

A New SFF Process for Functional Part Rapid Prototyping and Manufacturing: *Freeform Powder Molding*

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ABSTRACT

Freeform Powder Molding¹ (FPM), a new Solid Freeform Fabrication process capable of directly producing functional parts from a wide range of structural materials, is presently being developed. This paper describes the fundamental process concept currently pending patent and provides early results demonstrating process feasibility. Materials used in process validation experiments include copper, iron, nickel, 304 stainless steel, and titanium. The process has the potential to meet the needs of both Rapid Prototyping and small lot-size manufacturing applications.

1. INTRODUCTION

Solid Freeform Fabrication (SFF) processes have developed at a rapid pace in the past decade with many systems now deployed commercially [1-4]. Case studies cite very favorable cost and time savings on the order of 30-95% — with 50% quite common — when comparing SFF techniques to conventional prototyping methods [5-8]. These savings typically apply to either form and fit prototypes or functional prototypes indirectly produced by a secondary conversion operation [9]. Numerous applications for this technology exist [6, 7].

The important niche of directly manufacturing functional prototypes is presently underserved. Some processes have partially bridged the gap between using SFF for pattern making and direct functional part manufacturing by directly producing limited-run tooling which can be used to indirectly produce functional parts [8, 10]. Other developing processes, including the FPM process disclosed in this paper, will lead to direct functional part manufacturing capability [11-14]. For many processes, the underlying process physics or implementations can be somewhat limiting with regard to the types and variety of materials that may be processed. Stereolithography serves as one example [15]. Additionally, most processes appear to be focusing on the fabrication of homogeneous material parts.

The capability to manufacture geometrically complex, compositionally controlled parts will stimulate revolutionary changes in design practice. Homogeneous parts will be replaced by parts with spatially tailored material properties and microstructures which more effectively meet the needs of increasingly demanding applications. The ability to embed sensors and actuators within parts during fabrication will bring about new dimensions in performance monitoring and active control capability, and it should be an enabling tool for the advancement of “smart structures” research.

Since FPM is an additive powder-based process, these capabilities can be realized if a variety of unique powders can be carefully formed into desired component shapes and subsequently processed to create a solid component with a controlled microstructure. Before discussing the FPM process concept, it is useful to briefly review some terminology and background material related to powder processing.

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1.1 Form and Functional Parts

Categorizing parts as either “form” or “functional” prototypes introduces ambiguity. For example, the properties of a polymer SFF product originally intended to model object shape may be capable of satisfying end-use requirements for a particular application. In this case, the part could rightly be considered a functional prototype even though it possesses inferior structural properties when compared to most metal or ceramic parts. Throughout the remainder of this paper, parts which are fabricated primarily because of their geometric characteristics are termed *form parts*. Parts which are fabricated to identically or closely match intended final-product properties are termed *functional parts*; however, in this paper final-products of interest are limited to structural metal and ceramic components [8].

1.2 Powder Processing

Metallic, ceramic, and composite components can be produced using powder processing techniques drawn from the fields of Powder Metallurgy and Ceramics Processing. In general, these techniques involve shaping and consolidating powder into useful components. Powder is typically shaped using hard-tooling such as steel compaction die sets or porous slip casting molds [16]. Consolidation is often achieved by sintering or hot isostatic pressing (HIP), which causes interparticle diffusion and thus a connection among neighboring powder particles [17].

Initial FPM research has focused on manufacturing metal components using Powder Metallurgy (P/M) techniques. P/M is commonly used to manufacture a variety of high-performance components in the automotive and aerospace industries, as well as to process materials that are difficult to fabricate using alternate methods. Parts such as transmission gears, connecting rods, valve inserts, bushings, self-lubricating bearings and electrical contacts are commonly produced using P/M. Unique materials, microstructures, and properties can also be achieved through P/M. Since it is an additive process, high material utilization is common. Additionally, cost is cited as a benefit when compared to conventional operations such as casting [16]. Tooling complexity limitations typically restrict P/M parts to certain classes of part geometry. If these limitations are overcome by employing an SFF process to eliminate the need for hard-tooling, many new applications should emerge.

1.3 Future Rapid Prototyping and Manufacturing Needs

SFF has facilitated substantial cost and time savings by producing form prototypes which can be used either as-produced or serve as patterns for secondary processes capable of manufacturing functional prototype parts. Manufacturing functional prototypes using an SFF pattern and a secondary process has drawbacks. Increased process complexity extends processing time and, as more conversion operations are performed, additional errors may be introduced which compound and result in lower final product quality. Direct production of functional parts, by a simple and automated procedure, will minimize these problems. The FPM process provides one method for directly fabricating functional parts.

2. FREEFORM POWDER MOLDING

The Freeform Powder Molding (FPM) process described in this paper is a novel SFF process capable of directly producing functional metal, ceramic and composite parts as well as compositionally controlled structures. Because it removes traditional “single-material” design constraints, FPM should revolutionize product development by allowing designers to create advanced engineering structures with spatially tailored material composition. Parts with embedded sensors, actuators and electrical interconnects which are fabricated with, rather than being added to, each part can also be produced in this manner. Successful development and commercialization of FPM will have a significant impact on the future of mechanical and electro-mechanical design and manufacturing.

2.1 Fundamental FPM Principle

The fundamental principle underpinning FPM is that different powders have different diffusion kinetics and will therefore respond differently to identical thermal, chemical, and

mechanical conditions. By selectively arranging these different powders within a confining volume, it is possible to create a part whose geometry is defined by the interface between powder which consolidates at prescribed conditions and powder which does not. Powder which consolidates at prescribed conditions is termed *part powder*, and powder which does not consolidate at these same conditions is termed *tool powder*. Figure 1 illustrates such an arrangement for a simple open-ended tube by showing a cut-away view of a confined powder volume and a part which would result after processing.

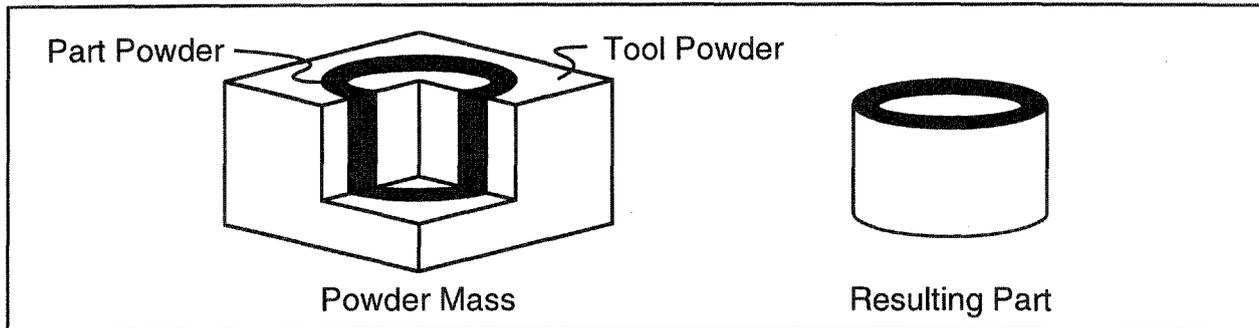


Figure 1 - Example of Object Shape Defined by Powder Interface

The tool powder serves both to define shape, in conjunction with the part powder, and to support the part powder. In essence, it can be thought of as “soft-tooling” which replaces the costly hard-tooling used in conventional P/M. After the powder mass has been created, it can be processed so that part powder particles join together. Sintering, for example, can accomplish this by exposing the powder mass to a sufficiently elevated temperature, thus promoting interparticle diffusion. It is important to emphasize that regardless of the final consolidation operation employed, it is the careful arrangement of part and tool powders which defines final component shape.

Since consolidation takes place after the entire powder mass is created, problems with residual stress build-up common with localized processing operations are avoided. Material waste is minimized because all part powder is used to construct the final product, and tool powder can be easily recycled. This is particularly important when costly, high-performance materials are being processed. Additionally, since FPM is a binderless process, difficulties associated with de-binding are not experienced. Many other benefits of powder processing also apply.

2.2 SFF Approach

The Layerwise Manufacturing Techniques [18] common to many SFF processes provide a useful paradigm for creating a computer-defined powder mass constituting a variety of powders such that the FPM concept can be employed. By constructing a powder mass in a layer-wise fashion as illustrated by Figure 2, it is possible to realize complex geometrical structures.

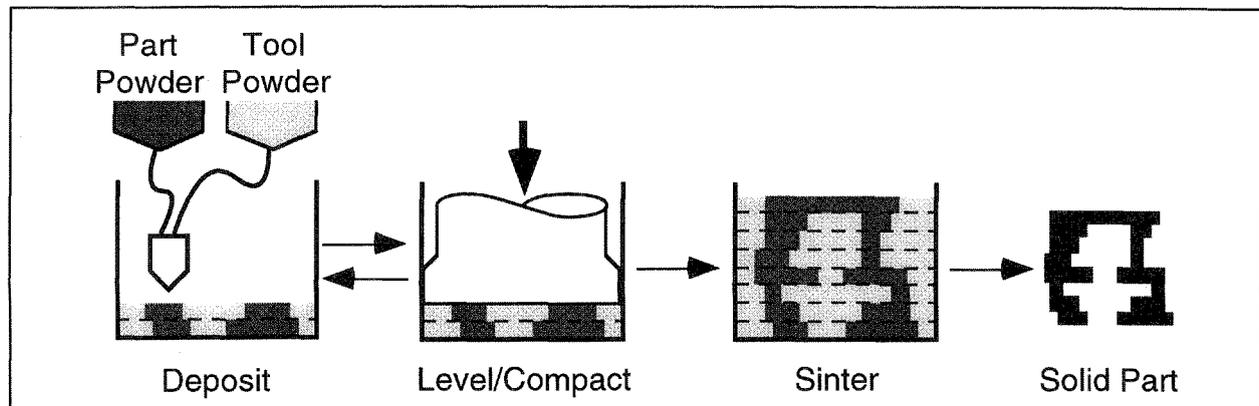


Figure 2 - Conceptual Overview of Freeform Powder Molding Process

Part and tool powders must be selectively deposited onto a planar substrate within a confining volume in accordance with CAD solid model cross-sectional information [19]. Part powder is deposited where solid mass is modeled and tool powder is deposited in the remaining regions of the layer to form a complementary shape. After all powder for a given layer is deposited, it is leveled, and possibly compacted, to create a planar surface for subsequent deposition operations. This build-up is repeated until all layers comprising a part have been deposited and leveled. Only then is the powder mass exposed to conditions necessary to induce selective sintering of the part powder. After sintering, the confining vessel can be inverted, thus causing the tool powder to pour out and the consolidated part to be readily accessible.

2.3 Alternate Consolidation Operations

Alternate consolidation operations, either in conjunction with or instead of sintering, may be selected to achieve desired final component properties. Some potentially applicable operations include: cold isostatic pressing (CIP), hot isostatic pressing (HIP), infiltration, and impregnation [16]. It is also permissible to allow the tool powder to sinter or become solid during processing if it remains separable by a subsequent operation, such as etching or brittle fracture.

In addition to consolidation operations classically associated with powder processing, it may be possible to selectively induce consolidation of part powder by using only mechanical or chemical stimuli. The first FPM proof-of-concept experiment was conducted using PTFE (Teflon) and paraffin wax powders with selective consolidation achieved using only mechanical pressure. It may also be possible to achieve FPM part fabrication by exposing a multi-material powder mass to the appropriate chemistry (gas or liquid) such that the part powder fuses together while the tool powder remains free.

2.4 Spatially Controlled Composition

Practicing FPM requires that both part and tool powders be precisely controlled and deposited to create a powder mass. The same technology which meets this requirement should prove useful for controlling and depositing multiple part powders so that spatially controlled composition parts may be fabricated. Composition may change either discretely or in a continuous fashion throughout three-dimensional space. This will enable the production of composite parts and parts with locally tailored material properties. It should also be possible to construct electrical interconnects, sensors, and actuators by employing an appropriate organization of certain metal and ceramic part powders. For instance, embedded strain gauges, thermocouples, piezoelectric vibration sensors, and piezoelectric actuators could be fabricated within a component.

Constituent part powders can be composed of powders with different chemical composition or of the same material with different powder characteristics. For example, since powders of different particle size sinter at different rates, it should be possible to tailor microstructure by the selective placement of different sizes of the same part powder.

2.5 Other Powder-Based Processes

Several processes with promise for directly fabricating functional parts are powder-based. Selective Laser Sintering (SLS) is being adapted to create metal parts by employing binder coated powders [10, 14]. An SLS variant can directly sinter metal powder using laser energy [20]. Laminated Object Manufacturing (LOM) is being modified to operate on “green sheets” of ceramic powder [21]. Directed Light Fabrication (DLF) creates fully-dense solid parts by melting powdered metal delivered to the focal zone of a laser [13]. Three Dimensional Printing (3DP) can directly produce functional parts by selective application of a binder onto a powder substrate [12]. Thermal spray shape deposition (MD*) creates objects by plasma spraying successive layers of powdered metal through shape-defining masks [11].

While some of these processes define object geometry by selectively adding energy or other matter to bulk-applied raw material, others selectively add material and bulk-apply the energy or stimuli necessary to effect consolidation. Each approach has unique benefits and limitations;

however, processes which selectively place raw material, such as FPM, appear to be most suitable for creating spatially controlled composition structures.

3. PRELIMINARY RESULTS

Preliminary experimental results demonstrating Freeform Powder Molding proof-of-concept are encouraging. Parts made of copper, iron, nickel, 304 stainless steel, and titanium were consolidated either by sintering or hot isostatic pressing. The complete path “from art to part” has been demonstrated for homogeneous material parts. A CAD model created using Pro/Engineer, shown in Figure 3, has been exported as an STL file.

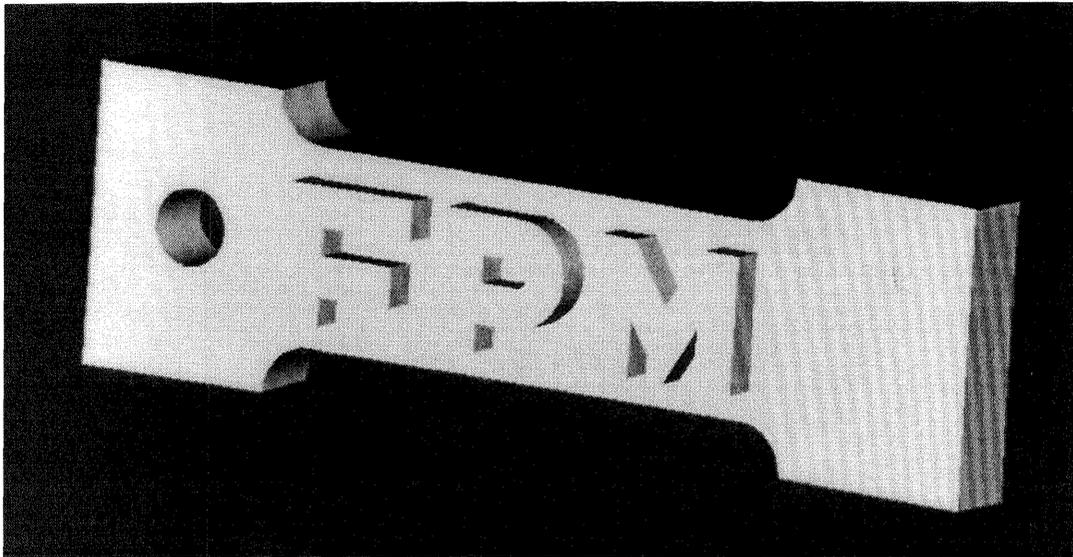


Figure 3 - Example CAD Model

This file was validated and converted to RPI format [19], the geometry was sliced into cross-sectional contours corresponding to the thickness of each powder layer being used to fabricate the part. Successive powder layers were deposited in a ceramic furnace boat with part powder located where solid material was represented by each slice contour and tool powder located in the remaining complementary regions of the container.

Alcan grade 155A copper powder served as part powder. Norton 199A ultra-pure alumina served as tool powder. The intra-layer leveling/compaction operation illustrated in Figure 2 was omitted in this experiment. After the powder mass was created, it was processed in a reducing atmosphere at a temperature of 900°C for 3 hours. This caused the copper powder to sinter and form a solid part approximately 85% of theoretical density. The alumina did not sinter and was easily removed to expose the resulting part, shown in Figure 4.

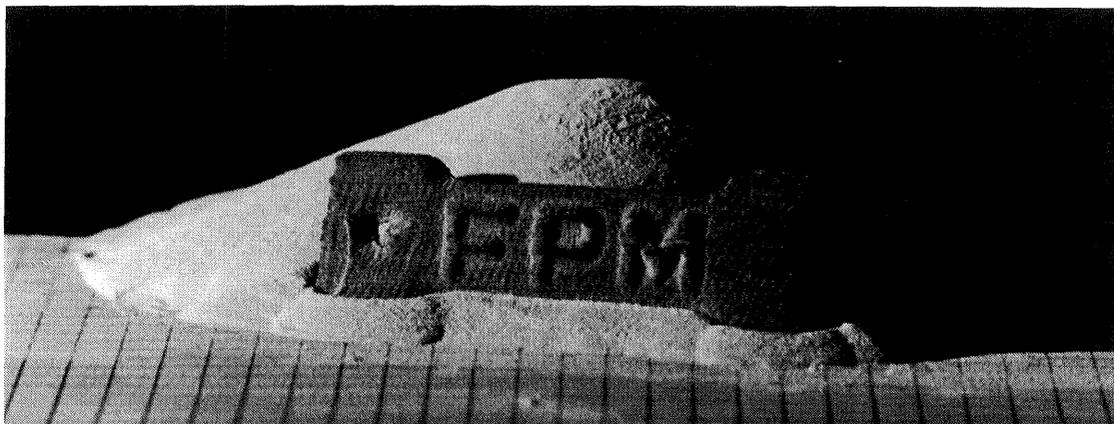


Figure 4 - Resulting FPM Part

Examination of this metal part highlights the need for significant improvement to the existing process implementation. Sharp corners in the CAD model have become rounded features in the resulting part. Relatively large layer thicknesses result in very rough surfaces normal to the layer-wise build plane. There are certainly many parameters which are subject to further investigation and control.

The part shown in Figure 5 has been fabricated using the same copper powder as the layer-wise FPM part shown in Figure 4. This illustrates an upper limit to the level of detail and quality one may reasonably expect given the current process definition, raw materials, and operating point.

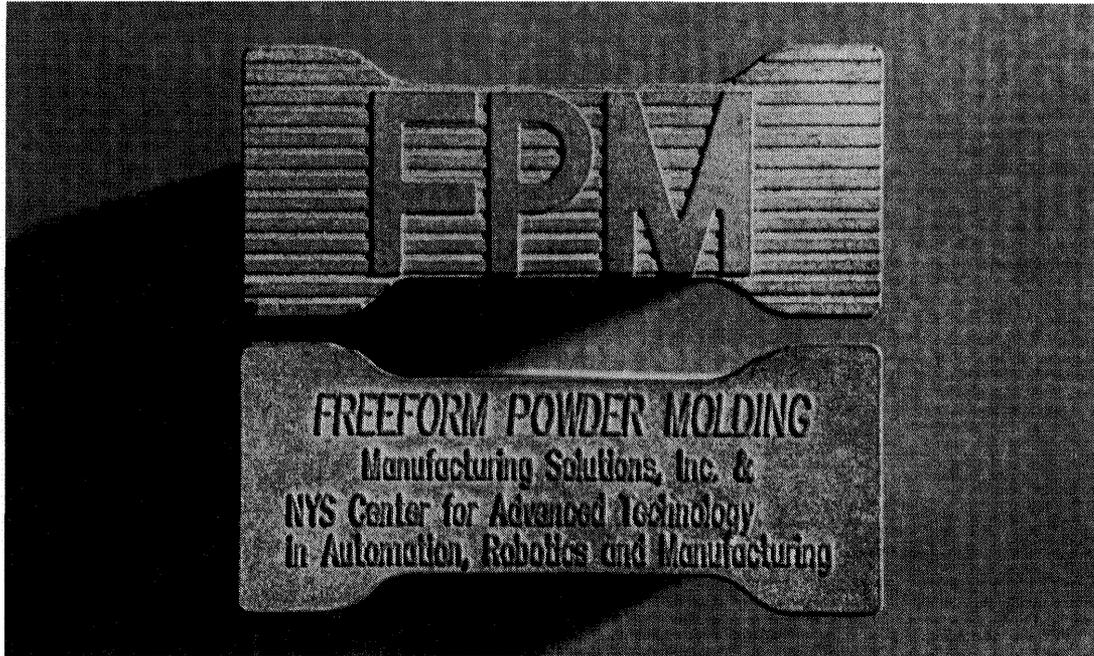


Figure 5 - Front and Back Views of a Molded Example Part

This part was shaped using a molding technique and subsequently surrounded by tool powder to simulate the conditions of layer-wise FPM. It was processed at conditions identical to the part of Figure 4 and illustrates that a significant quality improvement is possible for the layer-wise part.

4. CONCLUSION

SFF has been repeatedly applied with great success, reducing time-to-market and development costs for mechanical parts and systems. First generation non-structural SFF parts remain useful for modeling object form. These parts have also been effectively used as patterns for secondary conversion processes to indirectly manufacture functional parts. This practice will continue to have utility well into the future, but commercially available *direct* functional part manufacturing capability via information driven SFF processes — combined with the ability to spatially tailor material composition within a part — will elevate design and manufacturing competitiveness to new levels.

FPM is one process capable of spatially controlled composition, direct functional part fabrication. Although preliminary results are encouraging, several technical challenges remain to be overcome: the precision, accuracy, and speed with which a powder mass can be created must be improved; further research on the fabrication of compositionally controlled structures — both spatially continuous and discrete — must be conducted; alternate final consolidation and post-processing strategies must be investigated; and methods of controlling or compensating for part shrinkage must be determined. When these challenges are surmounted, it is anticipated that FPM will provide a cost-effective method for the rapid manufacture of compositionally controlled

functional parts, directly from CAD model information and using a large variety of engineering materials.

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