the image areas, exposing a wettable surface, which accepted ink from the rollers of the ink train. The blanket roller then transferred the inked image to the object to be printed. The developed and processed plate was installed in the high accuracy custom offset printing press. Thin 100 mm square ceramic substrates were firmly attached to individual precision carriages mounted in the press. Each substrate could accommodate formation sites for up to several thousand parts.

Negative and positive inks were prepared in the laboratory. One type of negative ink was based on a polyurethane acrylate resin[8] containing about 20 per cent boron nitride pigment. A typical positive ink consisted of an epoxy acrylate[9] containing about 50 per cent by volume of 17-4 PH stainless steel powder with an average grain size of 3 µm.

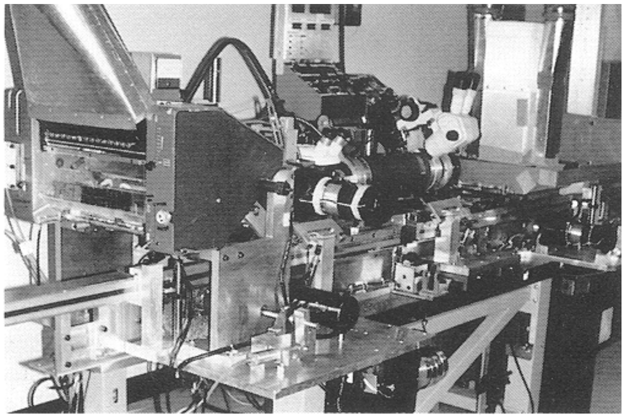


Figure 3. Printing machine

The development of this process required a custom printing machine, illustrated in Figure 3. The ink train, a series of rolls that transfer the ink to the plate, was adapted from a commercial product intended for adding an additional color to a common offset printing press. The plate and substrate were mounted on two separate identical slides running on the same precision linear way. A blanket roll was centrally located. In operation, the plate was shuttled between the inking station and the blanket roll, while the substrate on which the product was being formed was shuttled between the blanket roll and an ultra-violet light curing station at the opposite end of the machine from the ink train. The machine was designed to maintain very high precision in the repeat placement of the image. A knifing station for applying positive material was included. A planarization station has been conceptualized, but not implemented. The machine was capable of applying and curing multiple sublayers of negative material fully automatically and in register. Adding the positive material and planarizing the composite surface was done by hand in these experiments. The equipment was operated in a controlled environment that included yellow lighting so the UV-sensitive inks would not cure prematurely.

About 20-30 "microlayers" of negative material, each averaging about 0.5 µm thick, were printed in register onto the ceramic substrate. Each sublayer was individually cured with UV light. At this point the surface of the workpiece consisted of solid, raised plateaus in the shape of the space around the parts. Into this open shallow "form" of cured negative ink was knifed the positive ink containing the stainless steel powder. This material was also UV cured, and the composite surface comprising the negative forms and the positive fill was planarized, or lightly polished, by hand sanding. The entire process was then repeated until the entire desired thickness, e.g. 500 µm, was reached. During these tests the same image was usually printed in register upon itself, generating parts with vertical sides only.

Upon curing the final layer of positive ink, the entire substrate containing the solid block of semifinished product was placed in a furnace and subjected to temperatures of about 800 C. in a hydrogen atmosphere to debinderize the positive and negative inks by decomposing the organic resin components. At this stage the stainless steel powder was consolidated sufficiently to maintain its shape, and was surrounded by a porous, frangible boron nitride "scaffolding" that prevented the stainless steel surfaces from sticking or welding together.

The semi-consolidated product on its substrate was then sintered at a temperature of 1250 C. in an inert atmosphere containing a partial pressure of argon, to consolidate the stainless steel product to its final size, shape, and density. The remaining boron nitride and carbon residue was cleaned away in an ultrasonic bath.

Results and Discussion

Figure 4 shows examples of demonstration parts. Typical overall part sizes achieved to date range from 100 x 150 x 150 µm to 250 µm x 1 mm x 20 mm. Minimum feature sizes of 25 µm were predictably achievable, and features down to 10 µm were realized in a rough fashion. At these sizes, the entire system of plate, ink, blanket, and transfer mechanisms requires

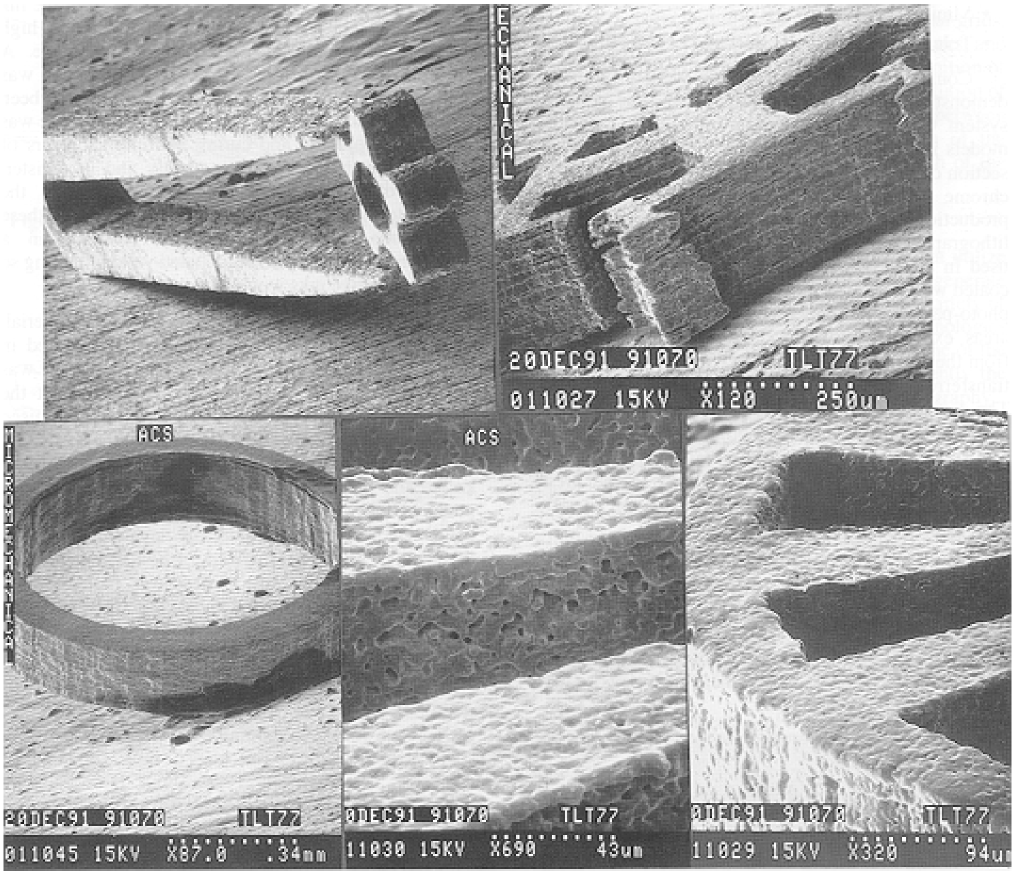


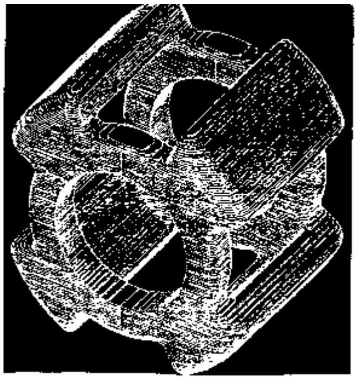
Figure 4. Demonstration structures realized to date in 17-4 PH stainless steel. Approximately 600 layers of negative material were printed, and 20 layers of positive material.

integrated optimization to be effective. As in the metal injection molding process, sintering caused shrinkage of about 20% in each linear dimension from the as-printed size. This is repeatable and predictable, so can be built into the product design. In metal injection molding, finished parts have 97% of their theoretical density, retaining some small non-connected voids, and we assume these parts to be similar, though no study to confirm this has been undertaken. Rigorous testing of the stainless steel parts has not been carried out, but they appear to be of sound structure and should be similar to parts made by metal injection molding, which are of high quality.

Before fully three-dimensional “spatially formed” structures could be produced, the printing process would need additional capabilities. These include the ability to index the substrate precisely between applications of layers of positive material, an automated system for these applications, and a precision planarizing station.

The epoxy resins used in the inks proved to be significantly more difficult to remove cleanly than the monomer and wax binders typically used in the metal injection molding process. Additional work is needed to optimize the debinderizing process.

This multi-disciplinary investigation required a team of workers and significant ongoing investment. All work was stopped in December of 1991 in order to redirect these resources.



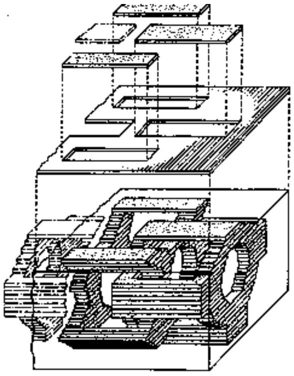


Figure 5 (left). Computer model of individual link showing about 120 layers, each approximately 3 μm thick. A complete structure would include about 150 such links formed fully interlocked with each other, with a coupler at one end and a spherical tip at the other.

Figure 6 (right). Diagram showing how inter-linking parts could be formed in a pre-assembled fashion.

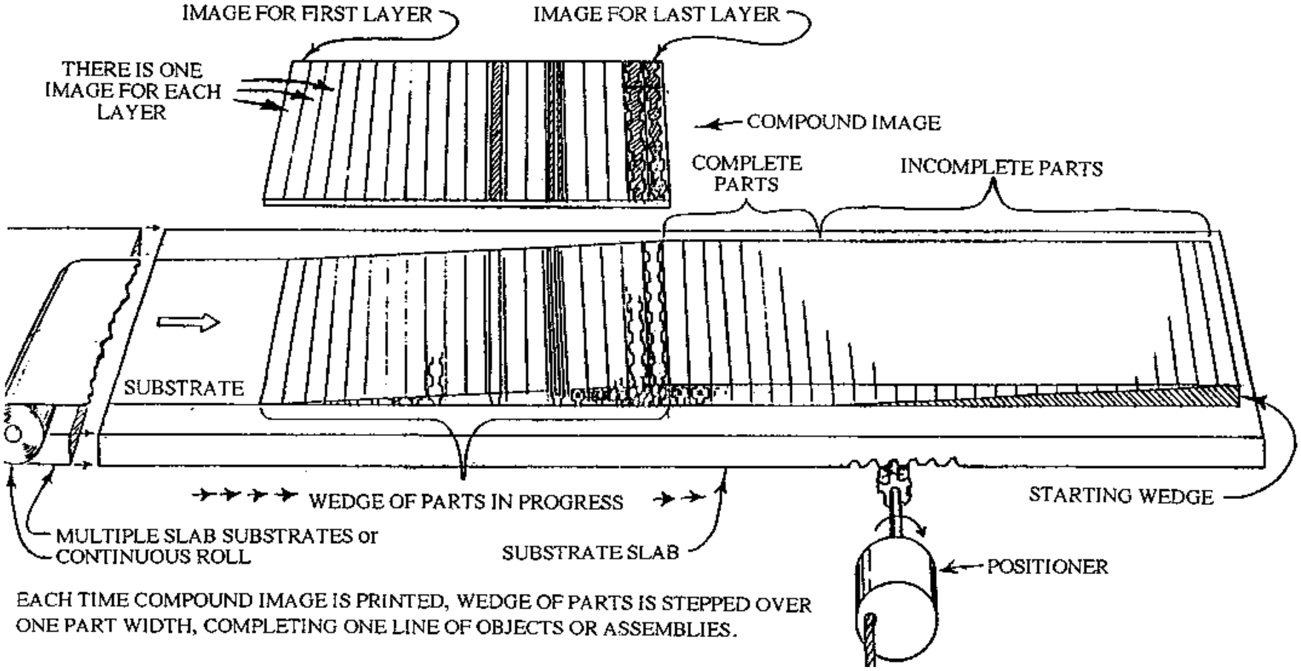


Figure 7. Principle of the progressive wedge manufacturing process. The image is transferred from an inked waterless offset plate to a blanket roller which applies it to the surface of the wedge.

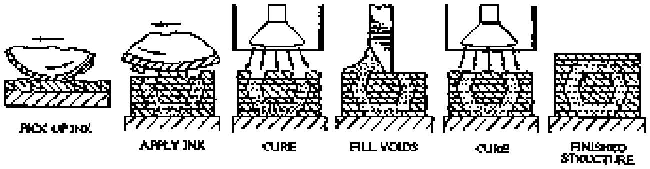


Figure 8. Schematic of forming process.

Progressive wedge

The “progressive wedge” forming method, which has not been demonstrated to date, is illustrated in Figures 7 and 8. It was developed as a way of continuously producing multiple structures, each comprising numerous layers. When combined with the rapidity of offset printing to form the individual layers (as opposed to the scanned “direct write” approach of most three-dimensional printing methods) this process should allow such structures to be economically mass produced.

This process is analogous to the use of the progressive die or transfer press in metal forming, or the transfer machine in general manufacturing. In these processes, each repetitive cycle of the machinery does a quantity of production that is enough to make one complete structure. However, the work is divided into multiple smaller steps, which typically must be performed serially. All steps are performed simultaneously, but on separate workpieces which are then indexed to the next station of the machine, where the succeeding step is performed in its cycle. Thus a train of works in progress makes its way through the machine and, once the machine is fully loaded with workpieces, a newly finished structure emerges with every cycle of the machine. At the same time another new part is started.

In the progressive wedge process, the wedge of parts in progress is analogous to the die strip within a progressive die. The image that is printed on the surface of this wedge contains material in the correct shape and sequence to form every layer of the structure being produced. If the individual layers are equally spaced and ordered from first to last, then indexing the substrate by the distance of their spacing causes the subsequent layer of material to be registered correctly.

The small size of our target structures in two of their three dimensions is advantageous; the overall width of the image to be printed is equal to the width of the structure plus any clearance between adjacent structures, multiplied by the number of layers to be formed. Our goal was to form the target link tip assembly in approximately 200 layers. Thus the 450 µm diameter tips with 50 µm between them and 20% shrinkage allowance would require an image 125 mm wide, well within the capability of the equipment. However, objects 3 mm wide of 200 layers would require a wedge 763 mm wide. While printing presses are commonly this large, the master mask could not be generated on the same kind of E-beam machine. If one chooses to use fewer but thicker layers, the size of the image can be reduced at the expense of resolution. The rough steps on curved or angled surfaces, inherent in layered objects, would be coarser.

When multiple sublayers of negative material are used, they are all printed during a cycle, and the wedge is indexed only after the positive layer has been applied and cured.

Summary

The feasibility of making particulate formed structures using offset printing techniques has been demonstrated.

Among the major accomplishments of this investigation are the following:

- World's smallest sintered powder metal parts (to our knowledge)
- First three-dimensionally printed metal parts
- The first use of offset lithography to create three dimensional parts
- Multiple "sublayer" technology for printing negative material
- Progressive Wedge sequential layer printing technique

Although this new spatial forming technology has initially been applied only to a limited range of three-dimensional stainless steel microstructures, it has potential application to a wide variety of objects and assemblies. For example, spatial forming provides the only known method for producing pre-assembled, inter-linking, arbitrarily complex micromechanisms.

We anticipate that eventually the technology will find its way into numerous and varied applications in many industries. A promising near term application that comes to mind is electrical interconnect devices. Thick film, co-fired, or multi-chip circuit boards could be formed with finer line widths and spacings, more accurately controlled dimensions and thicknesses, and much more complex three dimensional geometries than are presently obtainable. Various combinations of conductive materials with various non-conductive materials separating them could be applied to form a wide variety of circuits. Other example applications include disk drive heads, microconnectors, microswitches, sensor elements, electronics packaging, heat sinks, microwave components, three-dimensional grids for electronic tubes, and micro-fluidic components. And we hope and expect that spatial forming technology will eventually make significant contributions to the development of new generations of intravascular and endoscopic medical devices.

References

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[2] US Patent number 5,348,693; Taylor et al.

[3] US Patent number 5,003,989; Taylor et al.

[4] For more information (a selected list):

US Patent number 4,575,330; Hull. Stereolithography

US Patent number 4,752,352; Feygin. Laminated object manufacturing

US Patent number 4,863,538; Deckard. Selective laser sintering

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[6] T. M. Bloomstein, D. J. Ehrlich, “Laser-Chemical Three-Dimensional Writing of Multimaterial Structures for Microelectromechanics, Proceedings, IEEE Micro Electro Mechanical Systems Workshop, pp. 202-203, Feb. 1991.

[7] W. Ehrfeld et al., “Fabrication of Microstructures Using the LIGA Process,” Proceedings, IEEE Micro Robots and Teleoperators Workshop, Nov. 1987.

[8] Resin 783, Morton Thiokol Inc., Chicago, IL

[9] 600 Ebecryl , Radcure Specialties, Louisville, KY