Advances in Multiple Material Solid Freeform Fabrication

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Abstract

Due to their layer-based nature, Solid Freeform Fabrication (SFF) techniques offer the possibility of fabricating parts in which the material properties vary in three dimensions. Such a capability promises to allow engineers components and parts that are truly optimized with respect to material properties. This presentation discusses research at The University of Texas at Austin to develop a multiple materials capability for one SFF technique, selective laser sintering. Efforts to develop a representation for heterogeneous solid parts are described, and predicted methodologies for heterogeneous part design will be discussed. The status of efforts to realize a multiple material SLS workstation will then be reviewed.

1 Introduction

We believe that layer-based fabrication techniques, which have been termed Solid Freeform Fabrication (SFF), offer the possibility of exciting new manufacturing techniques for applications that can benefit from multiple material componentry. Imagine what would be possible if we could control the material composition of a part at any point in three dimensions. Over the past four years, we have challenged many designers in a variety of industries with this prospect. The answers we received have convinced us of the value of develop multiple material SFF.

In particular, we have identified two types of applications. In the first, the part consists of two (or more) materials that do not mix (e.g., conductors and insulators). We have termed this type of application “discrete multiple material” SFF. In the second class of parts, the materials are mixed in a variety of continuous concentrations. These materials systems have been termed “functional gradient materials” (FGM) in the literature. FGMs will be manufactured by continuous SFF. The material gradient may be one-, two-, or three-dimensional.

Research in the Laboratory for Freeform Fabrication at The University of Texas at Austin focuses on development of the Selective Laser Sintering (SLS) process. SLS uses a laser to selectively melt a powder layer to create the cross-section of a part (see Figure 1). Once the layer is completed, a new layer of powder is deposited by a counter-rotating roller and scanned such that not only is the next cross-section created, it is also fused to the previous layer. As successive layers are scanned this way, a three-dimensional part is fabricated. The SLS process is licensed to DTM Corp., Austin, TX.

Multiple material SLS will require development in three areas. The first is a modified material delivery system. The current roller-based system is designed for handling a single type of powder. The second development necessary for multiple material SLS, as well as other multiple processes, is a representation of the material distribution in the part. The third area of development focuses on identification of compatible material systems that can be processed by SLS and that meet customer requirements. In this paper, we report on our progress in these three areas.

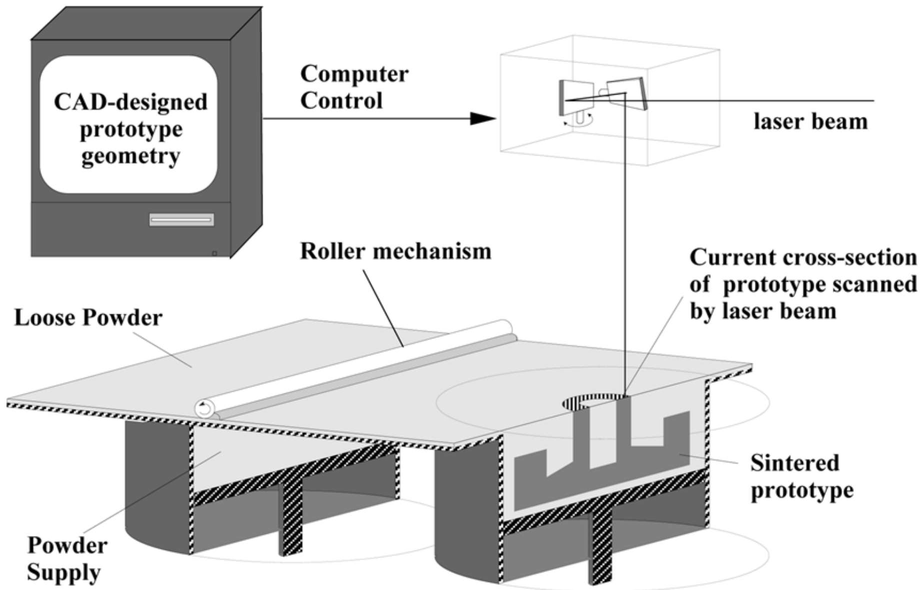

Figure 1. The selective laser sintering process.

2 Material Representation by Volumetric Multi-Texturing

Most commercial solid and surface modelers represent parts as homogeneous solids. Currently, these tools only provide support for attaching material information as a simple annotation to lumped regions for rendering and mass property calculations (e.g., mass and moment of inertia). Such schemes are not sufficient to define volumetric properties of parts. In this section we present a method by which continuous material distribution information can be associated with conventional geometric representations.

2.1 Related Work

Kumar and Dutta (1998) first introduced the concept of a material subset, (r_m-set), where a material dimension is added to the spatial dimensions. The complete material space is constructed by combining these r_m-sets through Boolean operations. Recently proposed models for specifying r_m-sets are based on two approaches: interpolating functions and discrete density data sets. Several trivariate function forms have been proposed to describe the spatially varying material gradient (Marsan and Dutta, 1998; Jackson *et al*., 1998). These functions can be categorized as either parametric or implicit representations. Both types have advantages and disadvantages, depending on how they are to be utilized for material processing. As a three dimensional extension of surface discretization, voxel-based and volumetric mesh schemes to store material density data have been extensively researched. Pegna and Safi (1998) proposed a representation method of spatially varying data by extending volumetric meshes used for finite element analysis (FEA). Their suggestion was that the nodal point set in the FEA mesh that models the physical state of a part could be used to model a spatially varying material distribution as well. This approach not only provides a means to store material data but also provides an interface to material gradient design using FEA. Kumar and Wood (1999) and König and Fadel (1999) have proposed similar approaches.

2.2 Procedural Approach

The major requirement of a material distribution representation is providing exact values at any given spatial point inside the solid. To meet this requirement, we choose an implicit procedural scheme. In this approach, a global implicit material space defined in a geometry space G^3 is generally represented by a set of procedural functions F_m with the following conditions:

$$F_m^i(\vec{p}_{int}) = d_p^i,$$
$$\sum_{i=1}^{n} F_m^i(\vec{p}_{int}) = \sum_{i=1}^{n} d_p^i = 1.$$

$\vec{p}_{int}$ = an interior point
i = material index
n = number of materials
d_p = density at $\vec{p}_{int}$

The function F_m^i does not explicitly or parametrically describe the pattern. However, the information does exist procedurally and implicitly, and is obtainable by querying for the density of $\vec{p}_{int}$ in the material space M^3. Since the material composition at any point $\vec{p}_{int}$ must sum to 1, n-1 functions F_m^i are sufficient to constrain M^3. Each F_m^i consists of a number of sub-functions, f_m that influence a query point $\vec{p}_{int}$. The number of required f_m's can vary throughout the part's geometry. A region composed of a single material may require no sub-functions. Interior regions near corners or edges may be composed of many contributing sub-functions. These sub-functions interact with each other as multipliers or through blending operations. The f_m's are thus wrapped together as a single procedure, and the wrapped procedure is only visible to users in the form of level sets of $F_m^i(\vec{p}_{int}) = d_p^i$.

2.3 Volumetric Texture Mapping

Our approach is based on volumetric texture rendering schemes in computer graphics (Ebert *et al*., 1998). Such schemes are very effective at representing fuzzy objects such as cloud and smoke. By analogy, FGM design can be visualized as the creation of material clouds in a confined geometric space in a structured and controllable manner. Another motivation for pursuing this approach is that, based on our research into expected applications, material gradients will be emphasized near the surfaces of a part. This is because many FGM applications are meant to replace or improve the surface coatings on components designed for severe thermal and mechanical stress environments. Hence, from the user's point of view, it is logical to optimize the design scheme for surface-to-interior material gradients.

Geometric gradient information is determined and controlled interactively by a density modulation function, which is used to modulate an object's density within its material space. The DMF used in this work consists of several procedural bias, gain, and noise functions that are the base level functions that higher order DMFs are build upon. These functions are used to control various aspects of an object's material distribution characteristics.

The bias function is mainly used to either push up or pull down an object's density around the middle of the fuzzy region[1]. The bias function is defined as $t^{\frac{\ln(b)}{\ln(0.5)}}$. By varying b, the values in an object's fuzzy region can be biased up or down smoothly (Perlin, 1989).

The gain function can be effectively used as an intuitive method to control whether a function is contained mostly near its middle range, or, conversely, near its extremes. As a result, the density distribution can be tweaked to be either flatter or steeper across the fuzzy region. The gain function over the unit interval, for example, can be defined as follows.

$$gain(0) = 0; \qquad gain(0.25) = 0.5 - g/2;$$
$$gain(0.75) = 0.5 + g/2; \qquad gain(1) = 1;$$

By controlling the value of g, the rate at which the midrange of an object's fuzzy region goes from 0 to 1, can be increased or decreased (Perlin, 1989).

The function is mapped onto the pre-determined material subspace domain that contains the graded portion of the secondary material only. If a discontinuous or isolated material distribution is needed, more material subspace would be created. The material gradients with different bias and gain factors are shown mapped onto a simple geometry in Figure 2.

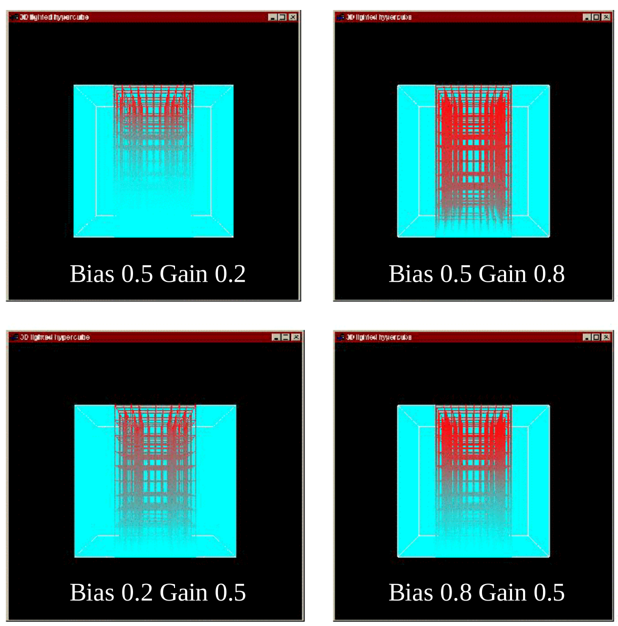

Figure 2. Material gradient for different values of bias and gain.

For cases where the material information is supplied as discrete data (e.g., directly from finite element analysis), the DMF consists of a polynomial interpolation that interpolates the data points in a mathematical form. One of the most popular bases for such polynomial approximation is the *Bernstein-Bézier* basis. The basic formulation is as follows:

[1] An object's "fuzzy region" is the interior region over which the constituent material's volume fraction varies (from 0.0 to 1.0).

$$P(x,y,z) = \sum_{i=0}^{m} \sum_{j=0}^{m-i} \sum_{k=0}^{m-i-j} W_{ijk} B_{ijk}^{m}(x,y,z)$$

$$B_{ijk}^{m}(x,y,z) = \binom{m}{ijk} x^{i} y^{j} z^{k} (1-x-y-z)^{m-i-j-k}$$

2.4 Application Example

FGMs of ceramic and metal materials can be employed in advanced dental and medical applications, mainly as implants and replacements. As bioceramic materials, such as calcium phosphate, favorably bioreact with existing bone, they can serve as porous media to support the ingrowth of new bone tissue, which results in permanent bonding with the body. The strength and life of implants can be improved by applying biocompatible metal such as titanium for the core of the implant.

A simplified human femur implant for a hip socket is shown in Figure 3. The model was created using blending and unions of implicit spheres and ellipsoids (a so-called "blob" model). Detailed features were added by feature based Boolean operations.

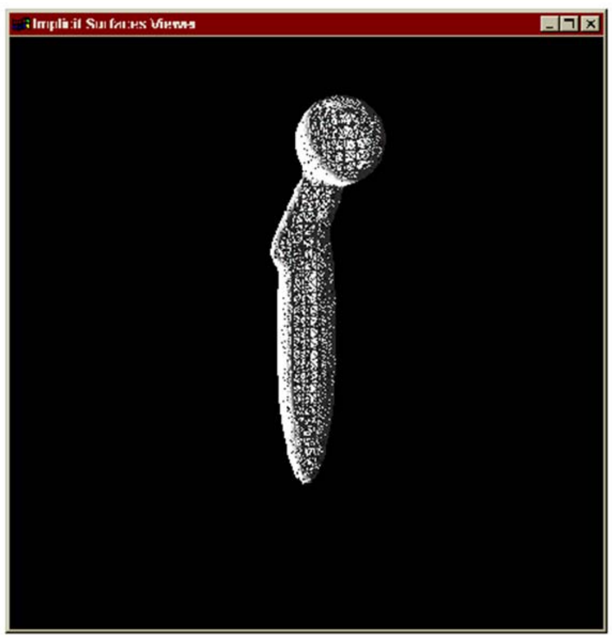

Figure 3. Implicit model of femur implant.

The same algebraic surface in implicit form was used for both the geometric and the material subspaces. The gradient region in the material subspace is specified as a function of radius within the range of the material subspace. Therefore, the material distribution has constant depth of a primary material shell. Localized distribution also can be achieved by modifying the blob model for the material subspace. The material gradient and a cross section along the z-axis of the implant are shown in Figure 4.

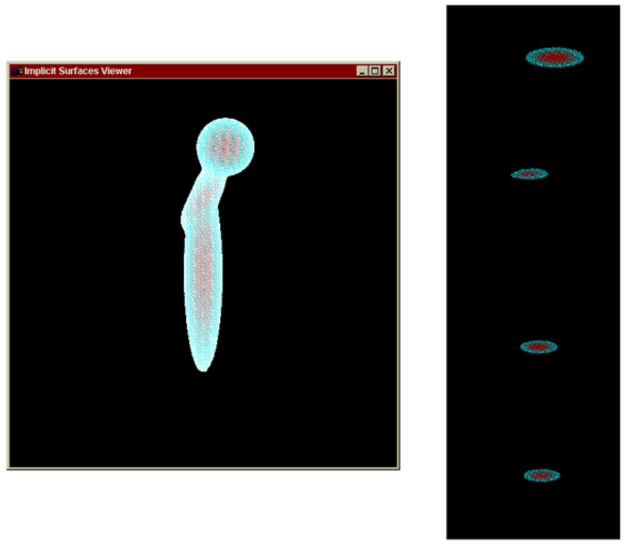

Figure 4. Material gradient in femur implant.

2.5 Advantages of the Approach

The procedural representation is very compact in storage because stores only procedural instructions and their parameter values. The size of a procedural gradient can be measured in kilobytes, while the memory size of voxel-based gradient data may require on the order of megabytes. Efficiency in memory becomes particularly significant when the material pattern is repetitive or uniform throughout the geometry, because the data for the mapping can be reused.

Another advantage of the procedural method is that it has no fixed resolution. In most cases, it can provide fully detailed information for any resolution required. Since a set of instructions procedurally defines the material gradient information, the affected region can be edited simply by modifying the instructions or definition without visiting individual nodes or voxels. Dimensional changes of a part with procedurally described material information do not require redefinition of the material space. Uniform or non-uniform scaling of the material space, therefore, becomes trivial.

Compared to other representation schemes such as voxels, parametric formulations, and volumetric meshes, implicit procedural models appear to be more suitable for generating machine instructions for fabrication. For material delivery tool path generation, for example, material gradient samples can be evaluated in an order determined by the process planning algorithm, not by the gradient design procedure. The implicit procedure fits perfectly in such an environment because it is designed to answer a query about any point in the part at any time. Parametric or discrete models, however, lend themselves to path generation based on a fixed sequence or discretization, which may not match the needs of the process planning algorithm. In most process planning programs, using an explicit routine or discrete data requires running the gradient design procedure as a pre-process to generate the material gradient, which must be stored in a buffer for retrieval as necessary for rearrangement or interpolation during process planning. This reduces the efficiency of the process.

3 Discrete Multiple Material Selective Laser Sintering

Our efforts to develop multiple material SLS have been motivated by potential industrial applications. This section focuses on sand casting as a potential application of discrete multiple material SLS. Sand casting is the process of imprinting a pattern into sand to form a mold, placing cores into the mold for internal cavities, including a gating system for molten metal, pouring the molten metal, and after cooling, breaking the mold to remove the casting. Sand castings allow for complicated shapes at a relatively low cost. The introduction of SFF to sand casting is fairly new but has resulted in reduced production times and increased part complexity not possible without SFF.

There are two SFF applications in sand casting: pattern making and coremaking. Patterns are used to form the imprint in the sand mold. Core arrays form the internal cavities or passageways of cast metal parts, such as internal geometries of engine blocks. Figure 5 shows a complex core array and the resulting finish casting. In conventional coremaking, cores are fabricated in many pieces that would have to be assembled with core paste and placed in the mold and gauged for accuracy of fit. Cored holes and features are usually limited to ¼" diameter.

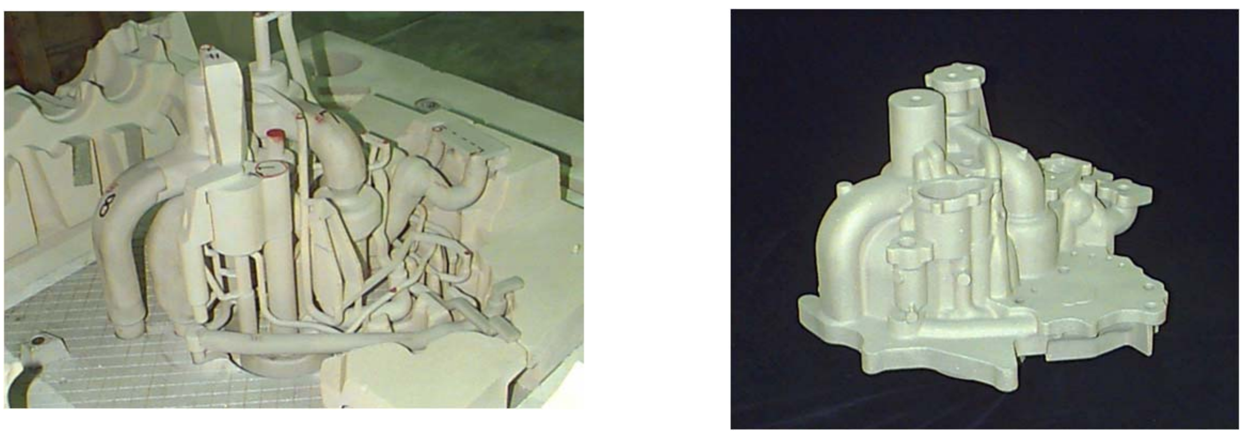

Figure 5. Core array and finished casting.

The SLS process is being used to produce sand casting core arrays. Sandform™, introduced by DTM Corp., is a polymer-coated sand that can be processed to produce complex core arrays, such as the one shown in Figure 5. With the introduction of Sandform, the whole core array can be manufactured in a SLS part, with no core assembling and reduced gauging. This new technology was hailed by the casting industry, but the process has many problems and limitations.

3.1 Problems with SLS Fabrication of Cores

Because cores are produced by SLS, extra polymer binder must be added to the sand/binder system to achieve a satisfactory green strength for the SLS build and handling of the part. This added binder causes more outgassing during metal pouring and solidification. Venting of the core arrays becomes more important to prevent gases entering the molten metal and forming pockets or cracks.

Venting is achieved by creating passageways inside the core itself. The vents connect to a core print in the mold to discharge the gas to the atmosphere. For any sand core feature, a vent hole must be present to outgas steam and gas from the polymer degradation during metal pouring. For a 0.125" cylindrical feature, an internal hole must be present in the feature to allow proper venting and still have strength. The vents inside the core can become quite small and intricate, and as mentioned before are limited to ¼" diameter, which restricts the feature sizes that can be realized.

Another problem related to venting is the mechanical removal of the unsintered powder. This is actually a problem for all SLS manufactured parts with small holes or cavities. Because of the vents in the sand cores, the sand cores are basically shells, so they are filled with unsintered sand powder. The low green strength of Sandform adds to the problem of removal because of the increased likelihood of breakage. Common removal methods are gravity, shaking or vibration, and pressure differences (suction or blowing), but with smaller and more complex features, these methods cannot remove the powder.

In addition, low green strength can result in damage to the part during breakout from the SLS machine, removal of the unsintered powder, and part cleanup. Some damage can be repaired with special adhesives, but many cores have to be scrapped. Also, the core can break or crack during the thermal cure cycle. As stated before, binder content cannot be increased to augment the green strength because more binder means more outgassing and more need for venting or larger vents.

All of these problems lead to an increase in the post-processing time of Sandform sand core arrays. Cleaning and repairing requires as much as four hours per part, which is a considerable amount of time even in low volume runs of less than a 100 pieces. Although SLS sand cores do cut the production times of cores, there is still potential to improve the process significantly.

3.2 Advantages of multiple material Sandform system

The current problems with Sandform point to a perfect opportunity to employ a multiple material system. We are currently developing a material system that will use Sandform along with a sacrificial material that could be removed chemically or thermally. The ideal sacrificial material would provide support to the Sandform part, even in the minutest passages, but would disappear with little or no trace upon exposure to the proper thermal or chemical environment.

A properly designed two material SLS system would greatly improve the functionality of Sandform. First, the unsintered powder removal step would be eliminated from the process, reducing post-processing time. At the same time, handling would be minimized because there would be no need to handle the core to remove loose powder, which would also cut down on the probability of breakage. The second material might also add green strength to the core, acting as a skeleton to give the part strength and support, thus further reducing breakage.

Besides addressing these problems, a two material system would enhance Sandform. The problem of removing unsintered powder would be eliminated, allowing smaller and more complicated features to be fabricated in core designs. Previous designs that were impossible to make because of the difficulty of removing unsintered powder might become feasible. Also, the added strength and support of the second material would ensure the integrity of smaller and more complex features. Another added benefit is reduction of mold assembly time. Since the core can be made in a single piece, less time would be needed to fit the core to the core print. Better accuracy could be achieved because there would be less chance for error in the placement of the core.

3.3 Conceptual Design of Discrete Powder Delivery System

In addition to designing a proper material system, a powder delivery system must be designed for delivering multiple materials to the powder bed. The delivery of the matrix material will most likely be accomplished using a roller system similar to that used on existing machines. As an example, one concept for a discrete multiple material SLS powder delivery mechanism is shown in Figure 6. In Step 1, a layer of Material 1 is spread over an existing layer; in Step 2, a laser beam under computer control scans the material selectively, fusing only powder, which will eventually form the part, and leaving an unscanned region. In Steps 3 and 4, loose powder in the unscanned region is removed by vacuum (e.g., by nozzle). In Steps 5 through 7, Material 2 is placed in the previously unscanned region (this could also be done with a nozzle rather than a roller as shown). In Step 8, Material 2 is scanned and solidified by the laser, and in Steps 9 and 10, excess Material 2 is removed. Completion of this process results in an object composed of two discrete materials. The required accuracy and resolution may not be possible with the method described above. A solution to this potential problem is the use of electrostatic deposition techniques as in laser printing, ionography or ink jet printing. Either insulating or conducting “toner” can be used with these methods.

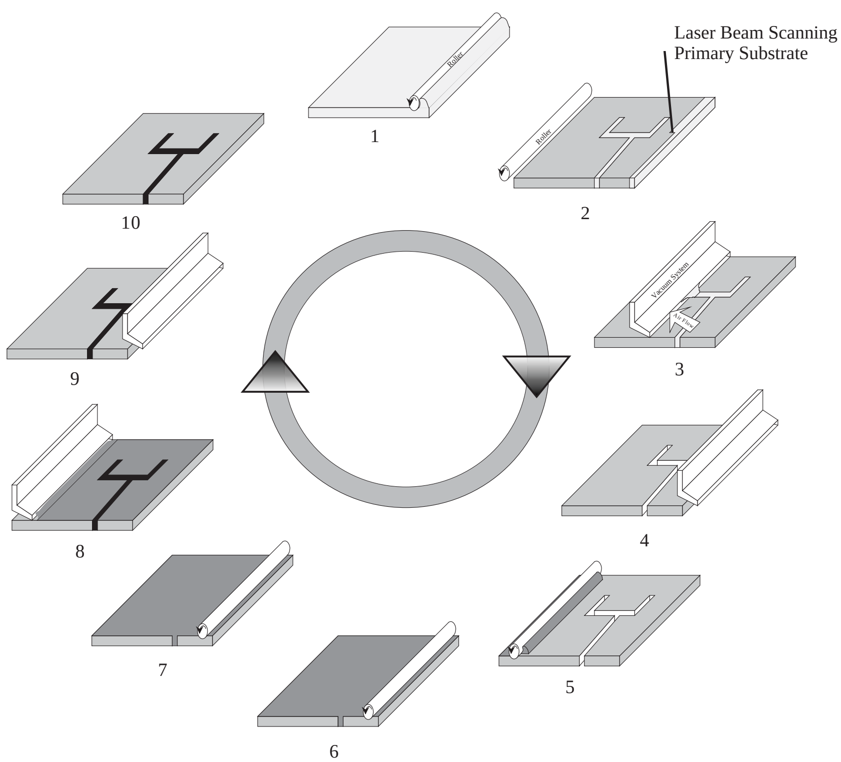

Figure 6. Conceptual design of multiple material SLS process.

4 Functional Gradient Multiple Material Selective Laser Sintering

In many ways, the most challenging application of multiple material SLS will be fabrication of parts with functional gradients. We are pursuing this capability in two stages. In the first stage, we are developing a SLS workstation that can deliver graded materials in the build direction only, providing a one-dimensional gradient. In the future, we will address the development a workstation capable of a full three-dimensional gradient.

The primary focus of the current effort is the development of metal components containing a functional gradient. A common drill bit head used in the petroleum industry provides the motivating example. The bit contains small tungsten carbide / cobalt inserts. Previous research has indicated potential performance enhancements with the use of FGMs in these components. For this application, tungsten carbide provides erosion resistance while the cobalt provides ductility and fracture resistance. Since high erosion resistance is desired at the tip of the insert, it is desired to increase the relative amounts of tungsten carbide at this location. At other locations in the insert, fracture resistance is the primary functional requirement so that a higher percentage of cobalt is desired.

A series of feasibility studies have been conducted in which single and multiple layer samples containing FGMs have been fabricated using manual techniques with the traditional SLS process (Jepson *et al.*, 1997; Jepson *et al.*, 1998). The results include a narrow region of optimal scanning along the FGM and sensitivity to scanning vector/FGM orientations. Optical micrographs of sectioned samples were collected and revealed gradients in material composition. Microhardness testing of samples was performed and revealed correlations between distance along FGM and hardness values (see Figure 7.)

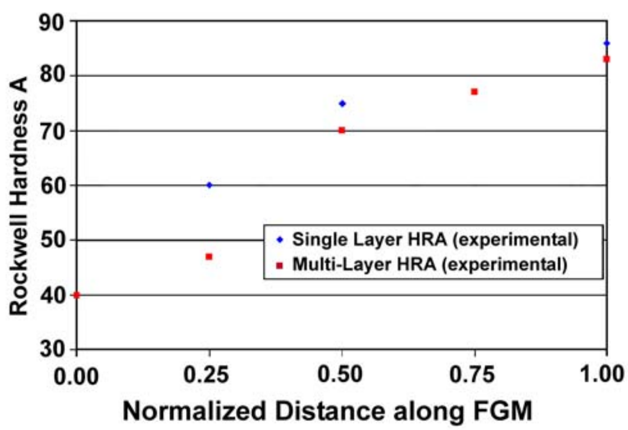

Figure 7. Correlations between FGM distance and hardness.

A series of single layer sintering trials have been conducted to determine the effects of atmosphere on sintering performance (Jepson et al., 2000). Finally, a multilayer FGM sample has been fabricated on a newly developed multiple material SLS workstation.

The powder mixing subsystem for this workstation employs two computer controlled screw feeders that determine the mix composition by controlling the relative flow rates of the two powders (Perez, 1998). A motor driven impeller then mixes the powders. Impeller speed may be varied to provide optimal mixing. Finally, the mixing chamber deposits the powder in a line for roller transferal to the part cylinder.

This system has been integrated with a counter-rotating roller and part cylinder present in the commercial SLS process. Additionally, scanning and optical control subsystems have been developed and tested. A simple shielding gas flow system is currently under development and will provide the initial atmospheric control. A chamber with gas flow and low vacuum purge capabilities will be developed as the second design iteration of the atmospheric control subsystem.

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