Powder Deposition and Sintering for a Two-Powder Approach to Solid Freeform Fabrication

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ABSTRACT

A two-powder approach is presented where Fused Deposition modeling (FDM) is used to create a thin shell in the shape of the part to be fabricated. The shell is filled with powder of the part material and surrounded by a support powder that has a high sintering temperature. Upon compressing and sintering the shell/powder system in a uniaxial hot press, the polymer shell burns out and the support powder compresses the part powder. The part powder consolidates into the desired part while the support material remains in powder form and can be easily removed. This paper presents results of initial experimental studies.

1. Introduction

Solid Freeform Fabrication (SFF) is a new class of manufacturing technologies that is characterized by layer-by-layer build-up of parts. These technologies promise to revolutionize manufacturing in many ways. Due to the layer-by-layer building approach, it is possible to create significantly more complex parts in one fabrication step than was previously possible. In addition, due to the relatively simple process planning required, the potential has been demonstrated to automatically fabricate a part under computer control given a solid model of the part. The first application of this technology was to create prototypes of designs for visualization and testing purposes. Hence this manufacturing technology is also referred to as *rapid-prototyping* technology. However, more recently the trend has been towards developing layer-by-layer fabrication methods that will directly produce either real parts or the tools / molds necessary to mass produce real parts.

To produce fully functional structural components, powder based approaches to SFF seem to be the most promising. This paper explores the possibility of merging fused deposition technology and powder based SFF technologies to create fully dense metal parts. Section 2 presents a brief overview of the current SFF technologies. The concept of creating parts using two different powders is explained in section 3, while section 4 explains the methodology for depositing powders in the desired fashion using shells created by FDM equipment. Section 5 contains results of experiments on the two-powder concept. Finally, section 6 gives conclusions and looks at challenges that must be overcome for the proposed process to become a viable technology.

2. Solid Freeform Fabrication technologies

Over the last decade, many different technologies for Solid Freeform Fabrication have evolved. The common factor that unifies all these methods is that they build parts by adding material layer by layer. This enables very complex shapes to be built in one step with minimal process planning. Therefore, these fabrications methods are able to build parts in a completely automated fashion under computer control. Broadly, the SFF techniques available currently can be classified as stereolithography, solid fusion and solidification, laminated object manufacturing, and powder based techniques (Kochan, 1993). These technologies are briefly described below.

Stereolithography Apparatus (SLA): The earliest solid freeform fabrication technology was based on stereolithography. It evolved in the 80s (Kodama, 1981), (Jacobs, 1992) and was first commercialized by 3D systems, Inc. in 1988. Stereolithography builds parts by solidifying a liquid photopolymer using a laser beam. Parts are constructed layer by layer by hardening the photopolymer using a laser beam that is projected in the shape of the cross-section of the part.

Fusion and Solidification: Many solid freeform fabrication technologies involve fusing and depositing material layer by layers. The technologies that fall into this category are:

(i) Fused Deposition Modeling (FDM): FDM involves depositing ABS plastic, wax, etc. through a nozzle (Crump, 1992). The raw material comes in the form of spools of wire. The material is heated and extruded through the nozzle so that it comes out in a paste-like fluid form. It solidifies quickly when deposited in a temperature-controlled environment. To construct complex shapes with overhanging features, support structures must be created. The support structures are also made of ABS plastic, but are deposited into shapes that easily peel off. These support structures have to be manually removed.

(ii) Ballistic particle manufacturing (BPM): BPM uses a piezo-electric jetting system to deposit droplets or particles of molten thermoplastic. This method also requires the creation of support structures, which are made perforated to enable easy removal. The BPM jet head is mounted on a 5-axis positioning mechanism and controlled by software to deposit material in the desired shape.

(iii) Shape Deposition Manufacturing (SDM): This method being developed at Carnegie Mellon and Stanford (Weiss, 1995), integrates material deposition and material removal. Layers of part material are deposited and machined to net-shape before additional material and further layers are deposited. Microcasting, a welding process, is used to deposit molten metal droplets for creating fully dense parts. In each layer, the part material is deposited in the shape of the part cross-section and the remaining area is covered using a support material which is etched away after the part is complete. For example, stainless steel parts may be made with copper as the support material.

Laminated Object Manufacturing (LOM): This method builds parts by gluing foils or sheets of material on top of one another (Feygin and Hsieh, 1991). A laser beam is used to cut the sheet into the desired shape of the cross-section. The material is stored as rolls of sheet material, which is unwound and routed over a platform on which the part is built. Sheet material is glued to the layers below by a heated roller. The laser beam then cuts the desired cross-section of the part. The material that is to be removed is cut into a cross-hatch pattern to facilitate easy removal.

In powder-based methods, powder is selectively consolidated into part and the remaining powder can be removed. One of the main advantages of powder based methods is that no support structures are typically required to create complex shapes. The main powder based techniques are:

(i) Selective Laser Sintering (SLS): In the SLS process (Kimble, 1992),(Nutt, 1991), a thin layer of powder is deposited in a workspace container and heated to just below its melting point. The powder is then fused together using a laser beam that traces the shape of the desired cross-section. The process is repeated by depositing layers of powder thus building the part layer by layer. The area that is not sintered remains as loose powder that can be easily removed after all the layers have been deposited. The materials that can be currently used for building parts are polycarbonates, investment casting wax, PVC, ABS-plastic, Nylon etc. (Nelson et al. 1993).

(ii) 3D printing: In the 3D printing process (Sachs et al. 1992), a binder material selectively joins powder deposited in layers. Ink-jet printing technology is used to print the binder in the shape of the cross-section of the part on each layer of powder. The powder is deposited on a platform that is lowered after each layer is deposited. After the whole part has been printed, heat treatment is required to consolidate the part. Regions where the binder was not deposited remains as loose powder and can be easily removed after heat treatment.

(iii) Freeform Powder Molding (FPM): This process is a two-powder method, similar to the one presented in this paper. Although, no specific method for powder deposition has been developed (Rock and Gilman, 1995), deposition of the powders through nozzles has been suggested. Rock and Gilman (1996), have presented application of this process for tool manufacture using metal powders. They use freeze molding to create the part shape where part powder mixed with an aqueous carrier is frozen in a suitable shaped mold. The freeze-molded part is then surrounded using tool powder and sintered.

3. Two powder part creation process

In the two-powder process (or FPM), two different powders are used as the part powder and support powder as shown in figure 1. The desired material for the final part is chosen as the part powder. The support powder is chosen such that it has a much higher sintering temperature than the part powder. The two powders are then selectively deposited (into a container or die) layer by layer. On each layer the part powder is deposited in the shape of the cross section of the part while support powder is deposited in the remaining area. Figure 1 shows a sectional view of the powders after deposition.

The part powder can be consolidated in a number of different ways depending on the actual material of the powders. Sintering at a high enough temperature will consolidate part powder due thermal diffusion effects (Rock and Gilman, 1995). This is feasible if the support powder does not sinter at that temperature. Sintering alone may not produce high-density parts. However, if the powders are compressed uniaxially within the die at a high temperature very high density is achievable as in the powder metallurgy process. Experimental study and theoretical modeling is required to fully understand the compaction and the associated shape change involved. Other ways of consolidating the part powder include mechanical pressure, chemical processes, addition of binder coating on part powder etc.

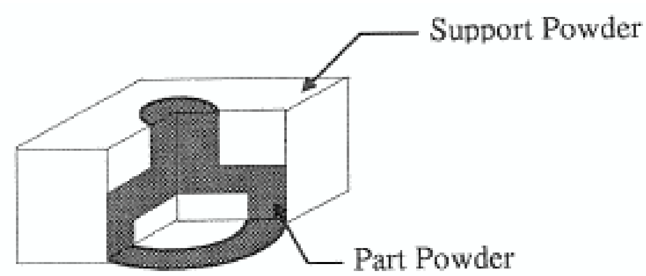

Figure 1: Two-Powder Based Freeform Fabrication

In order to experimentally study the feasibility of obtaining high density parts and to understand the shape changes involved we have studied a combination of metal part powder and ceramic support powder. These powders were deposited as shown in figure 1 into a die using a process described in the next section. The powders were then compressed and sintered in a uniaxial hot press at a temperature lower than the sintering temperature of the support powder. The envelope of support powder distributes (albeit not uniformly) the uniaxial pressure in a manner similar to a hot isostatic press (HIP). After cooling, the sintered, fully dense part could be easily removed from the unsintered support powder envelope. The details of the experimental results are described in section 5.

In order for the two-powder SFF process to produce quality parts with good surface quality, the two powders must be deposited with a clear interface separating the two. Typically, when a powder is deposited using a nozzle there is a heaping effect (such as the case in an hourglass). The line of powder tends have a domed cross-section instead of a flat layer. This heaping effect makes it very difficult to deposit two powders next to each other with clear interface separating the two. In the next section, we describe the use of a polymer shell to separate the two powders during deposition.

4. Implementation of the two-powder process using FDM

FDM (commercialized by Stratasys Inc.) is a Solid Freeform Fabrication technology that manufactures parts by depositing hot ABS plastic in layers of uniform thickness. The FDM machine consists of a temperature-controlled environment, which contains an extrusion head and a build platform. The extrusion head consists of two temperature-controlled nozzles, one for the part material and one for the support material. It has the capability to move horizontally (in the X-Y plane), while the build platform can move vertically (Z direction). The part nozzle is maintained at 270 F and the support nozzle is maintained at 265 F. Although both part and support material are ABS plastic, the support material is more brittle to facilitate easy removal during postprocessing. The software supplied with the FDM machine slices a CAD model (input as an STL file) into many cross sections at preset uniform distances.

FDM can be used to create a thin shell (approx. 0.015") of the desired part to be manufactured. This shell will serve as a clear interface between the part powder and the support powder. Once this shell is created, the inside of the shell can be filled with part powder and then placed into a container on a bed of support powder. Support powder can then be used to surround the shell to create a two powder - polymer shell system shown in figure 2.

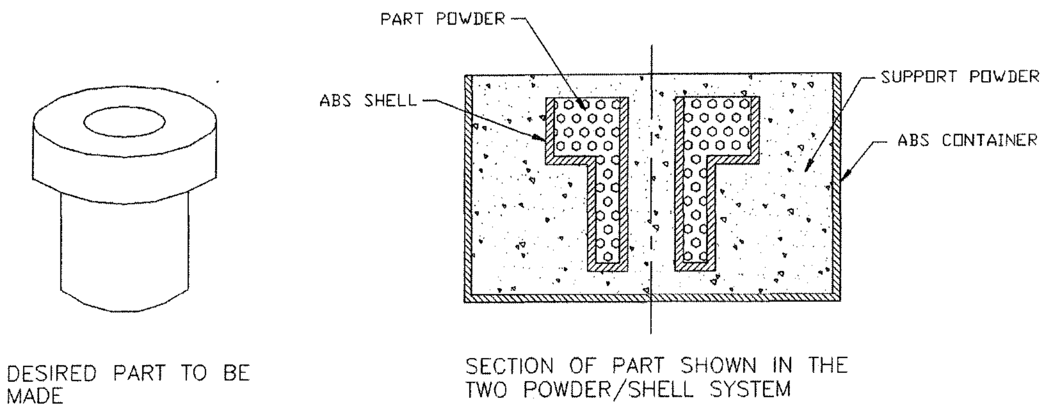

Figure 2: Two Powder-Polymer Shell System

The powder-shell system can then be transferred to a uniaxial hot press where it can be compressed and sintered. During the sintering stage, the polymer shell that contains the part powder will burn out and the support powder shifts to fill the void left by the shell. This requires that the support powder should flow readily under compressive stress. After the sintering and cooling process, the fully dense, sintered part can be removed from the unsintered, loose support powder.

If the process described above is automated by installing powder deposition system on to the FDM machine, then the two-powder approach could work as a solid freeform fabrication process. A two-powder delivery device can be fit on the FDM extrusion head so that the powder can be deposited at the same time that the shell is being built. The polymer container (see in fig 2) that holds the support powder would also be built at the same time. Therefore, on each layer, fused deposition modeling technique will be used to deposit polymer in the shape of the cross-section of the shell and the outside container. Then part powder will be deposited inside the shell, while support powder is deposited between the shell and the container. Finally, the powder layer can be made uniform by wiping excess powder off before starting the next layer.

Notice that both the part powder and the support powder can server as support material for holding up the layers of polymer shell. Therefore, polymer support structures are not needed for building the shell using FDM.

5. Experimental verification of the two-powder approach

The concept described in section 4 was tested using simple cylindrical shaped shell and container. The shell and container were created on a FDM 1650 rapid prototyping system. The powders were deposited manually. Copper powder of average size 45 microns (100 mesh), was used as the part powder. Titania and Alumina were tested as the support powder. Titania (TiO_2) powder used was approximately 0.25 microns while Alumina powder had an average size of 16 microns.

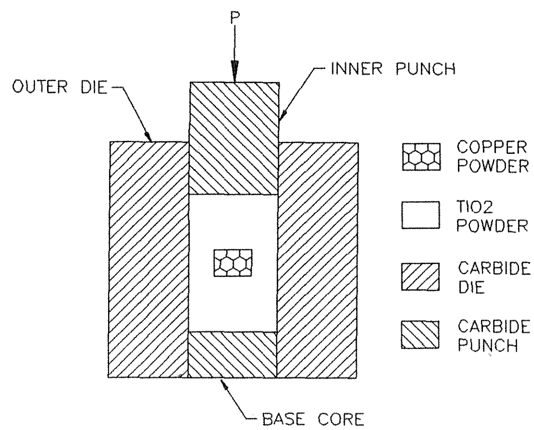

Figure 3: Schematic of Experimental Setup

The die in figure 3 has an inside diameter of 1-1/2" and the shell containing the copper powder was approximately 5/8" in diameter. The die/powder assembly was placed on a solid surface inside a uniaxial hot press. The press is capable of delivering the uniaxial load "P" while simultaneously heating the die using induction coils. A compressive load of 45 MPa was applied through the punch while the temperature of the die was held constant at 700 °C. The system was allowed to sinter for 20 minutes. During the sintering phase, the pressure on the die was maintained constant at 45 MPa. Subsequently, the die/powder system was allowed to cool for approximately three hours.

The compressed copper cylinder was removed and cut in half with a diamond saw. The cross section was then examined at 400X magnification. Although the inter-particle boundaries were slightly visible, the copper was approximately 97-99% dense. This positive result shows that the support powder did in fact transfer the applied load to the part powder effectively.

When titania powder was used as support powder, it did not stay as loose free-flowing powder. Figure 4, shows the image of the TiO_2 powder after compression and sintering under electron microscope. It can be seen that the support powder had necked and partially sintered. This is due to the extremely small size of the TiO_2 powder (< 1 micron) that was used, coupled with the large applied pressure. The necking and partial sintering can be greatly reduced through the use of larger sized powder. When large size Alumina powder was used as support powder, it stayed in powder form and was easy to remove. Large, mono-sized spheres deter mechanical locking due to their low packing factor. Spherical powder is also more fluid than irregular shaped powder due to the minimal contact area between adjacent particles. This will allow the support powder to more efficiently and uniformly distribute the applied load to the part powder. Lowering the sintering temperature will also help in decreasing support powder consolidation.

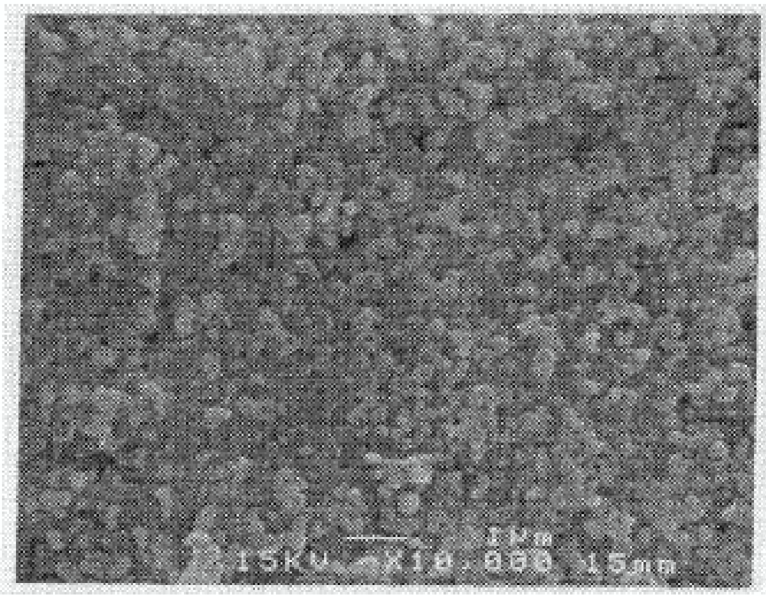

Figure 4. TiO_2 powder after compression and sintering

Significant compaction occurs due to compression and sintering. During this compaction, the part powder not only changes volume but also could change shape. One of the problems to be overcome is to minimize distortion and to be able to accurately predict the change in volume and shape. This is essential to be able to create parts that have desirable dimensional tolerance. Non-uniform deformation occurs in the powder near the die walls due to friction. Therefore, it is necessary to maintain a minimum separation between part powder and the dies walls.

6. Conclusions

The two-powder approach was found to be capable of producing high density copper parts when the powders were subjected to unaxial compression at high temperature. While this definitely demonstrates the potential of the approach for fabricating high density functional metal parts, it is obvious that much more research is needed to make this a viable process. Experimental studies are required to identify ideal temperature and pressure conditions for various powder combinations. It is also necessary to identify conditions that will ensure that the part powder undergoes uniform deformation during compaction. Methods need to be developed for depositing the powder in uniform layers. To manufacture dimensionally accurate parts, it is necessary to be able to predict deformations caused during compacting and sintering and scale the CAD model for the shell accordingly.

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