DIRECT MANUFACTURE OF SPATIALLY ENGINEERED COMPONENTS FOR AEROSPACE APPLICATIONS BY FUSED DEPOSITION OF CERAMICS

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ABSTRACT

The current progress of the AlliedSignal led team using the Fused Deposition of Ceramics (FDC) process is described. The program is focused on building and characterizing novel designs with spatially engineered multiple materials. This paper will describe the design, fabrication and properties of multi-material turbine engine components. The integration of process parameters, material properties, material modeling and stress analysis within the FDC manufacturing process will be highlighted using the example of a multi-material turbine blade. Improved build techniques to manufacture components not possible by regular techniques will also be demonstrated.

INTRODUCTION

We present here an overview of activities in Rapid Manufacturing (specifically, Fused Deposition of Advanced Materials) for the manufacture of high value components. Components manufactured by this process are intended to be functional and for insertion into components and systems. Issues relating to (a) feedstock and material development, (b) materials design, (c) novel component design, (d) toolpath and build procedures and (e) integrated design procedures. The program team members and their associated tasks are outlined in Table 1. The work presented here reflects the contributions of all the team members.

Descriptions of the Fused Deposition (FD) process are provided elsewhere [1, 3]. Figure 1 summarizes the process. The deposition is essentially 1-dimensional, and as such provides some unique capabilities to vary deposition within a layer. One goal of our program is to use this capability to demonstrate performance improvement through the use of multiple materials within a layer. For example, to produce compressive residual stresses. Also, the use of filament as the feedstock material and the extrusion process provide two other capabilities: production of unique material architectures in the filament which are retained after extrusion (e.g., fibrous monoliths); and enhancement of crystallographic texture by flow alignment of seed crystals in the filament. The concept of the fibrous monolith is sketched out in Figure 2.

To be used effectively, the capabilities described above require new design tools. Put another way, the ability to fabricate unusual material architectures is useless unless we have some design tools to help us decide what we need to build. Consequently, another facet of our program involves materials and structural design. Materials design may be defined as both optimizing individual material properties and also as the arrangement of two or more materials to maximize some property such as strength, elasticity or thermal conductivity. Structural design then incorporates this information to design components with improved reliability and/or performance, using these material designs as input and varying parameters such as their shape and location in the component.

Program Team

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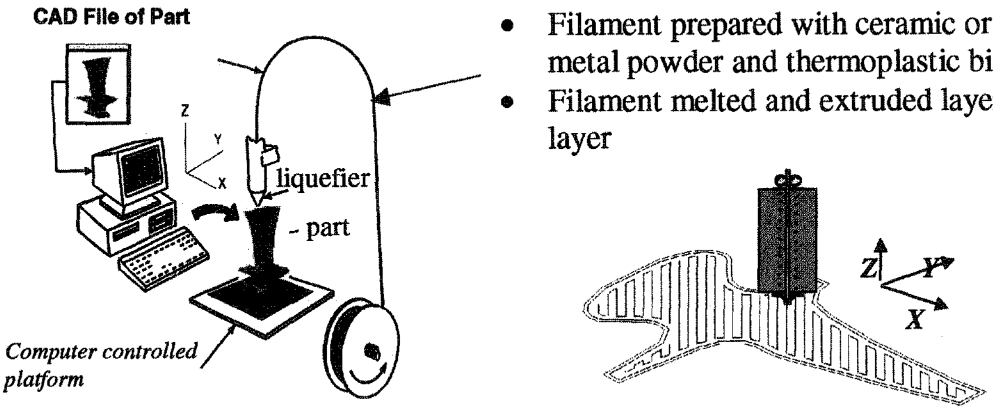
Table 1

Any design produced must be fabricated using FD, which requires modifications to standard toolpath software* to achieve optimum material properties. This work may be broadly characterized as changes in the toolpath required to ensure complete filling of the layer for all possible design elements. Finally, we will describe some of our preliminary efforts in design integration, which is the process of tying together all of the above ideas and incorporating them in a design procedure which includes process simulation, so that redesign and optimization can take place before the first "real" part is produced. Ultimately, this integration of design and manufacturing should lead to much faster design cycles. Our current FD process can produce a finished part in as little as two weeks (1-2 days for building, 9 days for binder burnout and two days for sintering). In the following, we will describe in more detail the work underway in our program that begins to tackle some of these issues.



- Filament prepared with ceramic or metal powder and thermoplastic binder
- Filament melted and extruded layer by layer

Figure 1: A schematic of the Stratasys FDM 1650 and a build layer.

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* Initial work used manual modification of toolpaths output from the Stratasys QuickSlice® software.

FEEDSTOCK AND MATERIALS DEVELOPMENT

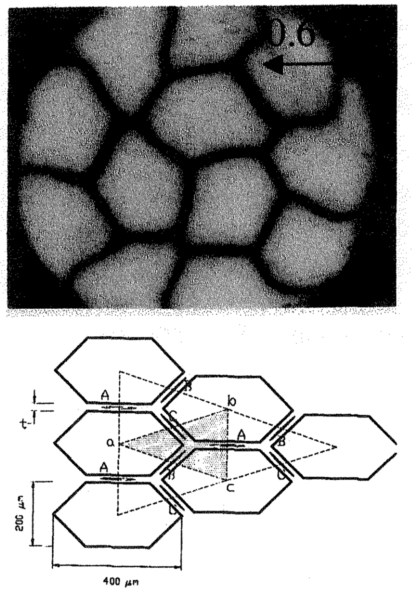

Figure 2. An example of the unique microstructures that can be produced by FD is illustrated by the FM microstructure above. Below is an idealized model used for predictive simulation as an aid in material and component design.

Development of a suitable solids-loaded filament was the primary focus of the work early in the program. This led to the successful development of silicon nitride (Si_3N_4) loaded filament. Parts manufactured from these filaments have been shown to have strength and properties comparable to conventionally processed material [2, 4]. More recently, we have concentrated on extending this work to include a variety of silicon nitride-based compositions, filaments with fibrous monolith microstructures and filaments containing β-Si_3N_4 seed crystals.

The work on β–seed crystals is designed to take advantage of the orientation of acicular crystals in the extrusion flow from the FD nozzle. The silicon nitride powders undergo a phase transition from α to β phase during sintering. The presence of the seed crystals will result in preferential growth of the β crystals during transformation, resulting in the development of crystallographic texture (the axis of the needle-like beta seeds corresponds to the c-axis of the hexagonal β- Si_3N_4 crystal). This orientation can be used to advantage to change properties that are dependent on crystal orientation such as elastic constants and thermal conductivity. Preliminary work has shown that alignment does occur during filament fabrication, during FD and is enhanced after sintering. Rutgers University has been responsible for producing the β–seed crystals and we are currently scaling up the process to produce filament at ACR.

In order to utilize the multi-material capability of FD, materials that are compatible and co-sinterable must be developed. Since silicon nitride is the high temperature structural ceramic of choice for turbine engine components, our work has focused on developing compositions compatible with this material. We have been developing silicon nitride-based materials which contain dispersants to increase the co-efficient of thermal expansion (CTE) and which can be co-sintered with the baseline composition. With the proper arrangement of the two materials, compressive residual surface stresses can be developed on cool down from sintering. A number of promising compositions have been developed and an example of their application will be presented in the section on Component Design.

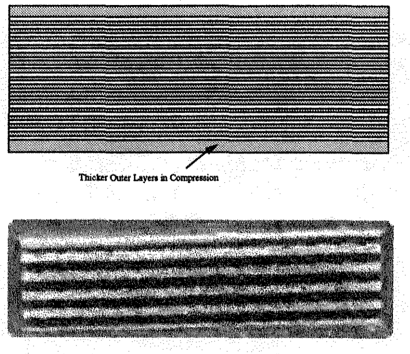

Figure 3: The modeling of a bimaterial ceramic component shown at top is manufactured and co-sintered (below).

Materials design work is being performed to understand the behavior of multiple material architecture. Most of the work to date has focussed on fibrous monolith and laminate/layered arrangements. The fibrous monolith microstructure has been modeled using finite element analysis and both residual stresses and crack propagation behavior have been modeled. The basic idea behind the fibrous monolith materials is to provide for crack deflection at cell boundary areas, thereby promoting graceful failure in an otherwise brittle material. The modeling work has identified properties required for the cell wall material in order to promote crack deflection. The concept of using FD to produce FM microstructures was verified early in the program using model materials consisting of carbon black and alumina [5]. We are now producing filament and building silicon nitride based FM materials. This material may be used to provide some damage tolerance in components susceptible to cracking from contact or impact stresses

By depositing alternate materials within a layer, complex laminate geometries with varying laminate thickness can be produced. One example of Anil Virkar's modeling work is illustrated in Figure 3. A multiple laminate is shown which produces a surface compressive stress and also a periodic stress in the interior. The advantage of this approach is that large compressive stresses can be produced with a lower risk of laminate interface failure and a higher resistance to internal crack propagation. A laminate design of this type is being evaluated for use in the blade attachment area of a silicon nitride turbine blade Details appear in the following section. A part built with laminations is also depicted in Figure 3.

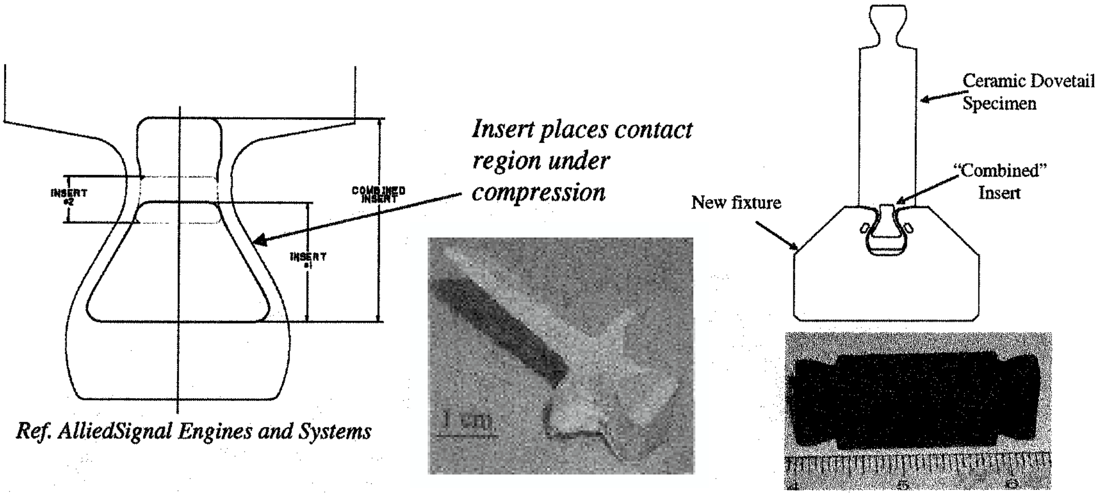

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Figure 4: Bimaterial blades. At left is a series of overlayed designs of possible insert cross-sections for a blade dovetail. At center is a bisque-fired section of a bimaterial blade. At top right is the schematic of a test rig for the bimaterial dovetail with a sample specimen (single material) shown below.

NOVEL COMPONENT DESIGN

The goal of our program is to demonstrate the capabilities of FD to improve the performance of a silicon nitride turbine blade. With the compatible and cosinterable materials developed under this program, we have been using the multi-material capability of FD to introduce surface compressive stresses in the attachment area of a silicon nitride turbine blade. The blade is designed for insertion into a cooled metal disk. The compressive stresses improve the resistance to contact damage in the dovetail attachment area, where the ceramic contacts the metal disk[†].

[†] A proprietary compliant layer system is also being used to reduce the stresses in this area.

The Engines & Systems division of AlliedSignal has been developing the insert design, illustrated in Figure 4 (at left). The size and location of the insert has undergone a number of revisions, with the goal of getting the maximum reduction in stress possible. One of the later designs is shown in Figure 4. The insert is calculated to reduce the maximum stress in the attachment area by 25% and the overall stress by 40%. Future work will examine the use of a more complex material architecture for the insert, including the use of laminates instead of a solid insert.

The insert design concept will be verified using pull-test specimens with and without the insert. Samples will be tested to failure to verify the expected strength increase for the samples containing the insert. The sample configuration is also shown in Figure 4 (at right), along with an example of a sintered pull-test sample. Another part of the concept verification process is to demonstrate the capability of FD to produce parts that meet the turbine blade specifications. Our approach to this problem will be described in the section on integrated design procedures.

In addition to the turbine blade insert design, we have prepared a number of "concept" parts to highlight the capabilities of the FD process. One of the most promising capabilities is the production of parts with conformal cavities. For example, cooled ceramic turbine blades – difficult or impossible to fabricate conventionally – can be built using the FD process. Figure 5 shows a demonstration turbine blade built using FD. It contains a conformal cooling channel and trailing edge slots.

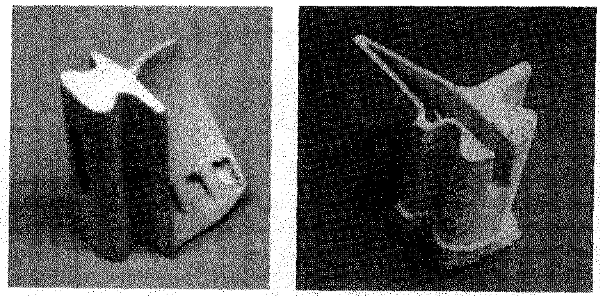

Figure 5: Conformally cooled Silicon Nitride blades, in bisque state. The blade to the right is sectioned to show the interior and has the support base intact.

TOOLPATH AND BUILD PROCEDURES

One of the limiting features of Fused Deposition of Ceramics is the formation of voids during slice filling. These voids can be caused by both procedural and systemic causes. Systemic loss of fill information is described in detail in [6] while procedural causes are addressed in [7]. It should be noted that surface finish of parts (primarily the stair-casing effect) is not attempted to be resolved in our studies. Appropriate flow control and deposition can minimize, but not eliminate these artifacts of the process[‡].

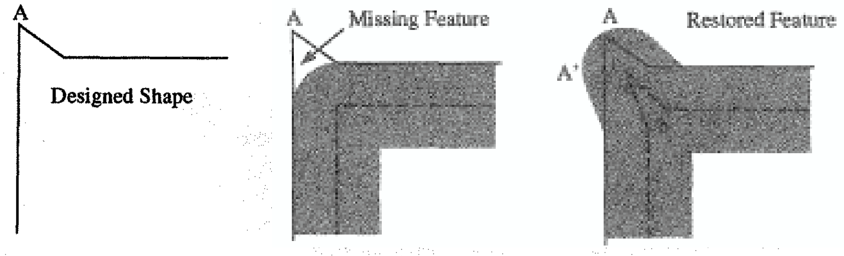

Figure 6: The corner of the component (at left) is not defined by the standard "minimum" distance offset procedure (center). The component built with a reformulated toolpath (at right) restores, to some extent, the original feature.

[‡] The blade we are building for this program will be surface finished in the so-called "bisque" state. Bisque sintering is a treatment that partially consolidates the component and increases part strength with little or no shrinkage. The material has the consistency of chalk and is easily machined. After machining, the component is sintered to full density.

The primary objective of this aspect of our program is to eliminate, or suppress, voids in the interior of the component. The secondary objective is to define features as required in the part design – including the disruption in connectivity that may be caused during toolpath generation. While the solution procedures and techniques are described in [6] and [7], highlights of the solutions will be given here.

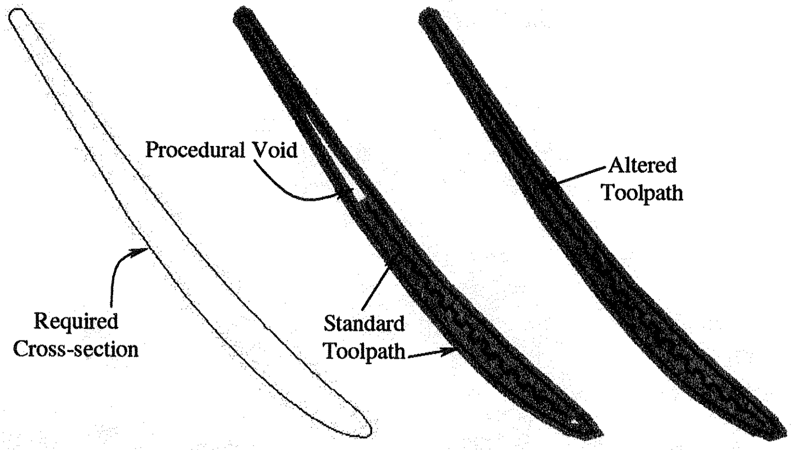

Figure 7: For the cross section defined to the left, standard internal offset procedures for internal filling leave a procedural void that will not be filled (top left end of the graphic at center). The altered toolpath for the graphic at right completely fills the void zone.

Voids are caused by improper toolpath generation – standard offsets from the perimeter of the 2-dimensional slice are inherently a *minimum* of the offset distance away from the perimeter. This implies that there are zones where the toolpath (perimeter or internal fill) is further away than the standard offset distance from the surface of the part. This leads to improper definition of a feature (Figure 7), incomplete fill (Figure 8) or persistent voids (Figure 9).

Techniques to remove these voids have been developed at AlliedSignal. The methodology to do this is to recreate contours while ensuring that the minimum distance from the surface of the component is the required offset distance. While this causes increased filling at some locations, the component does not have any procedural voids left in the virtually described slices. In the case of Figure 7, where the feature is too small for the road width required, the surface of the missing feature is used to recreate a similar feature – this "new" feature is not an exact copy of the original but is also not eliminated. Similar procedures are used to create the "dog-earing" of Figure 9 and the reformed filling of the narrow cross-section of Figure 8.

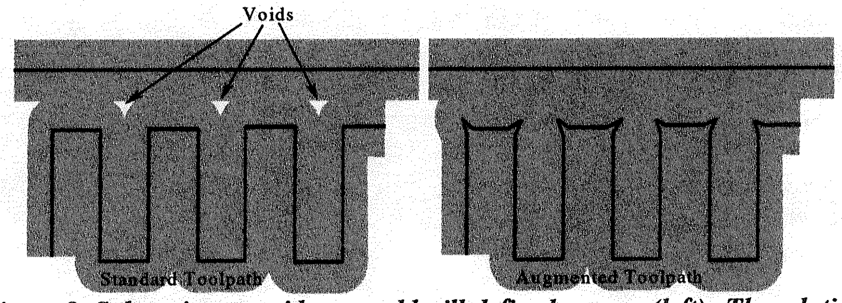

Figure 8: Sub-perimeter voids, caused by ill-defined corners (left). The solution is to relocate the corners such that predictable voids are removed (right).

The algorithms are currently being incorporated into a toolpath generation software package that will be available in 2Q00. Development of design procedures to incorporate manufacturing changes in the component are under way. These include design decision issues relating to feature interactions (described in some detail in [7]). Flow control issues, relating to the controlled deposition of material along with incorporation of multi-material deposition are to be addressed as well. The package is expected to provide a toolpath that guarantees void free components with component features defined as per design requirements.

INTEGRATED DESIGN PROCEDURES

Using SFF as part of this new manufacturing technology requires validation of its ability to manufacture parts with sufficient accuracy and reproducibility. We are using the design and fabrication of a silicon nitride turbine blade for this work. Our program calls for the fabrication of several blades by FD and the careful tracking of dimensional changes during the entire processing (including binder burn-out, bisque sintering, hand-finishing and sintering). A conventional slip-casting process and bisque machining of the same part (without an insert) is being used as a baseline for the purposes of comparison with a commercial process for functional quality parts. The FD part requires a minor amount of hand finishing to remove the stair-stepping texture of the as-built surface. In comparison, the bisque machining of each slip cast blade takes a few hours on a CNC machine. Moreover, the fixed costs and setup costs of the tooling/fixturing for CNC machining makes the individual cost of these components very high. Not only is SFF (in this case FD) able to produce parts difficult or impossible to build with conventional techniques (blades with inserts and/or conformal cavities), it provides them faster (3 weeks to the first part) and at a competitive cost (for "short runs").

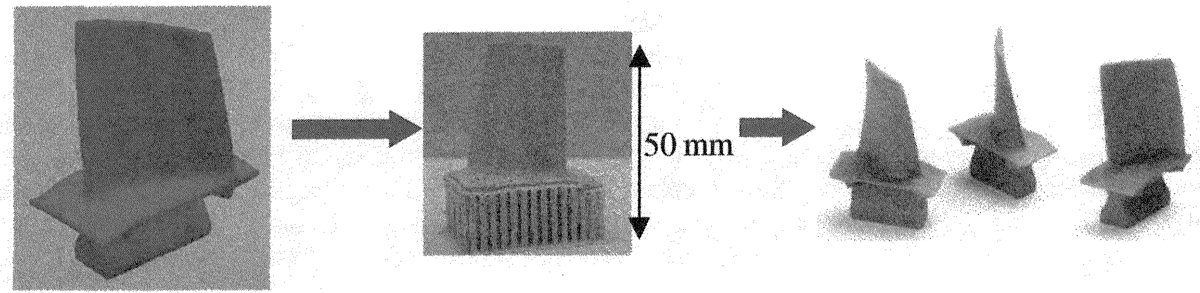

Figure 9: From concept to creation: A blade, designed on the computer (left), is manufactured within 4 hours (center) and could be available for engine testing within 3 weeks (right).

The first batch of monolithic turbine blades has been processed through sintering and is depicted in Figure 9. CMM measurements indicate that the green part needs to be redesigned to accommodate material removal during hand finishing and to compensate for some minor warpage. Assuming repeatability of these characteristics, it should be relatively easy to compensate for these or any other effects. We are now in the process of verifying this.

The FD process has many advantages and is worthwhile investigating and developing based solely on the advantages it brings in the ability to manufacture high value components. However, the true justification for this work lies in its integration with the new manufacturing paradigms looming on the horizon. Variously referred to as agile, digital or rapid manufacturing, this new manufacturing model emphasizes speed, lower costs and customized design. The use of computer-aided design, engineering and manufacturing allows a virtual part to be "built" on a computer. Combined with computer modeling of an SFF process such as FD, design optimization can be performed much earlier in the design cycle, allowing for faster, better and cheaper components.

Our program encompasses every significant aspect of a manufacturing process – from materials development, to component design to manufacturing. The nature of the program demonstrates the tight coupling of each of these aspects with one another. The success of the program hinges on the effective integration of each of these segments. In effect, we believe that not only is this manufacturing technology uniquely positioned to exploit integrated design procedures, it is critical for its insertion into commercial activity.

SUMMARY AND CONCLUSIONS

The work of the DARPA-sponsored team on solid freeform fabrication of advanced ceramics has involved the interaction of materials design and development, structural design fabrication and component testing. Our work to date has demonstrated the ability of FD to produce unique microstructures such as fibrous monoliths and multi-material laminates using compatible and co-sinterable materials developed under this program. In addition, parts with complicated internal passages have been fabricated which would be difficult at best to manufacture using conventional techniques. We are integrating the FD process in the design cycle by using the multi-material capability to build a composite turbine blade with improved resistance to contact damage and will test and verify performance using a variety of test techniques.

ACKNOWLEDGEMENTS

This manuscript contains work performed as part of the "Solid Freeform Fabrication of Advanced Ceramics Phase II" project, funded by the Office of Naval Research and The Defense Advanced Research Projects Agency under Contract #N00014-97-C-0154. We appreciate the support and advice of Dr. Stephen Fishman, program monitor and Dr. William Coblenz and Mr. Kevin Lyons, program managers for the project. We would like to acknowledge the input and suggestions of the entire team and others, including: Milton Ortiz and Boris Mitlin (AlliedSignal Engines & Systems), Dr. Philip Whalen (AlliedSignal Inc.), Prof. Stephen Danforth, Dr. Sriram Rangarajan and Brian Harper (Rutgers University), Dr. John Pollinger and Doug Twait (AlliedSignal Ceramic Components), Prof. Anil Virkar (University of Utah) and Prof. George Dvorak (Rensselaer Polytechnic Institute).

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