THREE DIMENSIONAL PRINTING: FORM, MATERIALS, AND PERFORMANCE

Michael J. Cima and Emanuel M. Sachs
Massachusetts Institute of Technology, Departments of Materials Science and Mechanical Engineering

Abstract

Three dimensional printing (3DP) is a process for rapid prototyping of functional components. Powdered materials are deposited in layers, and areas are selectively bound by deposition of a binder by ink-jet printing. The unbound powder is removed following sequential application of layers, resulting in a three dimensional part. The process is well suited to materials such as ceramics and some metal alloys that are normally processed via a particulate state. Here we review recent progress toward application of 3DP technology for the production of metal casting tooling. Complex-shaped cores and shells with high dimensional tolerance were prepared and used to produce castings of high temperature alloys.

Introduction

Initial interest in rapid prototyping technology was motivated primarily by the need to realize complex shapes in three dimensions. These renderings gave designers an important tool to speed the development of product concepts. Increased competition in the manufacturing industries has caused pressure to reduce the time to market for products and created further interest in freeform fabrication of objects. The development and commercialization of stereo lithography [1] was a milestone because of the direct link it provided between the modern computer-aided-design (CAD) environment and real objects of complex shape. Its success, however, is limited to materials that can be derived from photopolymerizable monomers. The added material constraints of a particular application pose significant demands on the chemical design of the monomer. Thus, only applications that can use these plastics directly, or where they can be used as molds, will be impacted significantly.

An alternative approach is to make true prototypes of components or tooling that are composed of the same materials as those in general use. This is the basis of new methods like selective laser sintering (SLS) [2] and three dimensional printing (3DP) [3]. Both SLS and 3DP construct components from powders and therefore could potentially replicate any material that is normally processed from a particulate state.

Particulate Forming Technology and Rapid Prototyping

Particulate forming processes are used primarily for parts composed of ceramics or certain alloys. Solidification or deformation forming techniques for these materials require conditions that are either unobtainable or may severely compromise the microstructural integrity of the component. Most often, powder forming technology involves compounding fine particles of the material with a binder and, in some cases, a liquid vehicle. The mixture is then molded into the desired shape by a number of methods, including injection molding, pressing, or slip casting. The methods vary greatly in their shaping strategies, but they all result in an intermediate state where powder of the desired material is held together by a binder which is either fugitive or may react with the matrix powder during subsequent heat treatment.

The materials objective in 3DP is to produce green components that are identical to those prepared by conventional methods. 3DP is unique in that a solid object is created by ink-jet printing a binder into selected areas of sequentially deposited layers of powder. Each layer is created by spreading a thin layer of powder over the surface of a powder bed. The powder bed is supported by a piston, similar to that used in the SLS process, which descends upon spreading of each powder layer. Another feature which is similar to other rapid prototyping technologies is that the instructions for each layer are derived directly from a CAD representation of the component. The area to be printed is obtained by computing the area of intersection between the desired plane and the CAD representation of the object. Thus, the individual sliced segments are joined to form the three dimensional structure. The unbound powder supports temporarily unconnected portions of the component as the structure is built but is removed after completion of printing. The binder used can be exactly the same as used in conventional fabrication of the object or may be designed to ultimately yield the same binder through chemical or physical changes that take place in the powder bed after printing. In this way, true prototypes can be constructed since both the macro- and microstructural features of the production component are reproduced. A more complete description of 3DP equipment can be found in other publications [3].

Foundry Materials and 3DP

We report here our recent progress toward the manufacture of investment casting tooling by 3DP. The materials used for this application are composed of refractory powders such as fused silica, alumina, or zircon and a bonding material that is usually glass. The glass bond fuses when the mixture is heated and forms glass bridges between neighboring particles. Conventional foundry practice involves machining dies for wax positives of the component and dies for cores to define hollows within the casting. The ceramic cores must be injection molded and fired before being inserted into the wax die. The wax is then molded around the core. A ceramic shell is created on the outside of the resulting wax positive by sequential dipping of the wax positive in a ceramic slurry. The wax is then melted out of the shell followed by firing to fuse the glass bond and give the shell some strength. Molten metal can then be poured into the shell and solidified. The ceramic shell is then removed by impact, vibration, or gritblasting. Ceramic cores are removed from the casting by a combination of mechanical action and chemical attack. Caustic solutions of sodium or potasium hydroxide are frequently used to dissolve the glass bond within the ceramic.

The glass bond in the shell is usually produced by colloidal silica in the ceramic slurry. Aqueous colloidal silica solutions contain as much as 20 vol% silica in the form of nanometer sized particles. The particle suspension is stabilized against aggregation by the development of charge on the surface of the particles. The charge is created by selective adsorbtion of charge-determining ions and is commonly controlled by adjusting the pH of the solution.

The materials used in investment casting must be highly optimized to meet all process requirements. The strength must be high enough to withstand stress during casting, yet low enough to accommodate shrinkage during solidification and to be removed from the cast part after processing. It also must not react with the molten metal and not change dimensions even with extended exposure to high temperature. Lastly, cores must be susceptible to chemical attack so that they may be removed from the interior of the cast parts.

These materials requirements demand that successful rapid prototyping methods use materials that are as similar to those in current practice as possible. We currently ink-jet print colloidal silica and spread layers of refractory powder such as alumina. The result is a material that is remarkably similar to investment casting refractories. Shown in Figure 1 are strength results determined by four-point bending of printed bars [4]. The bars were printed at line spacings of 0.13 mm, 0.19 mm, and 0.25 mm, and at relative binder volumes (total volume of silica and water to total volume of the bar) of 40%, 50%, and 60%. The latter parameter can be adjusted by changing the printing velocity at a con-

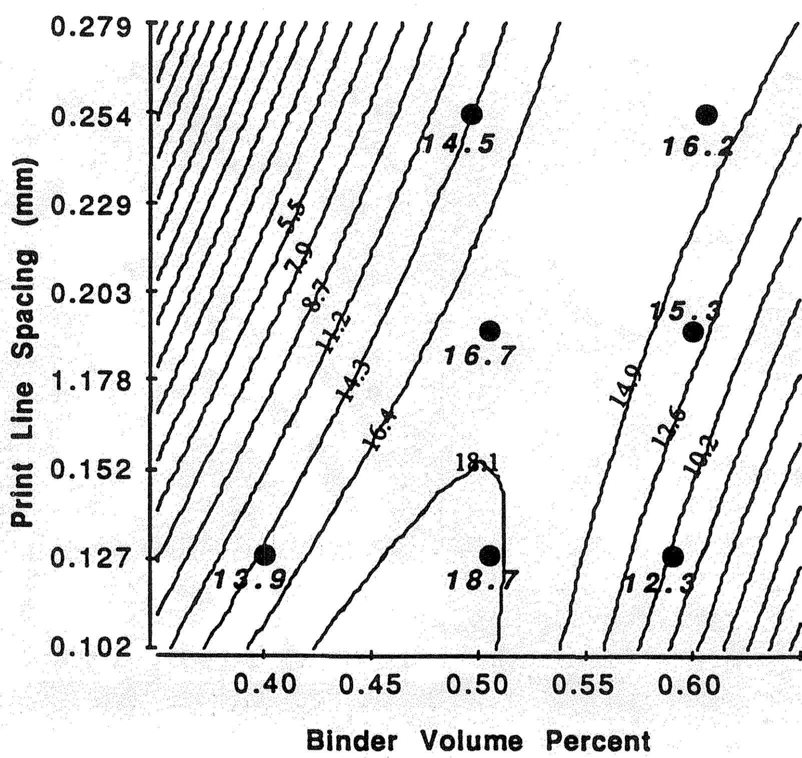

Figure 1 Maximum bending strength (in MPa) as a function of binder volume percentage and print line spacing.

Table I: Dimensional Control of Refractory Plates from 3D Printing.			
	Green (mm)	1000°C	150°C
Average	38.125	38.123	37.582
Average σ (along a part)	0.020	0.018	0.041
σ (part to part)	0.020	0.015	0.023

stant binder flow rate. Finally, the bars were fired to 1500°C prior to testing. Measurements were repeated four times at each combination of parameters. Also shown are contour lines derived by second order regression of the data. The strength is observed to vary from 12.3 to 18.7 MPa, values comparable to those in the foundry industry [5], and strength depends largely on the amount of binder used. The binder content at maximum strength is consistent with the literature on refractory shells [5]. Increasing amounts of binder serve to strengthen the component but eventually decrease its strength as the glass becomes the major phase.

Table I reports the dimensional changes of printed plates of refractory material at various stages of processing [4]. The intended width of the plates was 38.100 mm. A print line spacing of 0.19 mm and 50% volume fraction of binder were used. Two firing temperatures, 1000°C and 1500°C, were chosen as representative of the range required for casting many metal alloys. The shrinkage was small and very reproducible. The shrinkage occurring at high temperature may be related to the softening of the glass bond or reaction of the silica with alumina to form mullite.

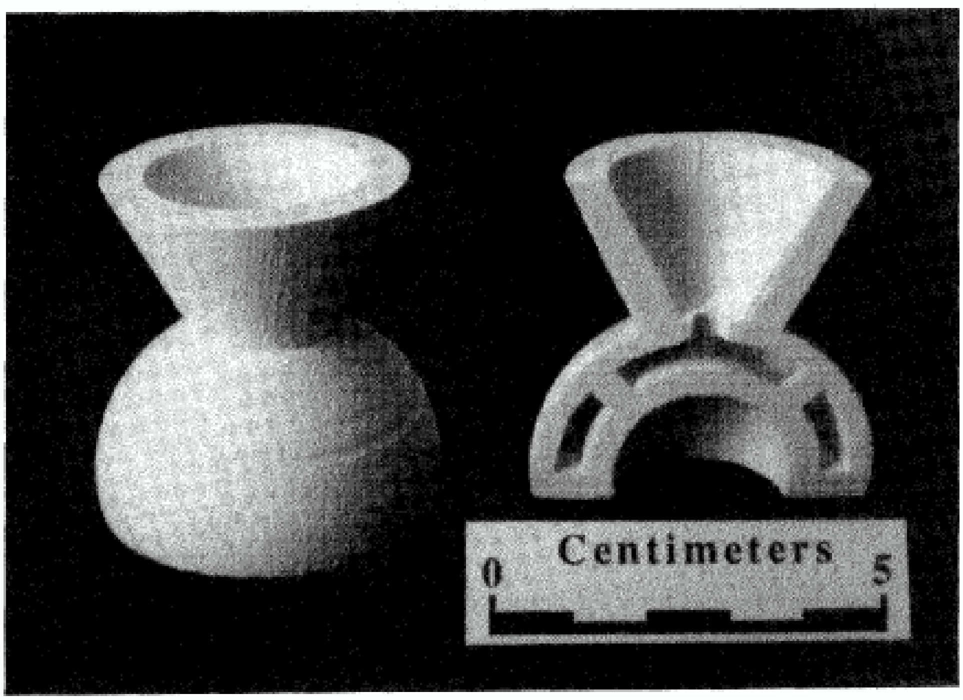

Figure 2 This photo shows a complete shell and an as-printed cross section of the same part. The shell consists of a pouring funnel connected by a gate to a casting cavity. The material is alumina powder and colloidal silica binder.

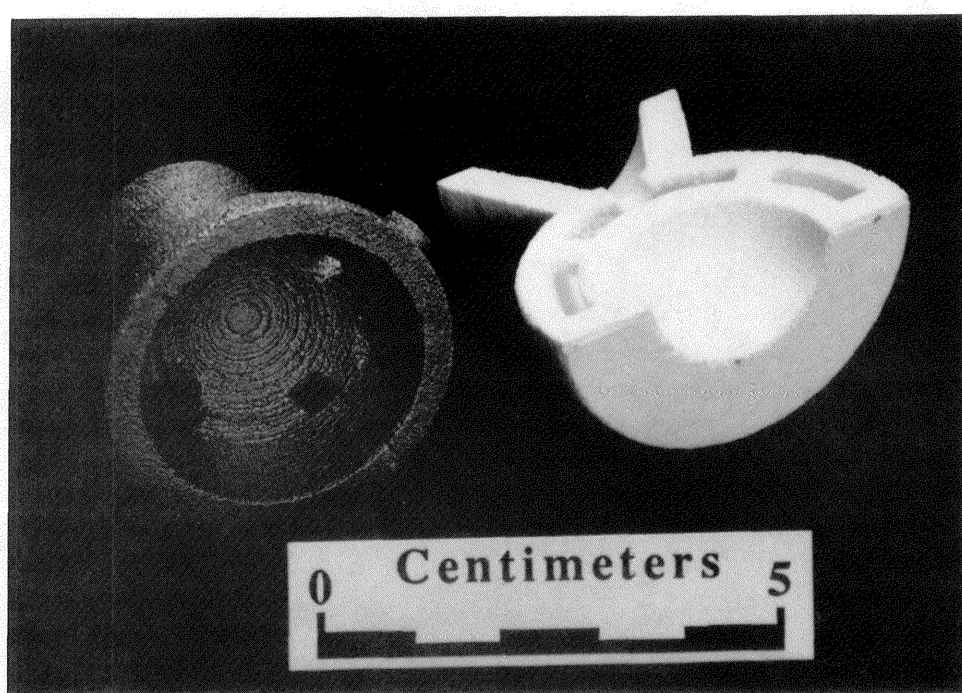

Figure 3 A cobalt-chrome alloy casting poured next to an as-printed cross section of the shell into which it was cast.

Shown in Figure 2 is a photo of a complete shell and an as-printed cross section of the same part. The shell was printed directly from a computer file description which was compatible with commercial stereo lithography systems. The shell consists of a pouring funnel connected by a gate to a casting cavity which has the shape of a hemisphere and contains several holes. Figure 3 shows a successfully cast cobalt-chrome alloy made in the shell shown in Figure 3. Because this shell was made with rather large layer height (0.178 mm) in order to speed its building rate, the surface finish would need to be improved for general applicability to the casting industry.

Figures 4 and 5 show a nickel superalloy casting made from a printed shell with integral core. The detail view in Figure 5 shows the hollow casting which requires that a core be printed during the 3DP process. The core was supported at the round cross section on top and at the rectangular cross section at the left when the part is viewed as in Figure 5. The core was printed *in situ* during normal 3D printing of the shell. A shell with integral core like that shown in Figure 4 cannot be constructed by conventional investment casting technology. This example illustrates how 3D printing may provide designers with prototypes that can not be produced any other way.

A second example where 3DP can provide parts that cannot be constructed by conventional means is the production of hollow cores. Figure 6 shows J-core test samples produced by 3DP. This simple shape is used to test whether a material can be successfully leached from the interior of a casting. The J-cores pictured are unusual, however, because they were constructed to be hollow. Long and narrow cores are often diffi-

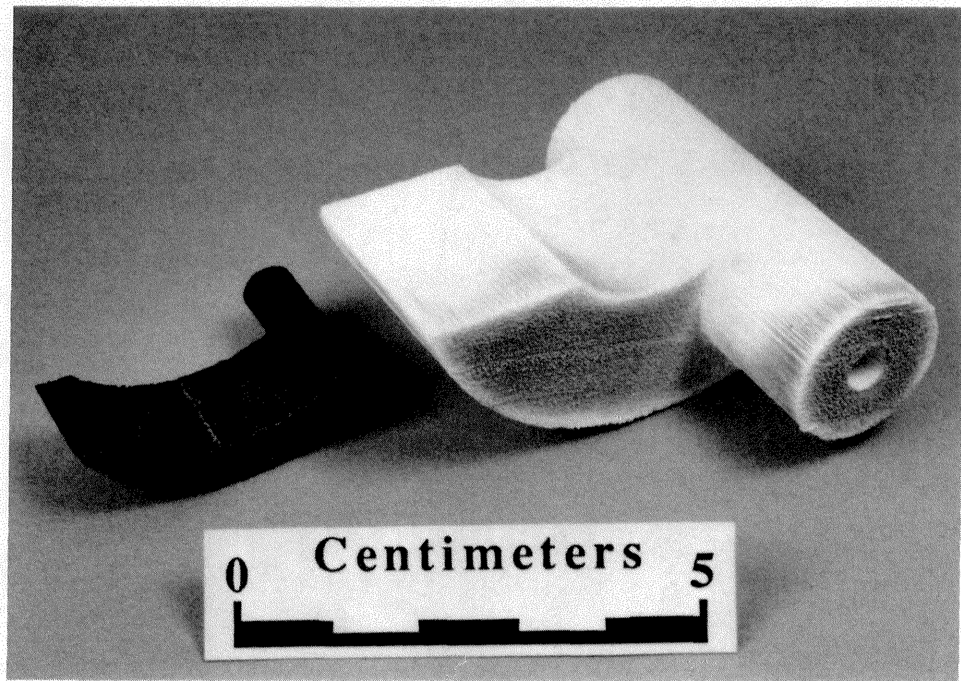

Figure 4 The part on the right is a complete shell with integral core. The metal would be poured into the lower front. The part on the left is a hollow casting (see detail below) which was poured into a shell like the one shown. The casting is shown in the orientation that it would have in the shell.

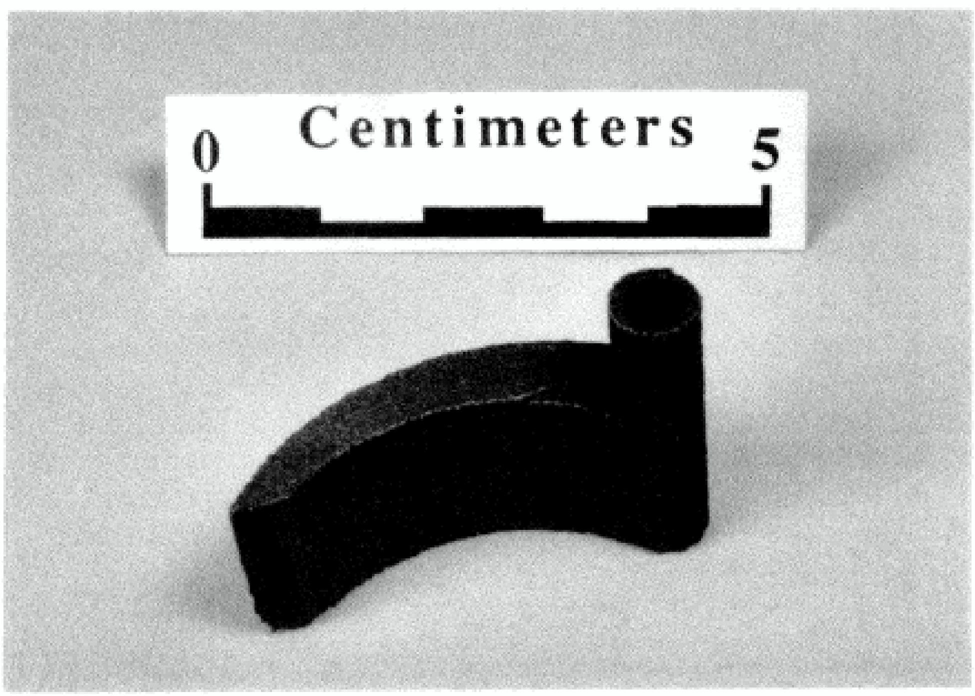

Figure 5 A detail of the hollow casting poured into the shell with integral core shown above. Note that the core which created the intenal cavity was supported at the round cross section on top and at the rectangular cross section at the left.

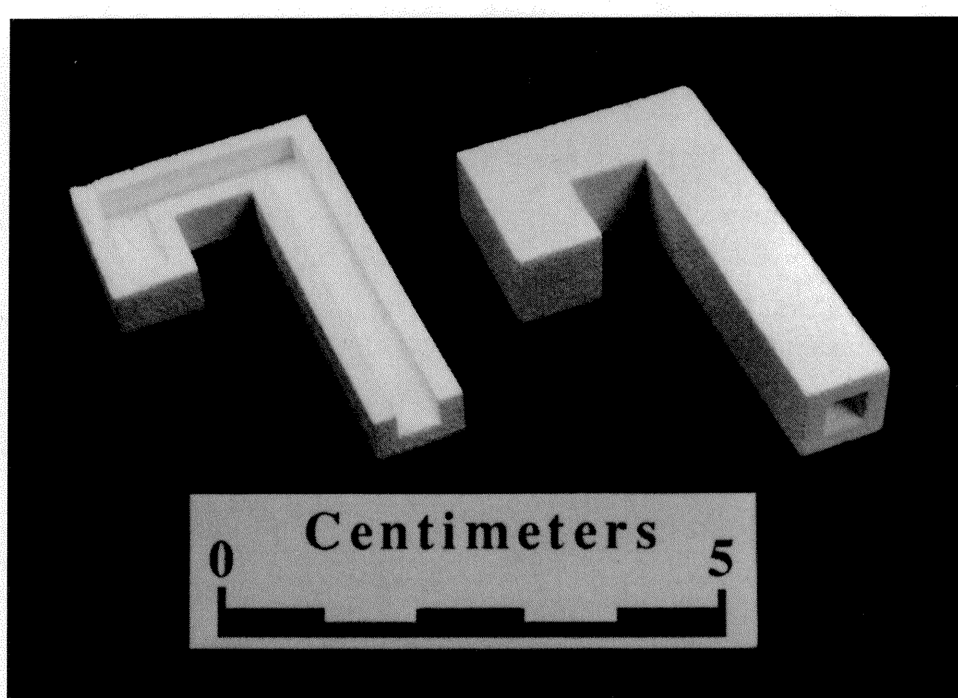

Figure 6 Hollow J-core samples produced by 3DP. Hollow cores facilitate core removal by increasing the surface area of material to be removed by chemical attack while simultaneously reducing the amount of material which must be removed.

cult to remove because they provide little cross sectional area by which to attack and remove the material. Hollow cores increase the surface area of material which can be attacked while simultaneously reducing the amount of material which must be removed.

Conclusions

Methods to rapidly prototype functional components directly from a CAD model are now a reality. Conventional powder-processed components such as ceramics can be produced by techniques like three dimensional printing. We have demonstrated the production of shells and cores for investment casting by 3DP. Even at this early stage of development, 3DP has revealed itself as a method toroduce components that cannot be produced by conventional processing methods. There seem to be no conceptual obstacles to applying 3DP to other materials. We are now producing components from powdered metals and have recently prepared complex-shaped silicon carbide preforms for metal matrix composites.

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