# FLUID FLOW APPLICATIONS OF SOLID FREEFORM FABRICATION

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## Abstract

Conventional fluid control valves contain several components that must each be produced independently and assembled. Solid freeform fabrication (SFF) is a viable alternative to the traditional production method for fluid valve prototypes or small quantity production runs. In 2002, a successful valve was produced using SFF that was truly innovative and proved several important concepts. The scope of this research was to improve upon what had been accomplished in this field and to advance the use of SFF in fluid flow applications. Precision flow control and improved sealing are two goals that this research has achieved. In addition, a downsized valve has been build that will broaden the applications of this technology. Through proper design, a valve has been built that retains the flow and sealing characteristics of a traditional valve, but has the advantages associated with SFF. The accomplishments of this research will allow functional prototypes of valves to be built and tested using solid freeform fabrication and influence the use of specialty valves in medical and engineering applications.

**Keywords: Valve, Fluid Control, Solid Freeform Fabrication, Stereolithography**

## 1. Introduction

The scope of this research was to apply solid freeform fabrication (SFF), a method of building 3D objects layer by layer, to the production of fluid control valves. The main advantage to using SFF over conventional manufacturing processes is the elimination of the need to produce a number of parts using different methods. With SFF, an entire valve may be produced by the same method and no assembly will be necessary. Due to the nature of this process, good accuracy, intricate internal passages, and complex geometries are possible. It has also been proven that moving parts and sealing materials can be integrated into a single build to produce a functioning part. Any valve built using SFF must perform comparably to a valve of the same type built using traditional production techniques; otherwise the use of this technology will be limited. To evaluate the performance of this method of production, a functional prototype valve that can be used for comparison with conventional valves was needed. This prototype should operate in a manner that would allow it to become a direct replacement for a conventionally produced valve of the same size and design. Previous research has made steps toward a fully functional valve produced via SFF, and several breakthroughs have been achieved. The use of seals in conjunction with SFF and the production of moving assemblies in a single build are the most important features that make valve production by this method of manufacturing possible. Through careful design and understanding of the production method, the goal of a functional valve that performs as well as a conventional valve has been reached.

## 2. Valve Background and Theory

In any fluid flow system, there exists a need to control the flow rate of the system, to have the ability to stop the flow, or to prevent backflow from occurring. For many years valves have been the method of meeting any one or all of these needs. There are basic requirements that a valve should meet regardless of its purpose or design. When in the open position, the valve should exhibit flow characteristics as near to a section of the open line in the system as possible. A closed valve should seal flow off as completely as possible, and in doing so should act like a blind flange. Finally, a valve should be easily adjustable to allow for changes in the opening or position of the valve [1].

In addition, for pressurized flow situations, a valve must be able to seal the fluid flow from the atmosphere so that pressure can be maintained within the flow.

There are variations in the components present in specific types of valves, but the majority of valve types are comprised of three main components; the body, the stem/ stopper combination, and the bonnet. A diagram showing the three components and their relationship to each other is shown below in figure 1. The body is the portion of the valve that the fluid flows through and is the component to which the remainder of the fluid flow system is attached. The stem/ stopper is the controlling component of the system that is actuated to provide the flow control. The bonnet covers the control mechanism and often provides the mechanical attachment between the body and the stem/ stopper. In addition to these main parts, seals, gaskets, fasteners, and other components such as the handle are also present. Each of these parts is produced separately by various methods such as casting and machining, and then must be assembled. The advantage to solid freeform fabrication is that it can greatly simplify this process by allowing all components to be produced in one process simultaneously.

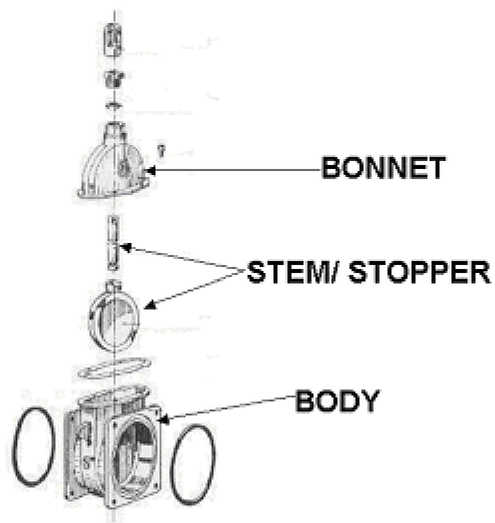


Figure 1 Valve components [2]

One additional consideration in valve design is the method by which the flow will be sealed when the valve is closed and the way in which the fluid flow will be isolated from the atmosphere. There are several methods of flow sealing used in valves. These methods can be classified into two areas; 1.surface contact and 2.the introduction of another material into the seal area. Fine surface finish and good fit will allow sealing in some applications, while others require an inserted seal material such as a rubber o-ring [3]. The applicability of each of these sealing options must be considered when using solid freeform fabrication as the valve construction method.

## 2.1. applying solid freeform fabrication to valves

Stereolithography is the SFF technique chosen for the construction of the valve. The stereolithography apparatus (SLA) is a machine that builds a part in layers by selectively hardening a liquid photopolymer with a computer controlled ultra-violet laser beam. The part is constructed on a platform, and after each layer is formed, the platform moves down one layer thickness and the next layer is hardened. The layer thickness is typically 0.005 inches. The advantages to this process over other types of SFF are that the material used is comparatively strong and this method offers good dimensional accuracy coupled with a relatively good surface finish. These characteristics of SLA provide a platform capable of the production of a fully functional fluid control valve. Figure 2 illustrates the SLA process and shows a photograph of the actual machine used in the building of the valve.

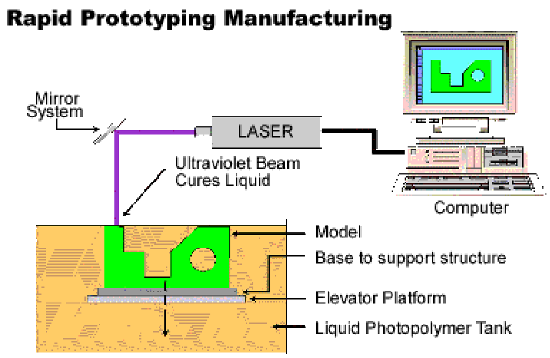


Figure 2 SLA process [4], SLA 5000 machine

The main advantage in using SFF as opposed to other methods of manufacturing is the prototype build time. Using SFF, only a computer file of the part is required to build a working prototype part. This allows the designer to instantly see a 3D model of a part and make changes as necessary. No expensive tools are required and overall design changes are as easy as editing the part's computer file. Several features of SFF allow functional valves to be built in a single process. Moving parts can be built in assembled form by allowing a tolerance between the parts. Previous testing has defined the minimum gap necessary to prevent moving assemblies from fusing [5]. Although this can cause some fit and sealing issues, proper design modifications will allow a valve produced using SFF to be as effective as a traditionally produced valve of the same type. Since SFF does not allow the tight tolerances and good surface finish required for a contact seal, some other method of sealing must be used. Previous experimenting in this field has shown that is it possible to use other materials in conjunction with the SFF process to provide the required sealing. Rubber o-rings can be inserted in the horizontal plane during the build that will allow the final product to be sealed and operational [5].

## 3. Precision Flow Control

For an effective valve to be produced using solid freeform fabrication, there must be some way of precisely controlling the flow opening. Since the stem or moving element in the valve typically must move linearly, a linear valve actuation mechanism at first seems like a viable option. The problem encountered is that it is difficult to accurately control this type of mechanism. To combat this problem, many current valve designs rely on a threaded connection between the valve stem and body. Not only does this connection provide a means by which to precisely control the flow characteristics of the valve, but also has the added feature of providing a mechanical advantage in applying force to the valve seat when the flow is shut off. For these reasons, a threaded connection was chosen as the actuation mechanism for the valve to be built using solid freeform fabrication. It is important to note that this research was breaking new ground in the region of threading and SFF. The following components are the first of their kind produced in the Rapid Prototyping Center at the Milwaukee School of Engineering.

Because of laser scattering (especially in the vertical direction) it is more desirable to use rectangular shaped threads with SFF. Since this approach is uncharted territory, it was appropriate to design and build test thread samples to evaluate the feasibility of creating a threaded connection with SFF. After designing the connections, the files were then sent to the stereolithography apparatus (SLA) to be built. Figure 3 displays three thread designs prototyped. The two parts that make up the threaded connection in figure 3A were constructed separately and proved that smoothly operating threads using SFF were possible. The threaded connection (figure 3B) was constructed in a single build as assembled. This was a breakthrough in that it proved functional threads could be made, integrated into a single build using SFF. The pitch of the threads in this sample was very steep so that supports could be avoided during the build. The SLA machine has to support structures that protrude out from the build in the horizontal plane. This is caused by the first few layers of an overhang not having enough strength to remain in place. These supports are removed after the build during the cleaning process. The problem in this high pitch is that the thread will unscrew itself under a minimal load. For this reason, a third thread sample (figure 3C) was designed and built on the SLA with a shallower thread angle. To eliminate the need for supports in this design, the outside thread diameter was narrowed in relation to the shaft. The smaller overhang allows the part to be built without supports.

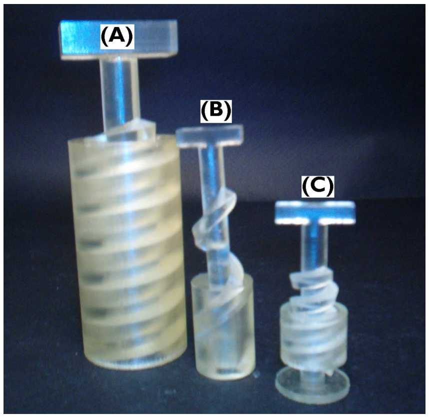


Figure 3 Thread design progression

Through the design and evaluation of the three test thread samples, a greater understanding of the ability to produce threaded connections using SFF was achieved. The final thread sample built (figure 3C) served as the basis for the thread design used in the valves.

## 4. Valve Design and Construction

Previously, a gate valve was constructed using solid freeform fabrication. This was a breakthrough in that it proved the concept was possible. There were some problems encountered in several areas of this valve design. Precision flow control was not available and there were sealing issues that were unresolved. With a threaded stem to body connection, the issues with precision flow control have been solved. The fundamental flaw in the gate valve design that does not allow flow sealing is that it relies on valve material to valve material contact. With SFF, and more specifically the SLA process, the attainable tolerance and surface finish is simply not good enough to facilitate sealing. To solve this problem a different valve design was needed.

While a gate valve has a relatively large sealing surface, a globe type valve has only a single, smaller sealing surface. One main advantage of the gate valve design is its low flow resistance in the open position. Globe valves have a very large flow resistance that contributes to losses in a flow system. To allow better flow characteristics, but still maintain the advantages in sealing of a globe type valve, an angle valve design was decided on. This design has a relatively low flow resistance (although larger than the gate valve) and uses the globe type seal to shut off flow. A comparison of both valve types is shown below in figure 4.

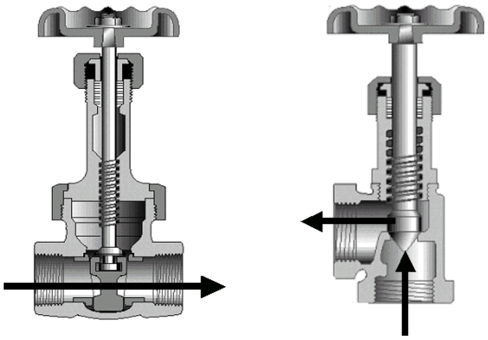

Figure 4 Comparison of gate valve (left) and angle valve (right) [6]

### 4.1. valve design objectives

At the outset of this research, several objectives were identified. The initial goals included implementing precision flow control and functional sealing into a single build (solid freeform fabricated) valve. Further objectives included testing the valve for flow characteristics, designing a much smaller valve to broaden the project's applications, and coming up with a way to sufficiently protect the material used. With the initial success of the threaded connection prototypes, the next step was to begin the design and production of working valves.

## 4.2. initial valve design

The goals of the first valve design were that it was fully functional and that it could be tested for flow characteristics. With this in mind, a 1.75-inch inside diameter angle valve was designed. This valve used three seals along with the threaded stem to body connection. Previous testing with the thread samples had shown that a gap of 0.020 inches was sufficient to prevent the stem and body from becoming fused together during the build process. This gap may have been larger than needed in the horizontal plane, but would not affect the functionality of the valve, and was necessary in the vertical plane. The body and stem were designed as separate CAD files and then mated together in a way that maintained a clearance at all surfaces of the assembly.

### *4.2.1 initial design build*

The CAD file for the initial angle valve design was submitted to the Rapid Prototyping Center (RPC) for manufacturing on the SLA machine. After a 25-hour build time, three identical valves were produced. To insert the seals into the valves the build was stopped, seals were inserted, and the build was restarted. There were some problems getting the seals to fully seat into their grooves at the time of the first build stop. This was due to the interference fit designed into the valve. Upon further reflection, this was an error as the fit was too tight and did not allow for proper seal insertion. Due to this problem, the photopolymer resin had to be manually placed over the stem area as the seal projected above the liquid level. It was decided at this time that the second seal would not be placed into the valves to prevent any additional problems. After the seal had been covered by resin, the automatic build was restarted and the valves were allowed to finish.

After removing and cleaning the valve, several problems were detected that affected its functionality (see figure 5). The main problem was that the threads would not turn (arrow 1), and therefore the valve could not be operated. The gap had not been large enough to prevent the threads from fusing together during the build. Although the gap allowed was similar to that of the test thread samples, the larger size of the valve may have compounded small errors in the machine, causing the problem. An additional concern was the strength of the stem in the area where the seal was inserted (arrow 2). When the resin had to be manually placed over this region, the layers may have been too thick. This caused several layers to be only slightly cured and resulted in a weak area in the stem that was easily broken. The final concern was that of trapped resin between the thread and the stem seal (arrow 3). This problem was quickly solved by drilling two small holes that allowed the excess resin to drain. These holes could later be sealed.

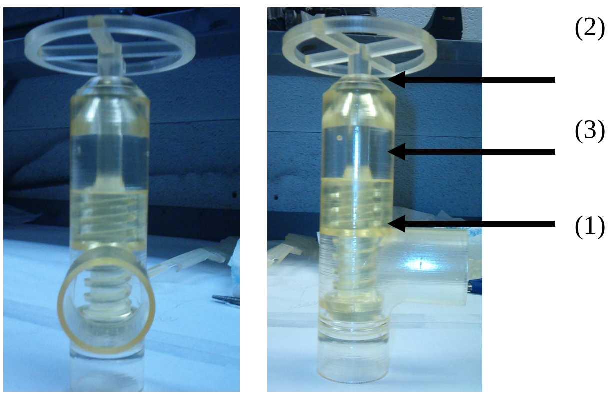


Figure 5 Initial valve constructed

## 4.3. downsized valve design

The second valve designed was essentially a scaled down version of the initial design. This valve's inside diameter was approximately 0.4 inches. The second design was finished and prepared for building when the results of the first design build were discovered. Because the small valve was designed with many of the same factors, some design changes were made before the valve was submitted for building. These included decreasing the interference fit of the seals and enlarging the clearance around the threads.

### *4.3.1. downsized valve build*

With the design changes made, two copies of the downsized valve were built. After cleaning and finishing, including draining the excess resin, the valves were found to function flawlessly. The final seal for flow sealing was inserted into each valve after the build, and informal preliminary testing with water has shown the stem and stopper to be fully sealed with no leakage occurring and flow is able to be completely shut off.

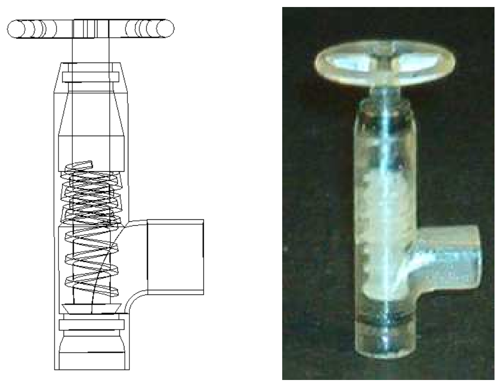

Figure 6 Wire-frame rendering (left) and finished prototype (right) of the downsized valve

## 4.4. redesign of initial valve

With the success of the downsized valve, the initial, larger valve has been redesigned and will soon be built. This larger valve will be used for testing in both sealing and flow characteristics. A similar valve produced conventionally will be acquired for comparison purposes.

## 4.5. valve performance testing

After the large valve is constructed, testing will be done to determine the performance of the valve in relation to others of the same type. As fluid flows through a system, each component of the system introduces energy losses into the flow. Equation (1) characterizes the energy loss caused by a component in a fluid flow system [7]. In equation (1) $h_L$ is the energy loss, K is the loss coefficient, v is the velocity of the flow, and g is the gravitational acceleration.

$$h_L = K\frac{v^2}{2g} \tag{1}$$

The term $h_L$ is often referred to as the head loss of a component and is described in units of length such as meters or feet. The loss coefficient (K) is experimentally determined for most types of fluid valves. Experimental determination of the SFF valve will allow comparison with literature values or with experimental data of a conventionally produced valve of the same type. In order to determine this loss coefficient, an experiment can be set up that allows the general energy equation for fluid flow to be applied. The general energy equation appears below as equation (2).

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^{\ 2}}{2g} + h_A - h_L = \frac{p_2}{\gamma} + z_2 + \frac{v_2^{\ 2}}{2g} \qquad (2)$$

In equation (2), p is the pressure, γ is the specific weight of the fluid, z is the elevation of the flow, $h_A$ is the energy added to the flow and $h_L$ is the energy lost from the flow. Using this equation in conjunction with an experiment, the head loss can be determined, and then using equation (1) the loss coefficient for the component can be calculated [7].

## 5. Material Considerations with Solid Freeform Fabrication

One limitation present when using solid freeform fabrication is the ability of the available materials to withstand environmental factors. Moisture and ultra-violet (UV) light in the atmosphere can cause deterioration of the polymer and of its mechanical properties. The stereolithography process initially uses a UV laser to cure the polymer. Exposure to low levels of UV over time can cause the material to become over cured and brittle. This is of far less concern than the problems associated with moisture absorption. An unsealed SLA part will, within months of production, begin to show signs of moisture related deterioration. The part may expand and lose some of its strength and rigidity. As a way to combat both of these types of environmental material concerns, effective ways of sealing or coating the material were explored.

Recall that when a set of moving components is designed for production using solid freeform fabrication, an appreciable gap must be provided so that the finished parts are not fused. One additional benefit to a coated set of parts is that some of this gap will be taken up by the added thickness. This may provide better fit and sealing characteristics in a valve processed in this manner.

### 5.1 acrylic lacquer clear coat

The method used for material protection was an automotive acrylic lacquer clear coat. For this process, an adhesion promoter was first applied to the SLA part. This serves the purpose of cleaning the surface and making it slightly tacky; both improve the adhesion of the coating. The clear coat is thinned using lacquer reducer, and can then be applied. The method of application used here was of dipping the part. A better surface finish and more uniform coating could be obtained by spraying the coating. The clear coat has shown that it adheres well to the surface and after some time has elapsed, its protective ability can be quantified as well.

## 6. Conclusions and Recommendations

Through this research done on the use of solid freeform fabrication in the construction of fluid control valves, several important concepts have been proven. Moving parts, integral o-rings, and threaded connections were all shown to be possible and allow the construction of operational valves using SFF that will function comparably to traditional valves. The original objectives of this research were met and in many cases exceeded. Due to time limitations, performing flow and pressure testing on the valves has not yet been completed, but will soon show the merits of this research in comparison to traditionally produced valves. The advantages of SFF over traditional production methods could make valves produced by this method the choice for prototypes and short run specialty fluid applications. Future research in this field should concentrate on the refinement of the production process and on testing the valves for flow characteristics and pressure capabilities. Additionally, specific applications of this process should be defined and research can move in those directions.

## 7. Acknowledgements

The author would like to express his appreciation to several organizations, institutions, and individuals for making this research possible. Thank you to the National Science Foundation for funding the Research Experience for Undergraduates program and making this work a reality. Also, thank you to the Milwaukee School of Engineering, the Rapid Prototyping Center, and their employees for providing the facilities, equipment, and advice necessary. The author would also like to express his gratitude to Dr. Subha Kumpaty who was instrumental through all stages of this program with his guidance and expertise. Finally, thank you to Ann Bloor, Betty Albrecht, and the students in the program who were all very helpful with support and ideas.

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This material is based upon work supported by the National Science Foundation under Grant No. EEC-0139142. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.