Manufacturing by Solid Freeform Fabrication

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ABSTRACT

The SFF/RP industry has grown steadily with the most significant gains made in the number of models produced per year – three million in the year 2000. Future growth is most likely to be in manufacturing applications of SFF where even a single application can double the number of models/parts produced annually. There are a number of factors or drivers which can motivate a manufacturing application of SFF either individually or in combination. These drivers include: *i*. avoid conventional tooling, *ii*. minimizing hand work, *iii*. mass customization, *iv*. geometric flexibility, *v*. local control of composition. The most intriguing of these drivers is that of mass customization – the manufacture of highly individual products, but on a mass scale. SFF offers the possibility of mass customization of components with complex 3D geometry. A prominent current example is that of Align Technology of Santa Clara, CA which produces unique plastic aligners for orthodontic applications.

There already are manufacturing applications where the advantages offered by SFF are so compelling as to overcome any barriers. However, widespread impact of SFF on manufacturing will depend on overcoming several barriers. The essence of these barriers lies in the distinction between prototyping and manufacturing. Manufacturing applications are far more demanding in terms of build rate and associated cost, demands on dimensional control and tolerances, properties of materials, and ease of use and serviceability of equipment.

INTRODUCTION

Intent of Paper

This paper will examine the impact of SFF on manufacturing and the importance of manufacturing applications to the future growth of the SFF industry. It must be said at the outset that this paper is not an exhaustive review of manufacturing applications. Rather, the goal is to gain a sense of:

- *The drivers for manufacturing* – factors which make an application well suited to manufacturing by SFF.

- *Barriers to manufacturing by SFF* – generic issues that arise when attempting to manufacture by SFF.

A great deal of the information and the thoughts for this paper were derived through discussions with leaders in the industries. These discussions are acknowledged as reference citations.

Industry Status

The recent growth of the SFF industry may be represented in a variety of ways including by dollar volume, number of participating machine suppliers, and number of machines sold. Perhaps the metric which is most relevant to the role of SFF in manufacturing is the number of models made across the entire SFF industry as a function of time. Fig. 1 presents data on the number of models made over the past three years [1]. The SFF industry has experienced steady and significant growth in the number of models made with three million models per year having been made during the most recent fully reported year - 2000. In fact, while the SFF industry has grown in both total revenue and in machine sales, the growth in the number of models made per year has been the fastest aspect of the growth of the industry.

Fig. 2 shows the breakdown of SFF applications by industry [1]. What is significant about this pie chart is that two industries (motor vehicles and consumer products) together account for more than half of SFF applications. Note, however, that medical, government/military, and aerospace together account for only 23% of total applications at the present time.

Forecast

Fig. 3 shows, in a rough way, a forecast for the future growth for the SFF industry [1]. As can be seen, Wohlers has divided the field into three categories. "Prototyping" refers to the classic applications which provided the foundation for the rapid prototyping industry. A second category is referred to as "3D printing". In this figure, Wohlers uses the term 3D printing to refer to the lower cost machines which have become available in the past few years and which are often referred to as "office modeling machines". These machines include the 3D Systems Thermojet, the Prodigy from Stratasys and the machines from Z Corp. (The Z Corp. machines are based on MIT's Three Dimensional Printing process, which is itself referred to as 3D Printing. Thus, the terminology used in fig. 3 from Wohlers might be subject to confusion. Wohlers is referring to the entire field of office modelers when he uses the term 3D printing.) The third category in fig. 3 is called "Rapid Manufacturing" – the subject of this paper.

The first message from fig. 3 is that the total need for prototypes is forecast to remain roughly flat. However, there is forecast a significant realignment within the industry as the low cost "officer modelers" or "3D printers" assume a larger market share of these prototyping applications. This is already taking place as the speed, accuracy, and materials properties of the office modelers, continue to improve.

The second key point from fig. 3 is that the anticipated future growth of the SFF industry will be provided by manufacturing applications. That this is likely the case can be understood by referring back to fig. 1 and noting that in the most recent year three million models were made by SFF. While three million prototypes has a very significant impact on the design process and the quality of the final designs, it is a small number in the context of manufacturing. As we will see, a single manufacturing application can double the number of models made per year. Thus, the forecast that the growth of the industry vies with manufacturing seems quite sensible. If this is to be the case, we will also expect that in the future, the distribution of applications by industry will be quite different than that shown in fig. 2. As noted, the medical, aerospace and military applications total less than a quarter of the applications. However, as we will see, these are the industries that have the greatest near term potential for manufacturing by SFF. Accordingly, we would expect this pie chart to change over time to reflect the increased importance of these three application areas.

It should be noted that the author is not quite as pessimistic as Wohlers as to the flat forecast for prototyping applications. Indeed, a substantial reduction in machine cost might result in some significant growth in prototyping applications. Nonetheless, the key points of the importance of the office modelers to prototyping and especially of the importance of manufacturing applications to the growth of SFF are undoubtedly on target.

DRIVERS FOR MANUFACTURING BY SFF

In the growing number of cases where SFF is used to manufacture components, the competitive advantage of SFF can be traced to one or more of the following "drivers":

- Avoid conventional tooling
- Minimizing hand work
- Mass customization
- Geometric flexibility
- Local control of composition

A given application may gain its competitive advantage from a single one of these drivers. However, often, two or more of these drivers are acting simultaneously. Each of these drivers will be examined and some applications presented.

Avoiding Conventional Tooling

The manufacture of hard tooling is notoriously time consuming and expensive. For this reason, the use of SFF to avoid the fabrication of conventional tooling has been the most common driver for manufacturing by SFF. Indeed, such tooling avoidance has also played a large role in the prototyping implications of the RP field. As tooling avoidance is perhaps the best documented of the drivers for manufacture by SFF, this paper will provide only a representative discussion.

SFF can be used to avoid conventional tooling either by using tooling made by SFF or by making parts directly with no tooling at all. One example of each of these approaches will be presented.

Castings – An Example of Tooling Made by SFF

According to Wohlers, castings (prototypes and manufacturing) account for 6.3% of today's SFF market. Indeed, castings were one of the first major areas of application of SFF.

The impact of SFF on castings has been almost exclusively in the fabrication of castings of complex geometry including complex sand castings and especially investment castings. In this regard there is a strong interplay between two drivers – avoiding conventional tooling and geometric complexity (see later section on geometric complexity.) As an example, let us consider the use of SFF for castings at Bell Helicopter [2]. Bell Helicopter makes extensive use of stereolithography "Quickcast" patterns primarily for aluminum investment castings. When Bell is designing a new aircraft, they need a batch of four to six pieces which are often made from Quickcast patterns. They destructively test one and the others go into test vehicles. As the aircraft moves into preproduction, they might make another two pieces, again, using Quickcast patterns. The next stage is a ramp up to production. If one were to look purely at the economics (without regard to timing issues) the choice would be to make conventional tooling and make wax patterns. This would be the economic choice because at this point the number of patterns needed would justify the cost of the tooling, especially given the fact that foundries charge a premium for making a casting from a Quickcast pattern (this premium presumably derives from two factors: 1. the fact that extra steps are required to burn out the Quickcast pattern and 2. the fact that Quickcast patterns are normally associated with expedited delivery times.) *However*, Bell often enters the ramp up phase with stereolithography patterns due to timing considerations. In some cases, there is insufficient lead time for conventional tooling while in other cases an oversight meant that tooling was not ordered even when there was time to do so. For these reasons, it is now common for aluminum castings derived from Quickcast patterns to be used in production vehicles. In some cases, such castings can account for a "large percentage" of the total castings in a vehicle.

Plastic Parts – Avoiding Tooling

SFF is used to avoid conventional tooling by the direct fabrication of parts which would be normally made through tooling. An intriguing example is the fabrication of plastic parts which would normally be made by injection molding. Fig. 4 shows cost projections for a small plastic handle which is pictured as both a stereolithography part and a part made by selective laser sintering on an EOS machine. As this information comes from Phil Dickens and Neil Hopkinson at De Montfort University [3] the price per piece is presented in Euros. The price for the injection molded parts is based on quotations. The price for the sintered part is based on a capital cost of 340,000 Euros with eight year straight line depreciation, a yearly maintenance cost of 30,000 Euros, a build rate of 17.7 parts per hour based on building 1,056 parts in a 60 hour build, and 7,884 hours of production per year. This projection shows that the cost for the sintered part has a break even with the injection molded part at about 30,000 pieces. Thus, if one expects to manufacture fewer than 30,000 pieces, one would be ahead economically with the sintered part while the expectation of more than 30,000 pieces would drive one toward injection molding. The interesting point is that this break even quantity of 30,000 is encouragingly high as there might be quite a lot of plastic components which one would desire to manufacture in quantities smaller than this. It should be noted that this is a small part and the break even quantity would decrease quickly with increase in part size. Further, this economic analysis assumes that no finishing is required of the sintered part in order to perform acceptably in the application.

There are indeed now a number of efforts underway to make direct use of sintered plastic parts. An example is the intended use of Duraform polyamide parts by Boeing for nonload bearing applications in military aircraft. According to DTM's website, such applications are now under study for certification.

Driver: Mass Customization

Perhaps the most intriguing single driver for manufacture by SFF is that of mass customization. In its cover article of July 14, 2001, the Economist Magazine (see fig. 5) defines mass customization as "the manufacture of highly individual products, but on a mass scale". The Economist draws an analogy between "built to order" approaches to manufacturing systems and mass customization. Indeed, one can consider mass customization to be a logical extension of "pool" or "just in time" or "lean" manufacturing systems. The limiting case of mass customization is that a single unit of a unique product is made to order.

The application of SFF to mass customization is intriguing because mass customization is the founding cornerstone of a number of companies which are leaders in their respective markets. For example:

- Dell Computer. Dell Computer functions by defining platforms and configuring these platforms (especially the software aspect) at assembly. As is well known, Dell Computer is now the market leader in PCs.
- Swatch. Swatch provides a huge variety of watches starting from platforms which are configured at assembly and with the addition of small amounts of custom fabrication. For example, fig. 6 shows Swatch watches built to order for the Museum of Modern Art (note the MOMA insignia on the watch face hands).
- Lenscrafters. Lenscrafters is a leader in eyewear and this leadership position is based on a stock of platforms (frames) and custom fabrication of the lenses using specialized equipment located in a distributed fashion at the stores.

In one perspective, SFF offers the key to mass customization opportunities which are based primarily on 3D geometry. There are now several intriguing examples which illustrate the potential of SFF for mass customization.

Align Technology of Santa Clara, California [4, 5]. Align Technology represents a new approach to orthodontics where a sequence of plastic aligners is used to move the teeth (rather than the method of attachment of brackets and wires). Fig. 7 shows one of these plastic aligners. Align Technology is also an excellent example of mass customization. This mass customization is accomplished by five sequential steps: *i*. a physical model is made, *ii*. a virtual model is created from the physical model, *iii*. the virtual model is edited, *iv*. a tool is made from the virtual model using SFF, *v*. aligners are formed using the unique and disposable tool. An orthodontic treatment would require a patient to wear a sequence of approximately 15 pairs (upper and lower, of aligners) each for approximately two weeks. Each of these approximately 30 aligners is unique.

Fig. 8 shows the plaster physical model which is made by casting into the rubber impression taken in the orthodontist's office. Up to this point, the technology is quite identical to that in use for a long time by dentists and orthodontists. Fig. 9 shows a sequence of images depicting the steps required to create a point cloud of data which can be turned into a virtual model of the plaster model seen in fig. 8. First the plaster models are coated with an epoxy. They are then imbedded in a solid block of polyurethane. Multiple plaster models are imbedded in a single block. The block is placed on equipment produced by CGI Corporation which uses a destructive scanning technique to produce a point cloud. The block is milled with a fly cutter, and then a scanner is used to create a 2D pixel image of that layer. The fly cutter then removes another layer and the process continues to deconstruct the physical model and construct a point cloud. Software provided by Geomagic of Research Triangle, NC is used to create the virtual model from this point cloud. In the next step depicted in fig. 10, the virtual model is sliced into individual teeth which can then be individually manipulated. As shown in fig. 11, software operators begin from the arrangement of the teeth in the patient and manipulate the physical model and progressively reorient the teeth in small amounts until they are in the final desired position (in the virtual model). This is a time consuming process which is performed using custom software. At the present time, over 700 software operators in Pakistan perform this operation for Align Technology.

In the next step, stereolithography is used to form tools which will later be used for thermoforming. At the present time, Align Technology has 16 SLA 7000 machine with approximately 39 more on order. Present production is 8,000 aligners per day (accommodating approximately 230 patients per day). As an estimate, 500 aligners are made per machine per day with each build having many aligners in it as can be seen in fig. 12.

The final step is to thermoform plastic sheet around the one time use stereolithography tool as shown in fig. 13 and then to hand trim this formed part. Fig. 14 shows aligners in bubble pack about to be sent to the orthodontist. This forming and trimming step is the most expensive step, primarily due to the hand labor of trimming. This step is performed in Mexico. Align Technology is clearly an example of mass customization in the limiting case of single part made to unique custom order (each customer actually gets about 30 unique parts). In addition, Align Technology demonstrates the importance of geometric flexibility as a driver for solid freeform fabrication. Indeed, Align might have considered milling of the disposal thermoforming tools, but favored SFF because of the need for detail in the regions where the teeth meet.

It is interesting to note that SFF is not the most expensive step of the Align process but rather is "in the middle". Most interesting to note is that even at the young stage of the company, at their current rate of fabrication, Align Technologies will make three million SFF models in the coming year. This single manufacturing application will double the number of SFF models over those made in the year 2000. This cogently demonstrates the importance of manufacturing applications to the future of SFF.

Another example of mass customization, again the medical field, is that of hearing aids [6]. In this application, being developed by Siemens Corporation (others are pursuing similar goals), a physical model, in this case, a rubber model molded into the ear and ear canal of the patient as illustrated in fig. 15, is the first step. This model is then nondestructively digitized using a laser scanning system and a virtual model is created as shown in fig. 16. This virtual model is then rendered as a shell and engineering detail such as the auditory channel shown in fig. 17 is added. Selective laser sintering is then used to create a shell. Fig. 18 shows an SLS shell on the right and a conventionally fabricated shell on the left. The electronics is added creating the finished hearing aid as shown in fig. 19.

This application is not only an example of mass customization but is also an example where the driver is the elimination of hand work. In the conventional practice of making hearing aids, a great deal of hand fabrication is used to go from the rubber physical model to the final hearing aid. While it is unlikely that SFF will yield a near term cost reduction over the conventional methods of fabrication, hearing aid companies are quite concerned about their continued ability to access the skill pool of hand work required in the conventional method. SFF answers that concern.

Another class of medical mass customization is the intriguing area of body parts. Perhaps the most likely early examples are bone replacement/reconstruction components. Fig. 20 shows a scan taken by MRI of a patient in need of reconstructive surgery of an eye socket. Fig. 21 shows bioceramic eye sockets made by Therics Inc. using Three Dimensional Printing [7]. Therics is currently in animal trials with bone replacement parts that will be produced in “shoe sizes”. While this is not quite customization, it is a step in that direction.

The military has a tremendous need to provide units or small quantities of spare parts on demand. In some cases, the original design is available, however, in many cases an existing physical component must be reversed engineered. Fig. 22 shows a sequence of mass customization which would pertain to the case where a component must be reverse engineered. The original component is subjected to an industrial CT scan. The metallic replacement part is then made by SFF, for example, by 3D Printing. The ProMetal division of ExtrudeHone is engaged in such spare parts mass customization under a program funded by the Navy [8].

Driver: Geometric Flexibility

In some cases, the ability to fabricate geometries, not practically possible by other methods can drive a manufacturing application. Two examples will be examined: *i*. conformal cooling and tooling, and *ii*. complex internal geometry in castings.

Quite a number of organizations are pursuing the concept of fabricating tooling, especially injection molding tooling, using SFF techniques. Participants in this area include ExtrudeHone/DME, POM Corporation, Express Tool, and others. Figures 23 and 24 show a case study of the application of conformal cooling provided by ExtrudeHone and DME which are partnered in an enterprise called "Mold Fusion" [8,9]. A relatively simple geometry plastic part was selected that the mold could be made with a number of conventional cooling approaches for comparison. The part is a capacitor cup made of polypropylene. The part is basically a cylindrical component with a wall thickness of 0.60 inch, a diameter of 2.5 inch and a length of 8 inches. Fig. 23a shows a mold core using a conventional baffle to flow the coolant through the core. Fig. 23b shows a mold which takes advantage of the simple geometry and provides seven cooling rings to bring the water near to the core surface. Fig. 23c shows the "mold fusion" core made by 3D Printing where a helical cooling channel was created and extra coils were packed in the regions felt to be most sensitive to cooling. Fig. 24 shows the cycle times broken down into Injection/Hold/Eject and Cooling Times. Note that the Mold Fusion core with conformal cooling shows a 49% improvement in productivity over the conventional baffle (parts per hour is plotted on the right.) The bronze insert with cooling rings is significantly better than the conventional baffle but not nearly as good as the conformally cooled core. Note, that with a more complex geometry, this bronze insert with cooling ring approach would not be feasible and thus the improvement of conformal cooling would be even more dramatic over the alternative. Such improvements of 20-50% in cycle time have been seen in quite a number of case studies.

The plastics mold making industry produces 200,000 to 300,000 molds annually on a world wide basis at a cost of 15 to 20 billion dollars. The possible future penetration of conformal cooling may be up to 15% of molds made, or 30,000 to 50,000 molds annually, a significant impact. However, it should be noted that the plastics molding industry is quite conservative and it will take some time for this penetration to take place. As a reference point, it has taken 30 years for Hot Runner technology to penetrate to 30% of all applications [9].

Another class of applications which is motivated by the ability to fabricate complex internal geometry is that of complex castings, especially those for pumps, valves and other fluid control elements. Fig. 25 shows a sand core made on an EOS SLS machine for a fluid manifold. Fig. 26 shows a mold and casting for a fuel cross over for Rocketdyne made by Soligen, Inc. using 3D Printing [10].

Driver: Local Control of Material Composition

One of the intriguing possibilities associated with some SFF technologies is that of controlling the local composition of the fabricated component. Fig. 27 shows two cell phone covers made by 3D Printing on a Z Corp. machine. One component is printed in "monochrome" while the other component has color printed in. The color part is a three dimensional representation of the output of a mold filling finite element simulation [11].

Fig. 28 shows some "flash dosage" oral dosage forms from Therics, Inc. These pills have drugs printed in an interior core with flavor masking on the exterior of the pill. Example applications are under study which would be based on the production of 50 million per machine per year [7].

While in many cases, the use of SFF technology to control the local composition can be enabling of new products, it is also true that these applications require a significant "stretch" from current practice as the products being considered may have no precedent and therefore no track record.

BARRIERS TO MANUFACTURING BY SFF

There are a number of issues or barriers which SFF must overcome if it is to have a large impact on manufacturing. These include:

- Speed/part cost
- Accuracy, tolerances, surface finish, detail
- Application specific materials properties
- Application specific machine design
- Product support (centralized manufacturing)
- Ease of use (distributed manufacturing)

Barrier: Speed/Part Cost

A primary driver of part cost is the build speed in the SFF machine. As documented in the appendix to this paper, the build rates of the fastest SFF machines today are on the order of one liter of part per hour. However, "standard" forming processes can be much faster. Certainly, there is a wide range of speeds associated with standard forming processes depending on the material being formed, the size of the part, and the process itself. However, as a generalization, standard forming processes can be 10 to a 1,000 times faster than today's SFF technologies.

It is useful to speculate about an SFF machine which can build 100 liters per hour, as such a machine would be competitive with at least some of the standard forming processes. An example of a machine which could achieve this build rate would be a machine with a bed size of one meter by one meter, building in layers that are 100 microns thick and forming each layer in 3.6 seconds. While such a goal is challenging, it is also within the realm of possibility, at least with some of the technologies. (For example, the author believes that such a machine is possible using Three Dimensional Printing technology.)

Barrier: Accuracy, Tolerances, Surface Finish and Detail

On the issue of accuracy, tolerances, surface finish and detail, a clear distinction must be made between manufacturing applications and prototyping applications. In a prototyping application, it is often acceptable to do selective final machining on the part and even extensive hand finishing can be tolerated because the combination of SFF with these techniques still yields a part much faster than available alternatives. However, in a manufacturing application, any secondary operation (other than mass processes like media finishing) is a threat to competitive advantage. Thus, there is a significant barrier to overcome in achieving the net shape component with the desired surface finish and tolerances by SFF [12].

Barrier: Application Specific Material Properties

As in the case of accuracy and tolerances, a clear distinction must be made between prototype applications and manufacturing applications in the context of material properties. For a prototype, a part is still of considerable use even if not all of the material properties are as good as those of the part which will be ultimately manufactured. When testing a prototype, the longevity of the test may not matter in some applications. One may be able to reduce the severity (for example, minimize the temperature exposure of the part) and still devise the required technical information. In general, one may be able to accommodate materials properties that are not quite up to standard by correcting the measured results in order to compensate for the expected improvement which will correspond to the final component materials properties. However, in the manufactured parts, all the material properties must exceed some minimum standards. It is quite possible, for example, that a given component could be acceptable in yield strength, tensile strength, impact strength, creep, coefficient of thermal expansion, and elastic modulus, but fail in its fatigue properties. Failure in one aspect will mean that the component cannot be used in the manufacturing application. This is a much higher standard than that which has to be satisfied for prototypes. The danger is that the SFF materials may have to be tailored for specific applications in order to satisfy many requirements simultaneously. This will be an extremely expensive proposition and could only be justified for high volume applications [12].

Barrier: Application Specific Machine Design

As noted if manufacturing applications are more demanding than prototyping applications and many applications will *simultaneously* push limits on: *i*. accuracy, surface finish and detail, *ii.* rate, and *iii*. material properties. In order to simultaneously satisfy these requirements, it may become necessary to design machines for specific applications. The most obvious example of the need for application specific machine design is the need to accommodate different part sizes and therefore to create machines with different build volumes. However, other considerations may be even more demanding. For example, in Three Dimensional Printing, fine ceramic powders are processed using slurries, while larger powders are processed dry. Fine featured small components such as those pictured in Fig. 29 are fabricated by traversing the printhead in a vector outline and then raster filling. Larger components, however, must be made using raster scanning methods only, due to considerations of rate. Thus, a particular application will be best satisfied by a particular combination of powder deposition, binder deposition, and machine architecture. While general machines can go a long way to satisfy the requirements of a specific application, application specific machine design may be required to gain the full benefits.

Barrier: Product Support (Centralized Manufacturing)

Manufacturing facilities demand "no" down time. If down time is encountered, they expect nearly instantaneous repair. Further, they expect the ability to make parts elsewhere while equipment is down. The net result is a very much higher standard of product support which must be satisfied for manufacturing applications, as opposed to prototyping applications [12].

<u>Barrier: East of Use (Distributed Manufacturing)</u>

Mass customization applications are best satisfied by having the manufacturing capacity distributed. As a model, consider the lens making equipment which is distributed at various LensCrafters facilities. Perhaps the closest analogy in today's manufacturing world is that of the machine shop. However, machine shops do not accomplish mass customization as the processes are not facile enough to interface directly to the end user. In a mass customization application, there will be far less tolerance of process quirks and software challenges as compared to today's machine shops. Thus, the software equivalent of "MasterCam" will not be good enough – it will be too hard to use. The software orientation will have to be toward the end use customer [13].

CONCLUSIONS

The SFF/RP industry has grown steadily with the most significant gains made in the number of models produced per year – three million in the year 2000. Future growth is most likely to be in manufacturing applications of SFF where even a single application can double the number of models/parts produced annually. There are a number of factors or drivers which can motivate a manufacturing application of SFF either individually or in combination. These drivers include: *i*. avoid conventional tooling, *ii*. minimizing hand work, *iii*. mass customization, *iv*. geometric flexibility, *v*. local control of composition. Avoidance of conventional tooling has been the most common driver today with prominent examples in the metals casting and injection molding areas. The most intriguing of the drivers is that of mass customization – the manufacture of highly individual products, but on a mass scale. SFF offers the possibility of mass customization of components with complex 3D geometry. A prominent current example is that of Align Technology of Santa Clara, CA which produces unique plastic aligners for orthodontic applications.

There already are manufacturing applications where the advantages offered by SFF are so compelling as to overcome any barriers. However, *widespread* impact of SFF on manufacturing will depend on overcoming several barriers including : *i*. increased build speed, *ii*. improved accuracy and surface finish, *iii*. improved and possibly application specific materials properties, *iv*. application specific machine designs, *v*. improved product support, and *vi*. greater ease of use. The essence of these barriers lies in the distinction between prototyping and manufacturing. Characteristics which can be tolerated in a prototyping environment become intolerable in a manufacturing environment. For example, the wide gulf in build speed between SFF and conventional forming processes will have to be at least partly bridged. Tolerances that are acceptable in a prototype are unacceptable in manufacturing as secondary operations are economically unacceptable. Demands on materials properties are greater. Mass customization demands ease of use in a distributed fabrication environment. As these barriers are addressed, manufacturing applications will proliferate and are likely to become a primary impact of the SFF field.

APPENDIX

In order to get a sense of the build rates of the current SFF technologies, a benchmark was attained for a fast "office modeler" and a "high end" machine targeted at manufacturing. The Z Corp. Z406 machine was chosen as the office modeler and the Vanguard machine from DTM as the high end machine. Data for a specific geometry was attained as it was felt to be more meaningful. An STL file was sent to Z Corp. and DTM and data returned from their build time estimators (not models were made) [11,12]. The STL file is pictured in Fig. 30. The volume of this part is approximately one liter.

	Starch (175μ layers)	Plaster (100μ layers)
One Part	1.45 hrs	2.9 hrs
Four Parts	5.8 hrs	11.6 hrs

Table I

Table I shows the build times returned by Z Corp. for two materials – starch and plaster. Build time estimates for one part and four parts are given.

	Nylon (150μ layers)	Metal (75μ layers)
One Part	4.4 hrs (2.75 warm up/dn)	6.6 hrs (no warm up/dn)
Four Parts	6.7 hrs (2.75 warm up/dn)	26.4 hrs (no warm up/dn)

Table II

Table II comes from DTM and has build time estimates for nylon and metal materials again for one part and four parts. Note that in the case of the nylon material the estimate for four parts is less than four times the estimate for one part as the nylon materials require a warm up and cool down cycle and this warm up and cool down would be the same for four parts as for one part.

The most important conclusion from these build time estimates is that current build rates are on the order of 0.2 – 1.0 liter per hour. The upper end of this range is the rate estimate used in the rate section of this paper. It is also interesting to note, however, that there is overlap in build rates between the office modelers and the "high end machines", although, it must be noted that making a direct comparison is impossible because the end product and the costs are so different.

REFERENCES

[1] Terry Wohlers, Wohlers Report 2001, Wohlers Associates, Fort Collins, CO, 2001.

[2] Lance Weihmuller, Bell Helicopter, Fort Worth, TX, communication with author.

[3] Phil Dickens and Neil Hopkinson, De Montfort University, Leicester, United Kingdom, communication with author.

[4] Len Hedge, Vice President of Manufacturing, Align Technology, Santa Clara, CA, communication with author.

[5] Mervyn Rudgley, Senior Director of Business Development, Stereolithography, 3D Systems, Valencia, CA, communication with author.

[6] "*LasR*™ Hearing Instrument Shells…Let your patients experience the most comfortable hearing instruments", Siemens Hearing Instruments, 2001, videocassette.

[7] Chris Gaylo, VP of Engineering, Therics, Inc., Princeton, NJ, communication with author.

[8] Michael Rynerson, Business Unit Manager, ProMetal Division, ExtrudeHone Corporation, Irwin, PA, communication with author.

[9] Larry Navarre, DME Corporation, Madison Heights, MI, communication with author.

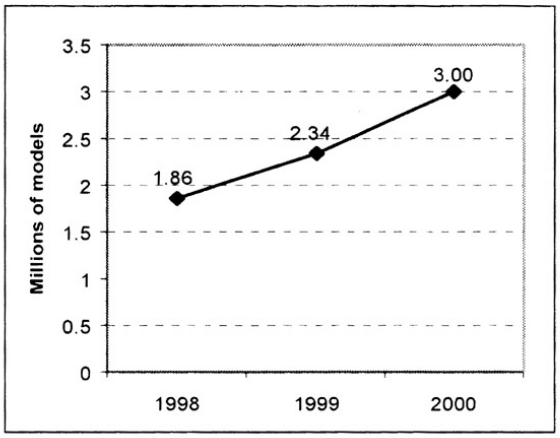
[10] Yehorem Uziel, President, Soligen, Inc., Northridge, CA, communication with author.

[11] Marina Hatsopolous, CEO, Z Corp., Burlington, MA, communication with author.

[12] Kevin McAlea, DTM Corporation, Austin, TX, communication with author.

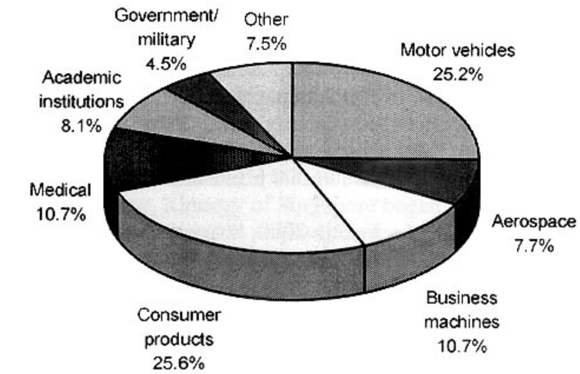
[13] Ping Fu. President, Geomagic, Research Triangle, NC, communication with author.

FIGURES



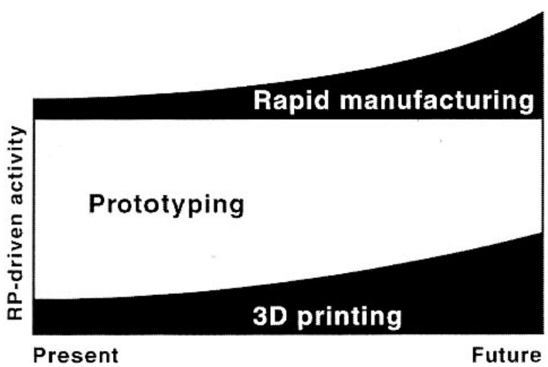
Source: Wohlers Associates, Inc.

Figure 1. The total number of models made annually by SFF for the past three years.



Source: Wohlers Associates, Inc.

Figure 2. The breakdown by industry of SFF applications.



Source: Wohlers Associates, Inc

Figure 3. A highly schematic anticipation of the future growth of SFF.

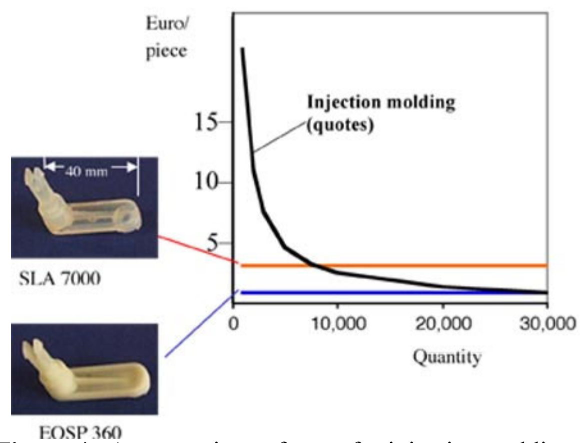


Figure 4. A comparison of costs for injection molding versus stereolithography and SFF for the small handle shown.

Figure 5. The cover of the Economist magazine from July 14, 2001 depicting mass customization.

Figure 6. Swatch watches, an example of mass customization.

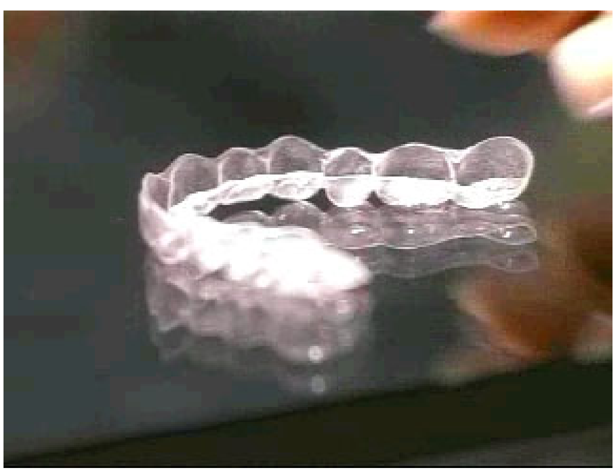


Figure 7. A plastic aligner made by Align Technology, Inc.

Figure 8. The plaster physical model taken from the rubber impression taken from the patient's teeth and gums.

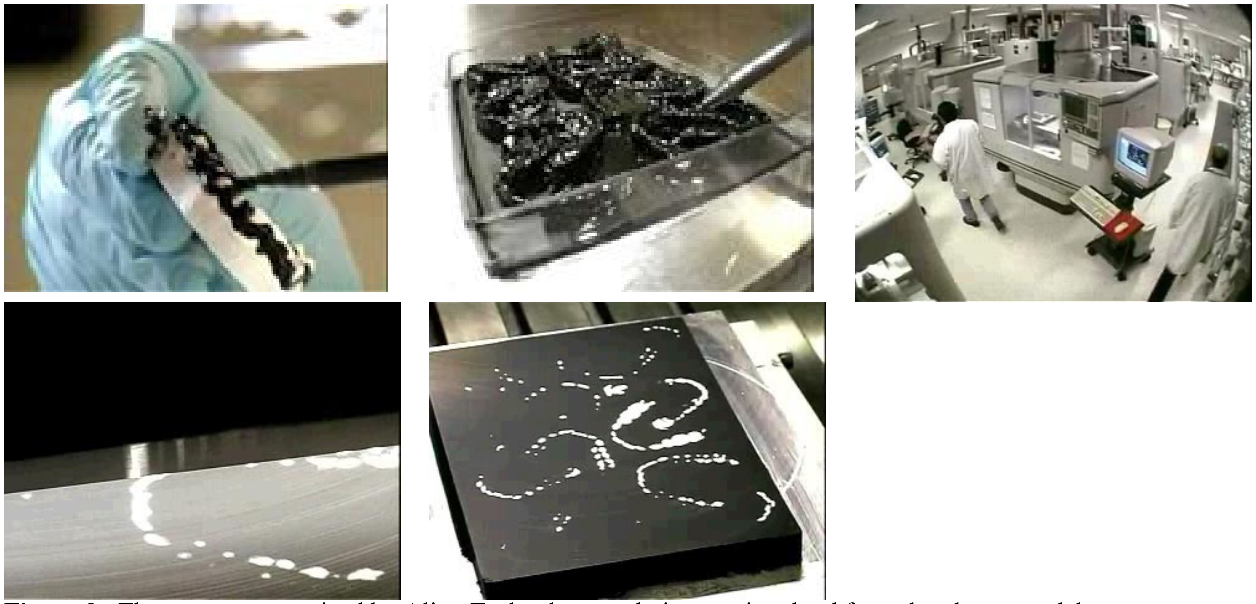


Figure 9. The sequence practiced by Align Technology to derive a point cloud from the plaster models.

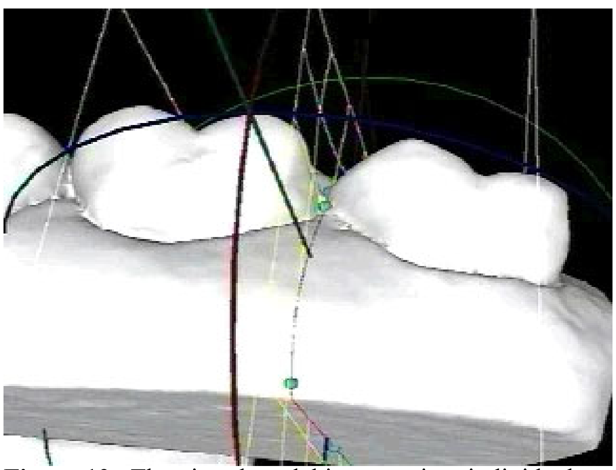


Figure 10. The virtual model is cut up into individual teeth.

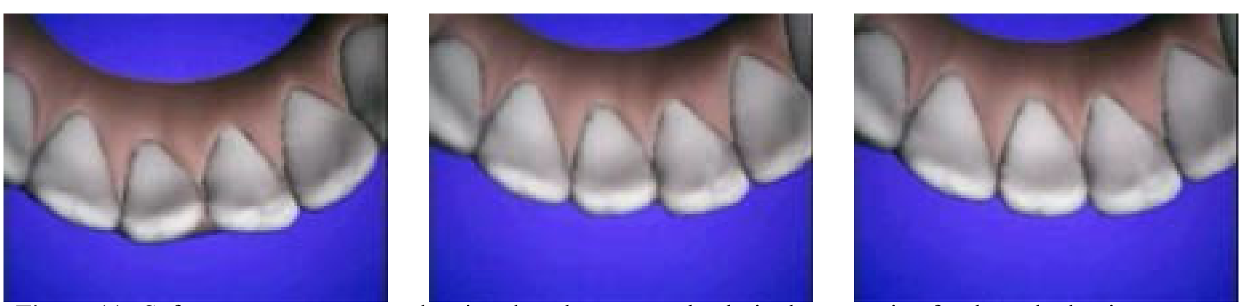


Figure 11. Software operators move the virtual teeth to create the desired progression for the orthodontic treatment.

Figure 12. The one time use thermoforming tools are made by stereolithography using SLA 7000 machines.

Figure 13. The aligner is made by thermoforming a plastic sheet over the stereolithography tool.

Figure 14. Aligners are bubble packed and sent to the orthodontist.

Figure 15. A rubber impression of the ear and ear canal is the first step in the manufacture of a hearing aid.

Figure 16. The rubber impression is scanned and turned into a virtual model.

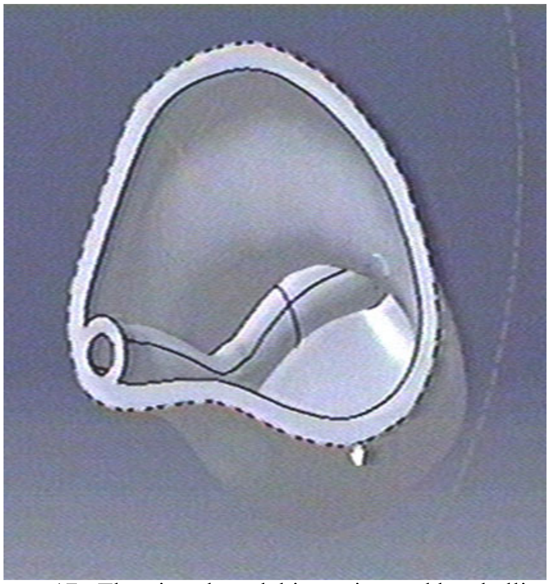


Figure 17. The virtual model is engineered by shelling and adding features.

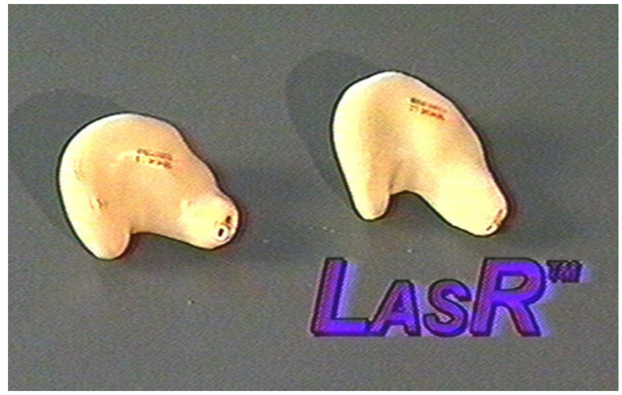


Figure 18. An SLS hearing aid is on the right while a conventionally fabricated one is one the left.

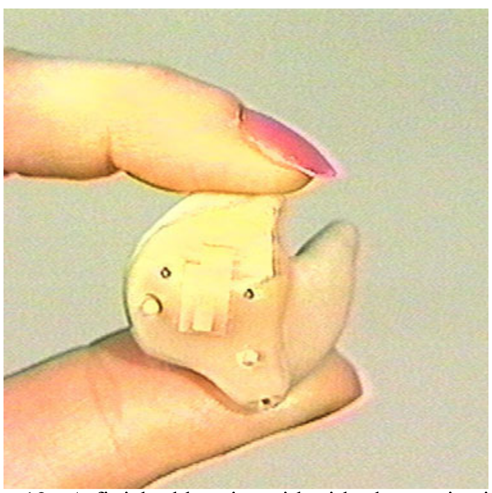


Figure 19. A finished hearing aid with electronics in place.

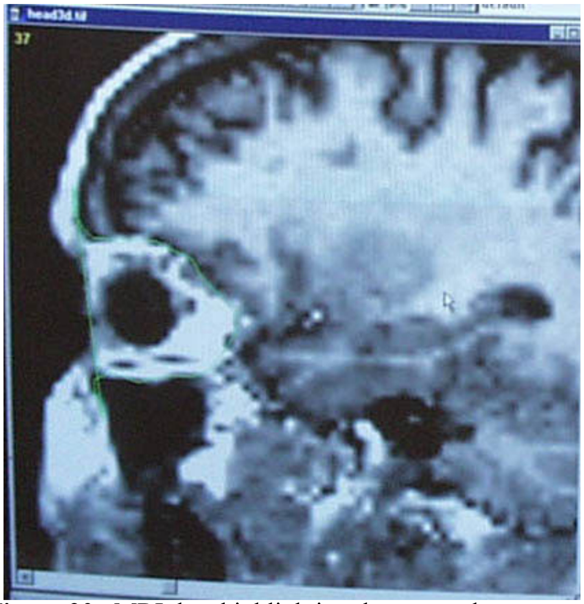


Figure 20. MRI data highlighting the eye socket area where reconstruction is needed.

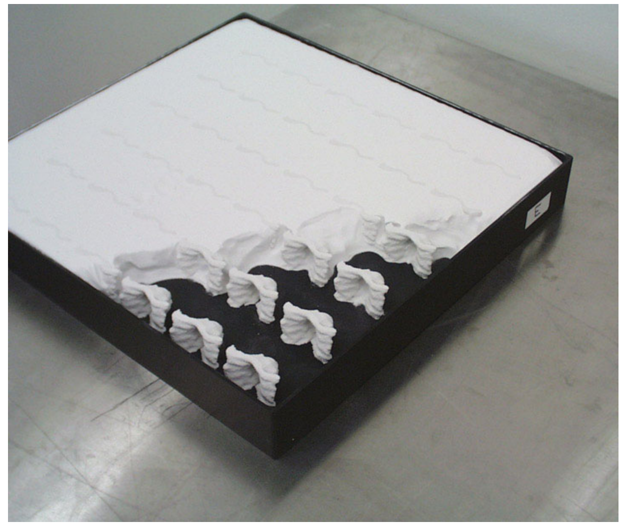


Figure 21. Bioceramic eye sockets made by 3D Printing.

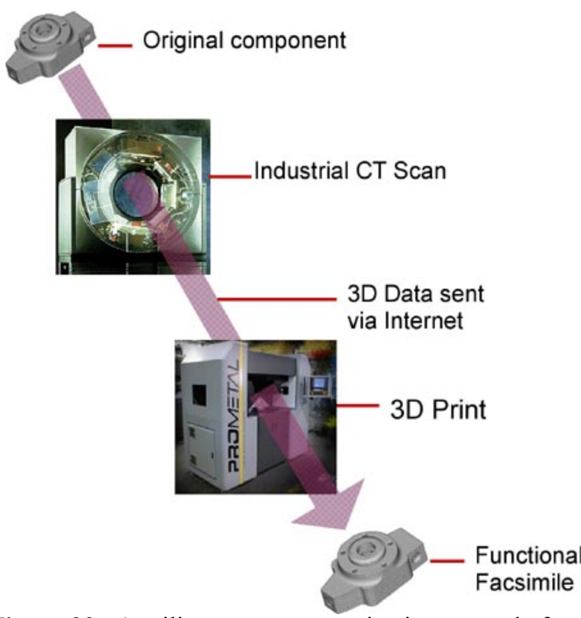


Figure 22. A military mass customization example for spare parts including reverse engineering and 3D Printing.

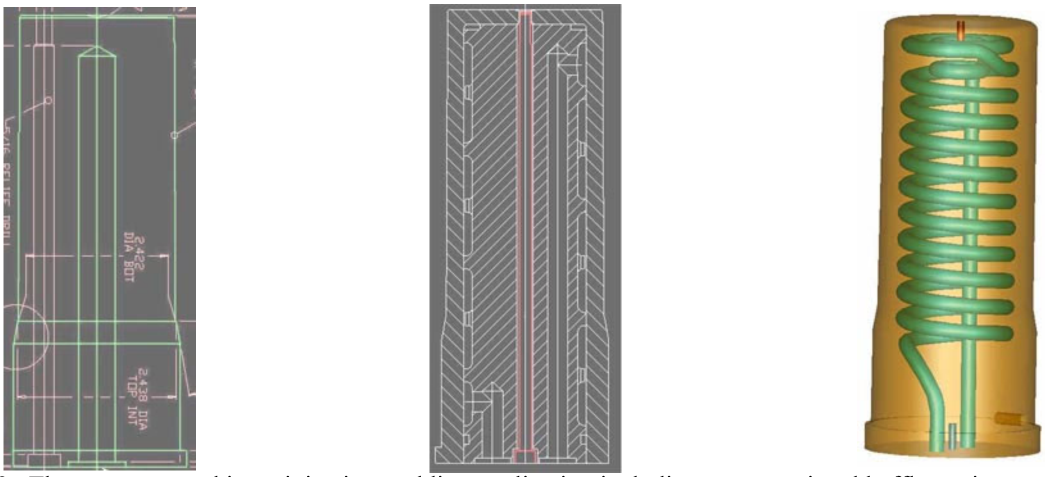


Figure 23. Three cores tested in an injection molding application including a conventional baffle, an insert with cooling rings and a 3D Printed conformally cooled core.

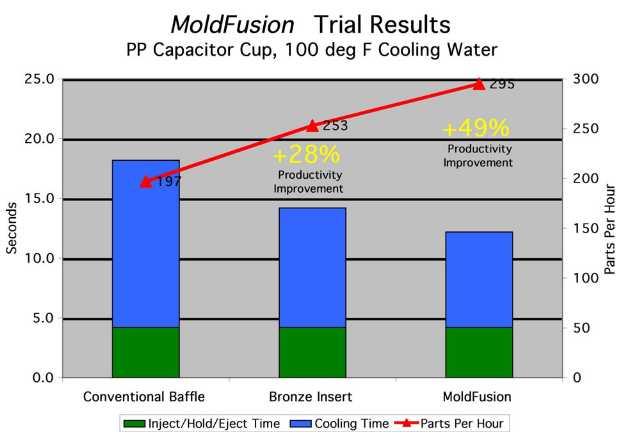


Figure 24. The cycle time in seconds (left) and the number of parts per hour (right) for the three cores shown in Figure 23. The green areas are the sum of injection, hold and eject times while the blue are the cooling times.

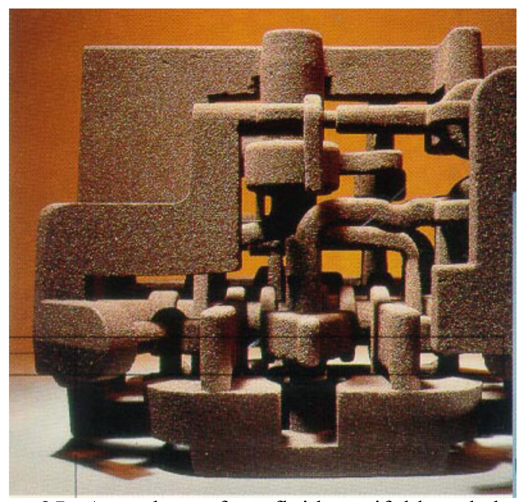


Figure 25. A sand core for a fluid manifold made by SLS on an EOS machine.

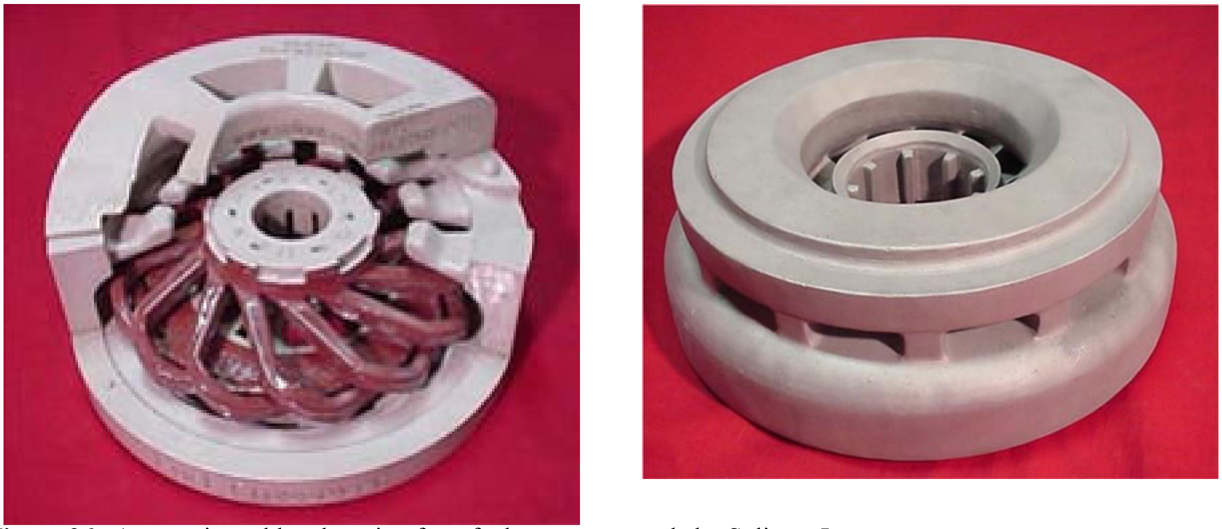


Figure 26. A ceramic mold and casting for a fuel cross over made by Soligen, Inc.

Figure 27. A monochrome and cover cell phone cover both made by 3D Printing by Z Corp.

Figure 28. Pills for oral consumption made by 3D Printing by Therics, Inc.

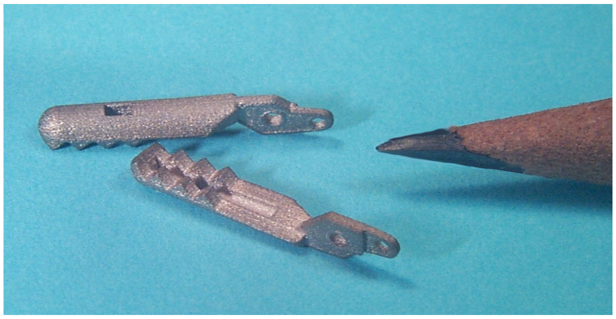


Figure 29. Sintered stainless steel components with fine features made by 3D Printing.

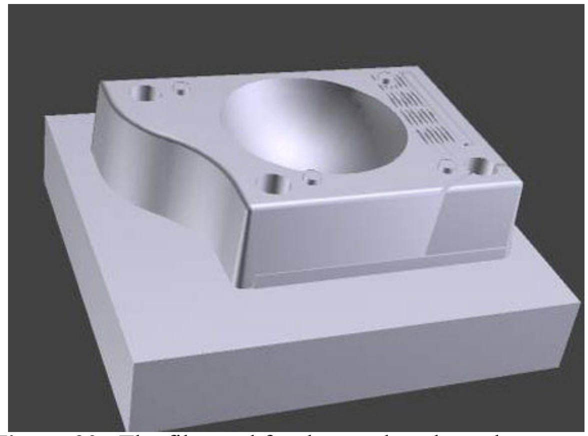


Figure 30. The file used for the rate bench mark. External dimensions are 140x135x57 mm.