Powder Removal from Internal Cavities of 3D Printed Parts

by

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Abstract

Three Dimensional Printing is a process for the rapid manufacture of tooling and prototypes from a CAD model. A layer of powder is spread and selectively fixed by an inkjet printed binder. Successive layers are spread and printed over the initial layer. After printing is completed, the unprinted powder is removed leaving a three dimensional part. The initial applications for this technology are the production of ceramics shells and cores for metal casting, the manufacture of ceramic preforms for metal matrix composite infiltration, and the fabrication of metal tooling for injection molding.

One of the valuable attributes of this process is the abilitiy to manufacture parts with internal cavities. However, the removal of the unprinted powder that fills these cavities poses some problems. Various methods to remove powder from internal cavities of ceramic parts were investigated. A simulated part was produced and different methods were attempted to remove $30\mu m$ alumina powder with a citric acid additive from this part. These methods included: vibration, ultrasonication, vacuuming, boiling, rinsing, and microwave boiling. Vacuuming and microwave boiling were the most successful in simulation, but neither method was as effective on an actual printed part. This was attributed to a change in the physical properties of the powder after firing.

Thesis Supervisor: Emanuel M. Sachs
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Chapter 1

Introduction

1.1 Motivation

Two of the major demands for remaining competitive in industry are reducing costs and increasing productivity. A new area of technology known as desk top manufacturing seeks to help industry meet these goals. This field reduces both the time and costs of developing and manufacturing a product. It makes possible the rapid production of prototypes by making them directly from a computer model, and thus provides the added benefit of rapid redesign. Some of the technologies in this field can be used to manufacture products, and thus have the advantage of allowing a wide variability in production with almost negligible lead times. Both the time and cost of special tooling are bypassed.

A new process known as Three Dimensional Printing accomplishes these goals by the rapid manufacture of ceramic shells and cores for metal casting and metal tooling for injection molding.

1.2 Three Dimensional Printing

Three Dimensional Printing makes possible the production of tooling and functional prototypes directly from a CAD model. Currently the process can print parts from a variety of ceramic and metal powders. The process can be used for prototype

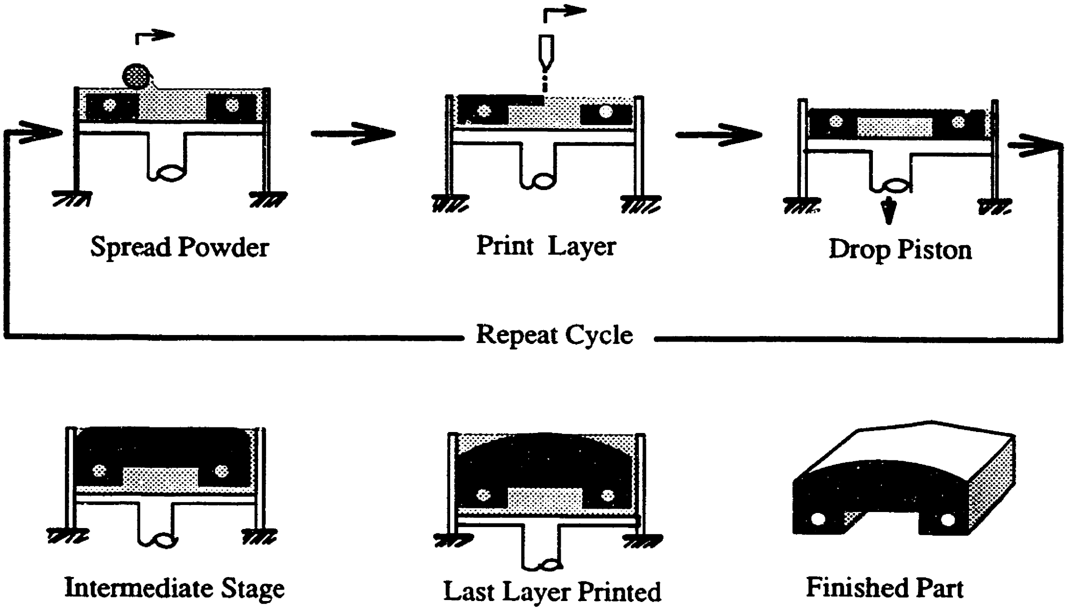

Figure 1-1: The Three Dimensional Printing Process

manufacturing, making one of a kind parts, or small batch manufacturing. Because of the short amount of time it takes to fabricate a part, design errors can be remedied without the cost in time and money associated with retooling. There are several applications for this process being investigated. Ceramic shells and cores for metal casting can be fabricated using Three Dimensional Printing. These molds would eliminate the tooling costs and long lead times associated with lost wax casting. Tooling for injection molding can be printed using metal powders. Finally, ceramic preforms for metal matrix composite (MMC) infiltrated parts can be manufactured.

The Three Dimensional Printing starts with a CAD model of the part to be constructed. A slicing program represents the model as a composite of two dimensional layers. The 3D-Printing machine than spreads a thin layer, typically less than 0.001", of the material to be printed over a powder bed. A printhead positioned by an x-y controller rasters over the powder bed and selectively binds the powder. After an entire layer is printed, the piston which the powder bed rests on is lowered. A new layer of powder is spread on top of the previously printed layer and the process is repeated. After the part is completed, it is heat treated and the excess unprinted powder is removed, leaving the part. The entire process is depicted in Figure 1-1.

1.3 Powder Removal

One of the advantages of Three Dimensional Printing over other rapid manufacturing processes, such as stereolithography, is the ability to make parts with complex internal geometries. This is because the part is printed in a powder bed, unlike stereolithography which prints in a liquid polymer tank. Therefore, a printed layer is supported by the powder underneath it, making overhangs and internal cavities easy to print. One negative aspect of this is the difficulty in removing the unprinted powder filling these cavities after printing.

After a part is printed, the excess powder must be removed before the part is complete. Excess powder can be removed from ceramic parts after they are fired. This is desirable because the post fired part is much stronger than the green part, and therefore damage is less likely to occur during powder removal. Powder on the external surfaces of the part is easily removed with a brush or by rinsing the part in water. However, unprinted powder filling internal cavities is more difficult to extract. Since ceramic parts will be used for metal casting, any excess powder left inside these molds might affect the quality of the casting. Therefore, it is important that an effective means of removing this powder be found.

Metal parts pose an even more difficult problem. Three Dimensionally Printed metal parts are fixed with a polymer binder, and the final part is sintered. The excess powder must be removed before sintering while the part is in its green state, and therefore weak. Excess metal powder left on the part will be detrimental to the final quality of the part. Therefore for metal parts, a method of effective post-printing powder removal is needed.

Chapter 2

Experimental Procedure

Effectiveness of powder removal is influenced by a number of factors. These include such things as the density of the powder to be removed, the geometry of the cavity the powder is in, the type of powder, the porosity of the printed part, and the grain size of the powder. In order to find the best powder removal method, many of these variables were held constant. A $30\mu m$ electronic alumina powder with a citric acid additive was used. This powder was chosen because it is currently the most commonly printed powder, and, since its a ceramic, the special problems of metal powders were avoided. The internal geometry that is most common but creates the most difficult challenge from a powder removal perspective is a cavity with only one exit. Most ceramic shells will only have one hole, into which the metal is poured.

2.1 Experimental Apparatus

There were several problems with conducting these experiments on actual 3D printed parts. First, the current 3D printing machine takes over 4 hours to print most parts. In addition, the green parts are usually fired and left in the oven overnight. Also, designing special parts to satisfy the experiments' requirements would take some time. Because, quite a few experiments needed to be conducted, this time delay was unacceptable. Another problem with using real parts was the difficulty in determining the effectiveness of the powder removal. It would be impossible to visually inspect

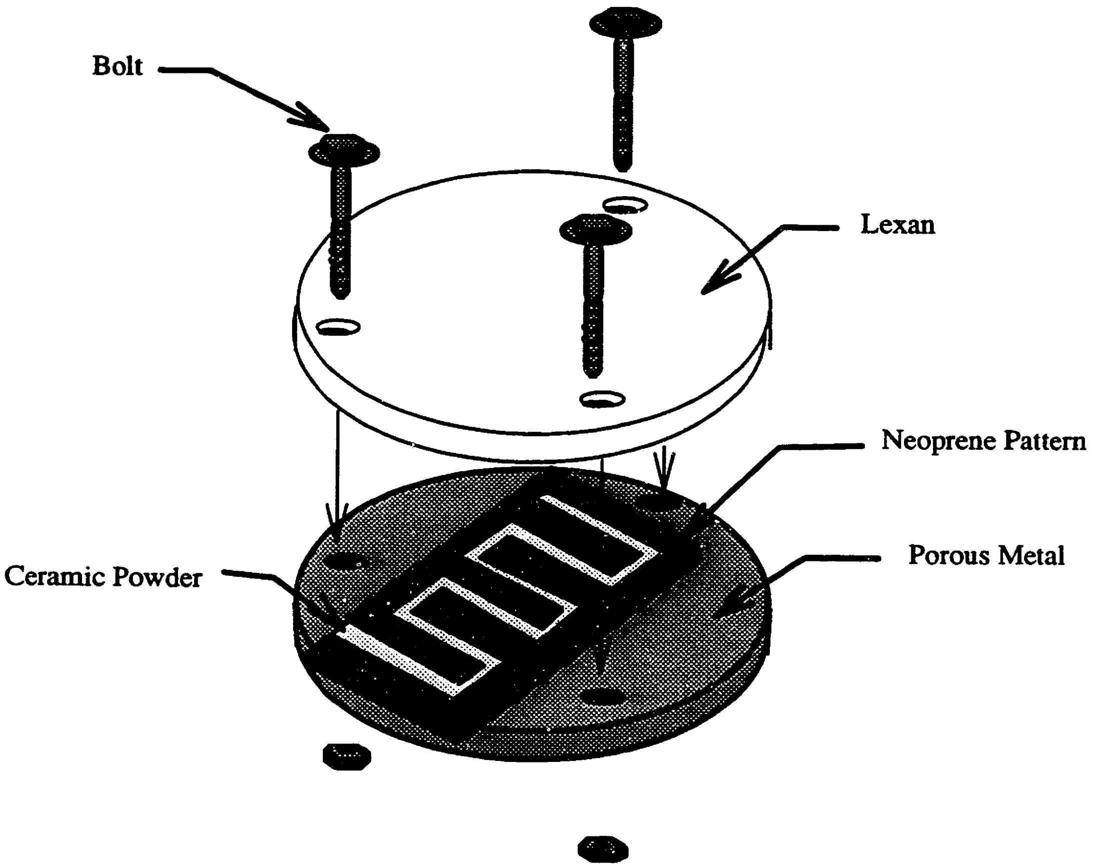

Figure 2-1: Experimental Apparatus

the inside of the part without destroying it, and by doing so the experiment might be compromised. Therefore, a method of simulating a 3D printed part was desired.

A simulation part required three attributes: visibility, porosity, and flexibility. Visibility requires that the powder in the part can be seen to determine the amount removed. The porosity of 3D printed parts simplifies powder removal. Because the powder is not packed too its full density and the water in the binder evaporates leaving spaces, the walls of 3D parts are porous. This porosity makes possible the mass flow of liquids and gasses into internal cavities through the walls of the part which can be used to move the powder. Finally, the simulated part should be able to represent different internal geometries, and be able to handle a variety of powder removal methods. These properties were accomplished using the apparatus shown in Figure 2-1.

Simple

Complex

Figure 2-2: Neoprene Geometric Patterns

Geometries of interest were cut into a piece of 1/16" thick neoprene. The cavity in the neoprene was filled with ceramic powder, and clamped between a piece of porous metal and a piece of transparent lexan. The porous metal was a 3" diameter x 0.25" thick piece of stainless steel with average pore sizes of 10μm. Pieces of 1/16" thick stainless steel with 20μm and 40μm pores were also used. Three 5/8" long 8-32 bolts were used to clamp the apparatus together.

Two basic geometric patterns were used for testing. The first offered some resistance to flow, but, if oriented with the exit point down, powder removal was assisted by gravity. The second pattern was too difficult for methods that relied on gravity alone to move the powder. These patterns are shown to scale in Figure 2-2.

Several methods were evaluated. These included: ultrasonicating, vacuuming, boiling, and microwave boiling. To conduct these experiments, the appropriate neoprene pattern was selected, the ceramic powder was spread into the cavities of the pattern, and the Lexan and porous metal pieces were clamped around the pattern tight enough to seal the powder. Finally, a method for removing the powder was attempted. The effectiveness of each method was assessed by measuring the time it took to remove powder, and visually evaluating the amount of powder removed.

Chapter 3

Results and Discussion

3.1 Ultrasonication

One common method of cleaning is ultrasonication. The ultrasonicator has a water tank in which high frequency sound waves are set up by piezoelectric elements in the body of the machine. These sound waves remove dirt from parts placed in the tank by vibration.

Initial experiments with ultrasonication had varied results. For these experiments the simple pattern shown in Figure and 10μm, 20μm, and 40μm porous metals were used. The alumina powder was loosely packed in the pattern. The apparatus was set in the ultrasound bath with the exit point of the pattern facing down. In only 20% of the experiments performed with the 10μ porous metal was all of the powder removed in about 30 sec. In the other cases, approximately 70% of the material was removed in the first minute and the rest was not budged by further ultrasonicating. The experiments with the 20μm and 40μm pieces were more successful. In 80% of the experiments, 95% of the powder was removed in the first 30 sec. However, in all of these cases over 70% of the powder fell out before the ultrasound was turned on. In the remaining cases, 1/3 or less of the powder remained in the pattern, usually at the top. There appeared to be two reasons for the powder that wasn't removed. The first was that the vibration caused by ultrasonicating was not initially vigorous enough to move the powder packed at the top of the pattern. The second was that small bubbles which formed due to the ultrasonicating moved up the pattern and blocked the flow of powder. These bubble dams could not be dislodged by further ultrasonicating or shaking the pattern manually.

Experiments performed with the complex pattern were even less encouraging. In the best cases only 1/3 of the powder was removed from the pattern. This was a result not only of bubble clogging but also because ultrasound relies mostly on gravity to move powder. Because of this, powder settled in the low spots of the pattern. The only feasible way of removing powder from a pattern of this geometry was to alternately turn it upside down and right side up. This was attempted but proved unsuccessful and tediously slow, taking over 10 minutes to remove even a little powder. Therefore, because of its lack of a mechanism to transport powder and cause powder flow, ultrasound was eliminated as a feasible method of powder removal.

3.2 Boiling

The failure of ultrasound illuminated the need for a method with an effective powder transportation mechanism. Large bubbles which formed near the exit point of patterns during ultrasonicating carried away significant amounts of powder when the jig was turned and they could escape. Therefore, methods which used large bubbles to push powder out of cavities were considered. The most obvious method of producing large bubbles was boiling water. The vigorous bubble formation caused by boiling water seemed ideal. If this bubble formation could occur inside a powder filled cavity, it would surely move some powder.

Initial experiments with both the simple and complex pattern proved very unsuccessful. The patterns were placed in a beaker, and the water was brought to a boil by a hot plate. In both experiments, over 80% of the powder remained in the patterns. The reason was simple, no bubble formation occured inside of the patterns. All of the bubbles formed on the exterior of the experimental apparatus and thus did nothing for the ceramic powder. This could be explained because the experimental apparatus and the ceramic powder itself acted as thermal insulators, and thus prevented sufficient heat flux from entering the part. Since part of the simulated part was stainless steel and thus a very good thermal conductor, it was assumed that an actual ceramic part would be even less likely to promote bubble formation. Therefore, pan boiling was dropped from the investigation.

3.3 Microwave Boiling

The source of failure with pan boiling was its inabillity to heat water inside of the part. This problem could be overcome by the use of microwaves. Microwave ovens work by rapidly vibrating water molecules which give off this excess energy as heat. Ceramics glass, and plastics transmit microwaves freely, and thus microwaving should be able to boil water inside the part.

Since metals reflect microwaves, the simulated part couldn't be used for experimenting with microwaves due to the porous metal and bolts. Therefore, an initial experiment was performed to determine how well microwave boiling could agitate a ceramic powder. A 10 ml beaker was filled with alumina powder, and suspended in a larger beaker filled with water, as shown in Figure 3-1. As a control experiment, the water was first boiled by placing the beaker on a hot plate. As expected, almost none of the powder was removed from the small beaker. The experiment was then repeated by placing the beaker in a microwave oven. After several minutes at high power, the water in the beaker boiled vigorously and 90% of the alumina was removed from the small beaker. The experiment was repeated several times with similar results.

With the feasibility of microwave boiling proved by this initial experiment, a modified version of the simulated part was required to perform powder removal from cavity experiments. The porous metal piece was replaced by a piece of porous fritted glass with pore sizes ranging from 25-50μm. This porous glass was attached with epoxy to a grooved backing plate made of Lexan. This backing plate served to support the glass while allowing water flow to it, and to allow the Lexan cover piece to be bolted to the glass. The metal bolts were replaced with nylon bolts. This apparatus can be seen in Figure 3-2.

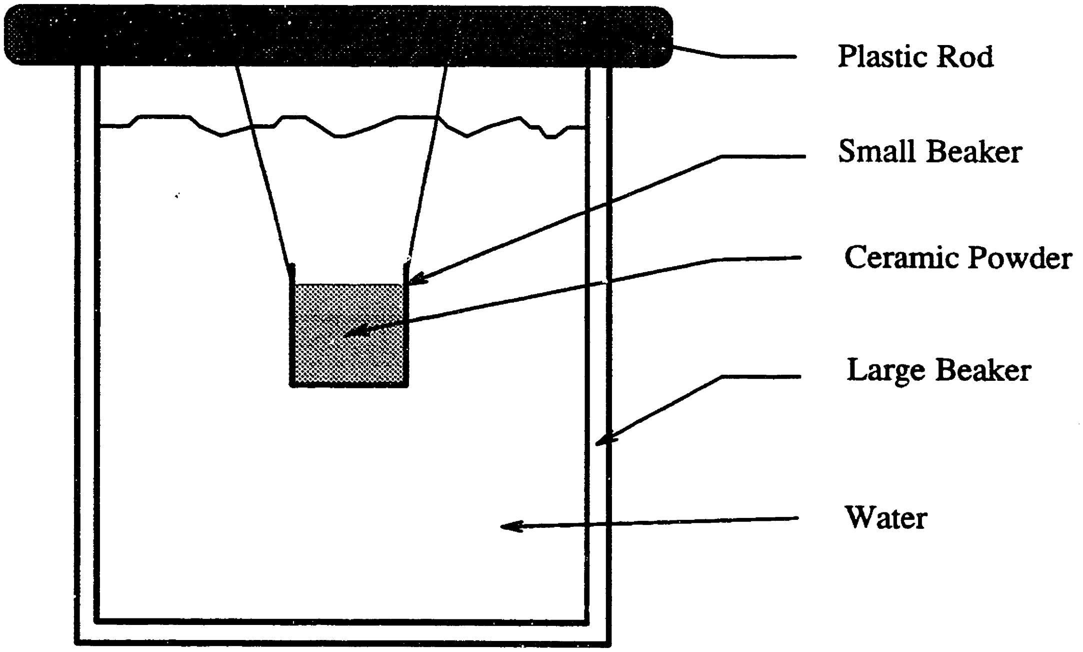

Figure 3-1: Boiling Experiment Apparatus

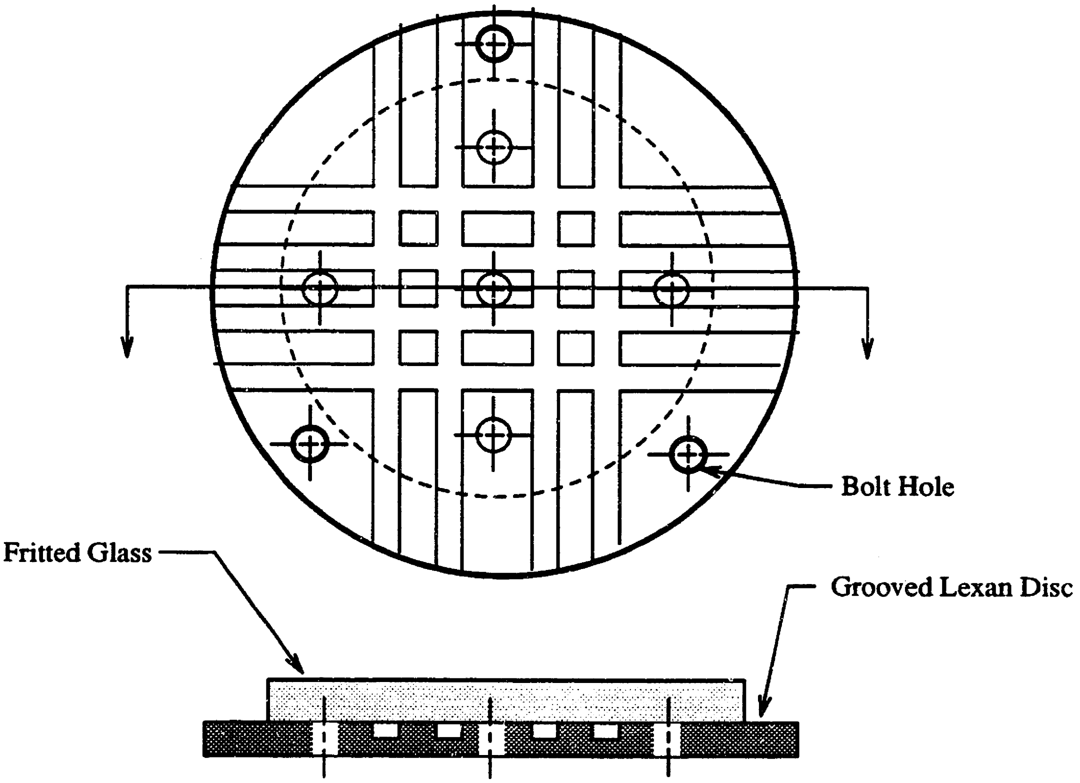

Figure 3-2: Simulated Part for Microwaving Experiments

Microwave boiling proved very successful in removing powder from both the simple and complex patterns. An intitial experiment was performed to determine the best orientation of the exit point of the pattern. simple pattern was placed in a beaker full of water with the exit point facing down and then again with it facing up. The microwave was set to high and the water was brought to a boil. Although, some powder was moved with the exit point down, the majority of powder remained in the pattern, because the bubbles remained in the pattern. However, when the experiment was performed with the exit point up, all of the powder was quickly removed. The experiment was repeated with the complex pattern. In only one or two minutes in both cases, 99% of the powder was removed. Bubbles forming within the pattern traveled up and out of the pattern carrying ceramic powder with them.

3.4 Vacuuming

Although microwave boiling was successful in simulation for ceramic powders, it isn't feasible for metal powders. Therefore, one other method of powder removal was investigated, vacuuming. Vacuuming relies on air flow through the porous walls of the part to move the unprinted powder out of the exit hole. The lab's vacuum cleaner was used to perform these experiments.

Initial experiments were performed with the original simulated part and $10\mu m$ porous metal. The $10\mu m$ porous metal part was chosen because it provided the most difficult test since it was the most resistant to air flow. The first tests were performed with loosely packed alumina powder filling the simple and complex patterns. A small diameter attachment was put onto the vacuum hose, and the vacuum was applied at the exit point of the pattern. These initial experiments looked promising. 99% of the powder was removed in under 3 seconds in all of the experiments performed with the simple pattern. Comparable results were obtained with the complex pattern, however in 25% of the attempts a small amount of powder was not initially moved from the end of the pattern. This powder almost always dislodged after the part was gently shaken, however, this behavior aroused questions about the effectiveness of vacuuming denser powder.

The theoretical density of alumina is 3.97 gm/ml. However, the alumina powder I used when loose had a density of 44% of this density. The highest density this powder can achieve through physical agitation is called its tap density density. For 30μm electronic alumina powder, this tap density is about 55% of the theoretical density. To measure the tap density of powders, a device was constructed by members of our lab. This device shook a sample of pattern vigorously, and was able to bring a powder to its full tap density in a couple of minutes. This device was used to bring the powder in a pattern to its tap density. The Lexan half of the simulated part with the neoprene pattern attached to it was connected to the vibrating surface on the shaking device. A pile of alumina powder was than placed on top of the pattern, and the machine was turned on. After several minutes of vigorous shaking, the simulated part was removed from the device. The excess powder was removed and the top half of the simulated part was then attached. The shaking device can be seen in Figure 3-3. Vacuuming had more difficulty with powder near its tap density. The time to remove powder from the simple pattern increased to around 10 sec. Likewise the time it took to remove all of the powcer from the complex pattern increased to 20-30 sec. and instances of powder clogging occurred 1/3 of the time.

These results suggest that, although successful for the size of the simulated parts, vacuuming may not be as successful on larger parts with deeper recesses. The air flow occuring at the deepest parts of a cavity would be insufficient to remove the unprinted powder lodged there. Heavier powders, such as the metal powders, would magnify the difficulty.

3.5 Comparison of Methods on 3D-Parts

Vacuuming and microwave boiling were performed on actual 3D printed parts to test the accuracy of the simulation. Two fired paddle shell parts were obtained for these experiments. A picture of this part, on the right, and a cast model of this part can be seen in Figure 3-4. Neither method was very successful. Both methods were able to

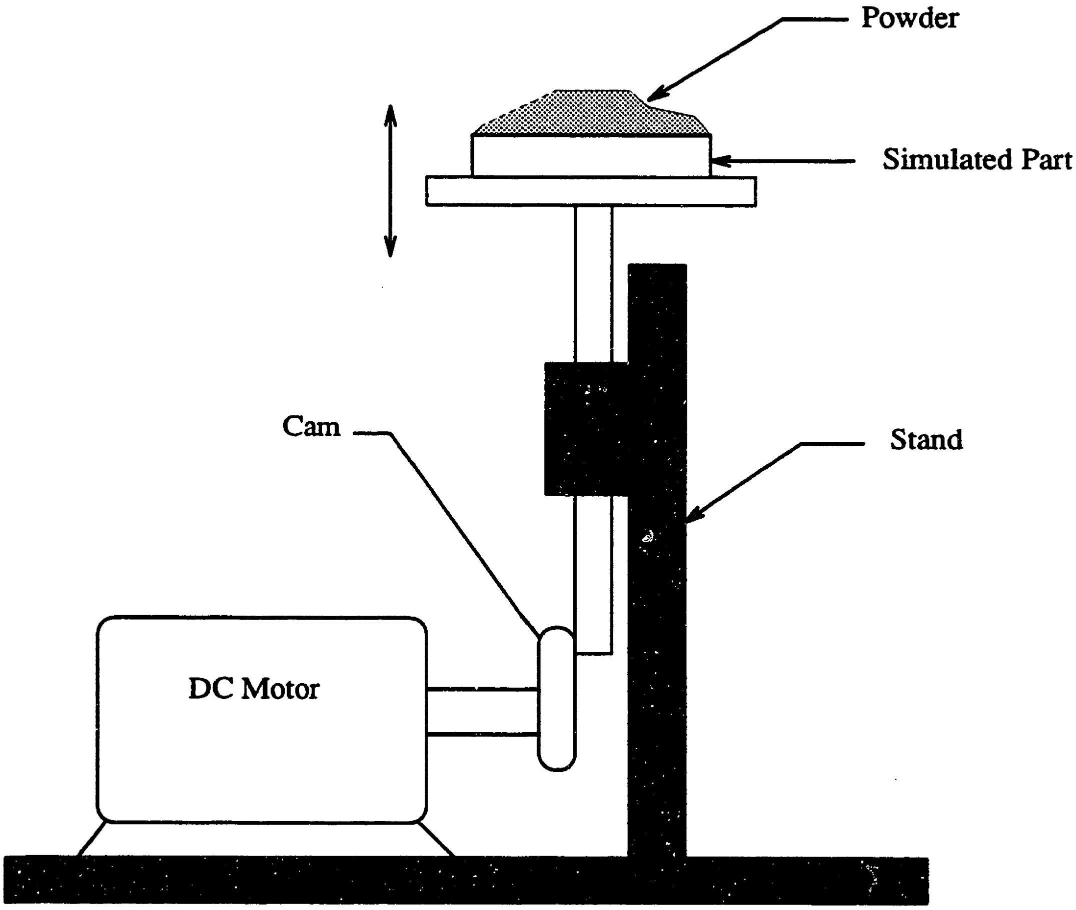

Figure 3-3: Tap Density Shaking Device

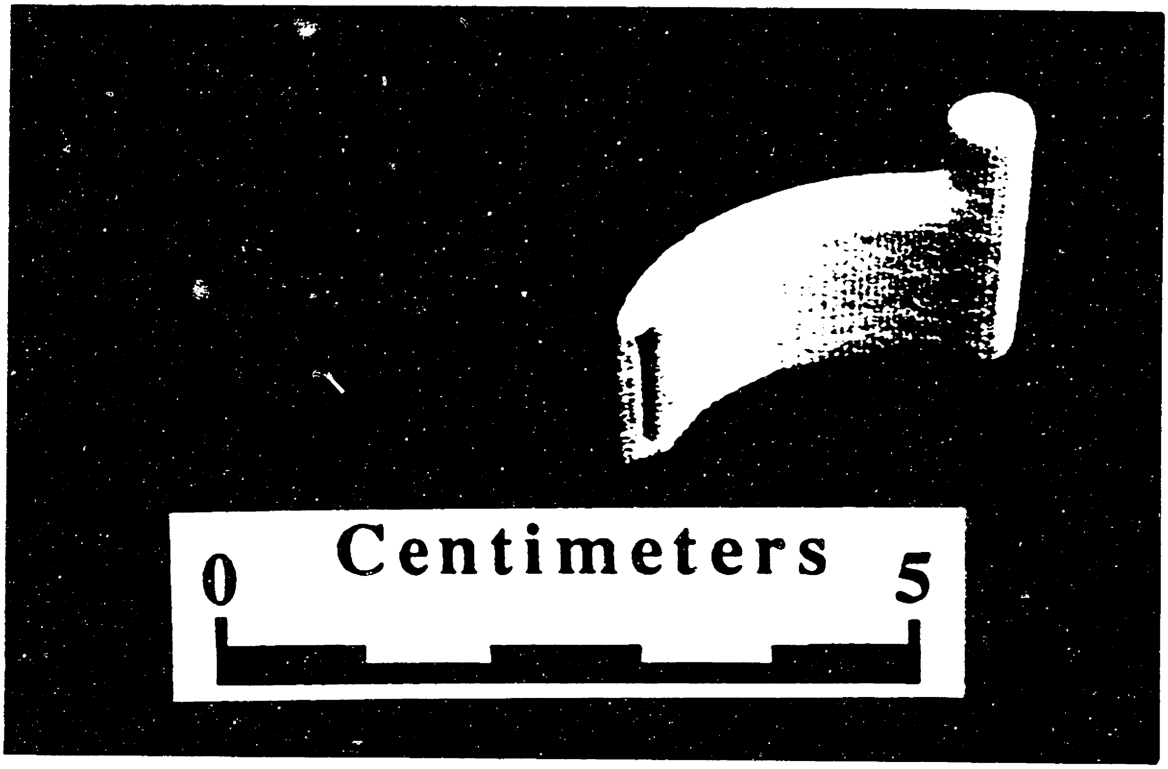

Figure 3-4: Paddle Shell

remove a majority of loose powder, however neither method came close to completely cleaning the parts. A clump of powder formed in the cylindrical recess of both parts, and neither method had any effect on it. The bubbles formed by microwave boiling traveled around the clot without moving it, and vacuuming proved less effective.

The major failure of the simulation appeared not to be an inaccurately simulated part, but rather a change in the physical properties of the powder after firing. This change might have been caused by the citric acid additive present in the ceramic powder. It was hypothesized that some reaction between the alumina and citric acid occurred during firing, which caused the powder to conglomerate and reduced its flowability. This proved the ineffectiveness of vacuuming denser powders and revealed a weakness of microwave boiling.

Chapter 4

Conclusions and Recommendations

Out of the methods investigated, microwave boiling shows the most promise for successfully removing excess powder from ceramic parts. This method was very successful in simulation, and moderately successful when tested on actual 3D-printed parts. The probable explanation for the problems with actual parts is a change in the physical properties of the ceramic powder after firing. The post fired alumina powder tends to form dense clumps, and it becomes much less flowable. This may be a result of the citric acid added to the powder to prevent bleeding of the binder. To combat this effect some combination of ultrasonication and microwave boiling might be explored. Although not very effective at transporting powder, the ultrasonicator is very good for breaking apart condensed powders. Also, a wetting agent might help, by allowing water to more easily penetrate these clumps, boil, and thus break them apart. Another suggestion is to lower the firing temperature of the parts, because it might reduce the clumping effect seen in the post fired part. Of course, none of these methods has provided an effective means for treating metal parts. Vacuuming was the most promising for this application, but its problems with dense ceramic powders imply that it will be even more ineffective with metals. Therefore, these issues should be explored further.

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