Development of Direct SLS Processing for Production of Cermet Composite Turbine Sealing Components - Part I

T. Fuesting[†], L. Brown[†], S. Das[‡], N. Harlan[‡], G. Lee[‡], J. J. Beaman[‡], D. L. Bourell[‡], J. W. Barlow[‡], K. Sargent[§]

Abstract

This paper presents the development to date of SLS (selective laser sintering) technologies for production of cermet composite turbine sealing components, the particular application being an abrasive blade tip. The component chosen for the application is an integral part of the low pressure turbine in a IHPTET (Integrated High Performance Turbine Engine Technology) demonstrator engine. Both indirect and direct SLS techniques are being developed. Initial trials and process development involved the use of fugitive polymeric binders. Sequential refinements were performed to develop a binderless direct SLS process. Results from mechanical testing indicate that acceptable microstructure and properties are attainable by SLS with substantial cost savings as compared to the currently employed production method. This is the first instance of direct SFF methods applied to a functional component.

INTRODUCTION

Since its inception in the 1930's, the gas turbine engine has grown to be the workhorse power plant of modern aircraft. Advanced technology propulsion systems are very important from an overall system affordability viewpoint since higher engine performance can result in a smaller airframe. In 1988, the United States Department of Defense and the National Aeronautics and Space Administration combined forces with industry to focus gas turbine engine research and development efforts toward the goal of doubling current levels of propulsion capability by the turn-of-the-century. Known as the IHPTET (Integrated High Performance Turbine Engine Technology) program, this aggressive technology development plan's specific goals are to increase thrust-to-weight, reduce fuel burn, and reduce the cost of high performance gas turbine engines.

Increased affordability can be accomplished by either increasing engine performance without cost penalty or by decreasing engine cost without sacrificing performance. The two principal aspects that IHPTET is targeting to reduce engine life cycle cost are engine unit acquisition cost and, operating and support costs. The technological developments required to lower the cost of future engines are advanced materials, innovative structural designs, improved aerothermodynamics, advanced computational methods, and advanced manufacturing techniques. The integration of these advanced technologies will not only provide the benefit of improved performance, but will also help to make engine systems more robust and more affordable. IHPTET cost reduction studies[1] have found that a key to engine cost reduction is cost effective fabrication and manufacturing. These studies have also shown that several principal factors can contribute to lower manufacturing costs for the advanced technology engine, including its smaller size, reduced parts count and cost effective manufacturing methods.

An example of advanced manufacturing methods that can impact cost reduction of engine components is SFF. This technology is striving towards decoupling cost from volume[2] by making it possible to produce the first unit at a recurring cost equal to the hundredth unit[3]. The IHPTET program has chosen an application to demonstrate this technology. It is a cermet composite component that is an integral part of the low pressure turbine in an IHPTET demonstrator engine.

† Allison Engine Company, Indianapolis, Indiana

‡ Laboratory for Freeform Fabrication, University of Texas at Austin

§ Wright Laboratory, Wright-Patterson AFB, Ohio

This paper begins with a brief background on gas turbine sealing technology. The objectives for pursuing the research described herein are discussed next. The potential for significant cost savings by pursuing SLS as a manufacturing technique is demonstrated. The Allison Engine Co. "standard cermet" production technique is described, followed by a description of materials and methods used in this research. The results section compares properties of cermet material processed by SLS with those of cermet produced by the standard production technique. Problems encountered with materials interaction in the cermet composite and their solutions are discussed. Conclusions and plans for future work are presented.

BACKGROUND

Gas turbine efficiency is highly dependent upon minimizing leakage of the gas away from and around the working gas path. Therefore, clearance between rotating and static parts is critical. This clearance changes with component expansion and contraction due to the thermal cycling experienced in gas turbines. One of the primary methods developed for accounting for this expansion and contraction is an abradable seal system[4,5]. This seal system works by attaching a cermet composite abrasive blade tip (ABT) to the sealing surface of the rotating component. The circular stationary component is coated with an appropriately engineered semi-porous abradable ceramic which is abraded by the rotating cermet to form a shroud type gas path seal around the rotating component.

The semi-porous ceramic component is relatively inexpensive and simple to manufacture. However, the abrasive cermet (0.035-0.060 inches thickness) is difficult to manufacture on a production scale and contains expensive components. The cost of the raw materials makes scrap highly undesirable. Manufacturing of this layer typically involves rolling and pressing a mixture of the ceramic and metal alloy powders with an organic binder to the correct thickness. The rolled mat is then vacuum sintered. It is evaluated for proper microstructure, machine ground to proper thickness, laser cut and metallurgically bonded to the rotating hardware. This complete process is labor intensive and can result in a significant amount of scrap if stringent manufacturing processes are not adhered to.

Due to the difficulties encountered with standard abrasive cermet production, an alternate approach for producing this material is desired. Since the standard production material is capable of being laser cut to final shape, laser sintering of the constituent powders was the primary alternate approach chosen. SLS (Selective Laser Sintering) is a rapid manufacturing technique that builds parts from a powder base. SLS creates freeform 3-dimensional solid objects without the use of any tooling or human intervention. Details on this process are described elsewhere[6,7,8].

SLS has been commercially developed by DTM Corporation and is in use for prototyping models from polymeric powders and for creating investment casting wax patterns. More recently, DTM has introduced RapidTool, a technology for creating prototype metal tooling from polymer coated metal powders[9]. This process uses indirect SLS techniques[10] which involve the use of fugitive polymer binders to produce a "green" shape that is subsequently post-processed by binder burn-out, sintering and infiltration to produce high density metal and ceramic parts and tooling[11,12,13,14,15]. A functional metal part, porous or fully dense, has not been made previously by direct SLS. The terminology "direct SLS" implies a binderless SLS process in which the material constituents are directly laser sintered to produce a high density part requiring little or no post-processing.

The expensive and difficult to manufacture abrasive cermet composite can potentially be directly laser sintered, therefore making it an ideal part for processing by direct SLS. An SLS process for producing abrasive cermet composite can potentially provide a uniform, repeatable manufacturing process that would eliminate much of the manual labor as well as reduce scrap and make all unsintered fall off materials reusable.

OBJECTIVES

The primary goal of research described herein is to develop an SLS process capable of producing the cermet. The cermet produced by SLS must have properties equivalent to the current production material used by Allison Engine Company. The process developed should allow for possible reuse of all unsintered fall off material. Another goal is to eliminate a low melting point braze constituent which will extend oxidation life and possibly allow higher operating temperatures.

Reducing production costs and achieving a repeatable production process are the primary motivation for pursuing SLS as a manufacturing technique in this application. The typical manufacturing method of tape casting and rolling requires a fixed amount of material input per lot, independent of the actual parts needed per lot size, up to lot sizes producing 1000 parts. For prototype lot sizes to produce 100 parts or less, this method becomes expensive considering the cost of the materials involved. Moreover, sintered material left over after the laser cutting step, "fall-off", is scrap. Since direct SLS does not utilize a binder, it eliminates nearly all scrap material by enabling recycling of all fall- off materials from a lot. This significantly reduces the cost and results in the primary portion of the cost savings. The remainder of the cost savings are realized by elimination of labor intensive tape casting and rolling in the currently employed production process. A cost break-down, shown in Figure 1, was performed to illustrate the potential benefits of developing an SLS process. The details and assumptions used to formulate this break down are provided in Table 1. Obtaining a repeatable production process also results in very large cost savings which are not directly measurable. The current production process has variable yield, resulting in a significant amount of scrap due to unacceptable porosity.

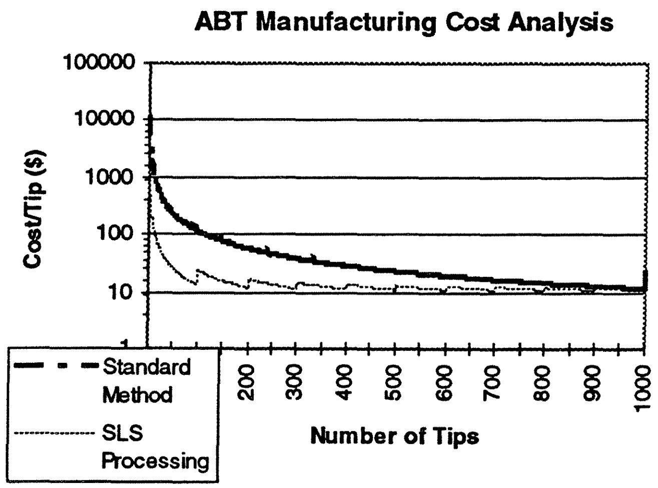

Figure 1. Standard method Vs SLS processing cost comparison

Assumptions
SLS - Lot size of 100, 90% efficiency, material costs $900
Standard method - Lot size of 1000, 80% efficiency, material costs $10,000

	Material	Mixing and Casting	Cutting and Programming	Grinding	Sintering
SLS	$900	2 hours	4 hours	0.5 + (0.02 X N)	0
Additional Lots	$900	2 hours			
Standard	$10000	8 hours	4 + (0.03 X N)	0.5 + (0.02 X N)	8 hours
Additional Lots	$10000	8 hours			8 hours

N= number of cermet preforms

Table 1. Cost breakdown

MATERIALS AND METHODS

Standard Cermet Production

The standard abrasive cermet composite is composed of two different types of titanium coated ceramic abrasive grit, a nickel alloy matrix, and a lower melting point cobalt based braze material. The compositions of the metal alloy components are provided in Table 2. The titanium coating on the ceramic grit functions as a bonding interlayer to promote a metallurgical bond as opposed to a mechanical interlocking bond which would result from using uncoated grit. A metallurgical bond is more effective in preventing grit pull out which occurs during rubbing or abrading of the cermet composite. Physically or mechanically interlocked grit has a high tendency to be pulled out of the matrix by the shear forces encountered during rubbing. Removal of grit particles results in reduced abrasive for cutting a clear path which has two consequences: (1) the metallic matrix will be rubbing the ceramic abradable seal material, increasing friction forces and reducing efficiency, and (2) occurring but less likely, the pullout introduces a gap for compressed gas to leak around the working path. Additional details are described elsewhere[16,17].

Material	Ni	Co	Cr	Al	Ti	W	Si	B	Mo	Ta	Hf
Mar-M-247	Bal	10.0	8.4	5.5	1.0	10.0		0.01	0.7	3.1	1.4
*CMSX-3	Bal	4.6	7.8	5.6	1.0	8.0			0.5	6.0	0.1
∅Amdry 788	21.0	Bal	22.0			14.0	2.0	2.0			
* CMSX-3 is a registered trademark of Cannon-Muskegon Corp.											
∅ Amdry 788 is braze alloy from Sulzer Plasma Technik, Inc.											

Table 2. Nominal compositions of matrix materials used in the cermets

To produce a "lot" of this material via tape casting and rolling, a fixed amount of material input is required regardless of the lot size. These materials are mixed by low energy ball milling followed by the addition of an organic binder. The mixture is then tape cast and subsequently rolled to eliminate porosity and obtain the desired thickness. After rolling, the material is fired in a vacuum furnace to burn off the binder and consolidate the mixture by melting and diffusing the braze constituent. After densification the material is metallographically analyzed to determine whether it meets homogeneity and porosity requirements. To meet homogeneity requirements, the sintered material must exhibit no discrete layering or agglomeration of abrasive particles which would result in grit pullout causing a decrease in efficiency. Porosity requirements allow for no more than 20% linear porosity as determined from a metallographic montage using a line intercept method. If the material meets these specifications, coupons are removed and brazed into the gage section of a test bar conforming to ASTM E139 and subjected to an application specific stress-rupture test. The details of this test are provided in the results section of this paper.

The strength and oxidation resistance of the cobalt braze component are factors currently limiting the application temperatures. There are alternate methods of making brazeless cermets, such as HIP (hot isostatic pressing), ROC (rapid omni-directional compaction) and Electro-depostion. However, they are more labor intensive. Therefore, development of a direct SLS process for production of brazeless cermets will not only provide significant cost savings but also performance enhancement over that of the braze containing composition.

Cermet Production by SLS

Apparatus

The apparatus used for this research included SLS workstations equipped with Nd:YAG and CO_2 lasers. The indirect SLS work was done at ambient atmosphere using a 25 Watt CO_2 laser. The direct SLS work was conducted on SLS workstations equipped with 100 Watt and 250 Watt Nd:YAG lasers, powder bed heating capability and controlled atmosphere.

Processing Methods

Two SLS processing methods were investigated concurrently. The most desired method is direct SLS which involves directly melting and consolidating selected regions of a powder bed to form a desired shape having high or full density. Direct metal laser sintering involves melting the component matrix and obtaining the appropriate amount of flow from the molten material. The appropriate amount of flow is critical and can be described as the flow that eliminates porosity, produces a highly dense part maintaining dimensional tolerances and minimizes other defects such as hot tearing. The appropriate amount of flow is controlled by several factors such as atmosphere, powder bed heat and three characteristic variables affecting laser energy density: laser power, scan spacing and scan speed.

These SLS processing parameters can be refined within a working window depending upon the mechanical properties desired. In addition, a post-process heat treatment may be applied to modify the microstructure. The parameter used for microstructure refinement was the energy density[18] defined as

$$A_N = \frac{P}{v \cdot \delta} \quad (\text{J/cm}^2)$$

where

P is the incident laser power (Watts)
v is the laser scan speed (cm/s)
δ is the scan spacing (cm)

An alternative method investigated is indirect SLS. The term "indirect" implies that the metal powder is not melted directly by the laser. Instead, a low glass transition temperature polymer binder either mixed into the powder or present as a coating on the powder particles softens and flows during selective laser sintering. This polymer acts as the binding phase, giving strength to the "green" part. The "green" part is post processed to burn off the polymer and sinter the metal powder. The goal of this processing method was to develop the procedure into a process that incorporates laser volatilization of the binder immediately before or during direct SLS.

Indirect SLS material preparation

The constituent components were combined according to the compositions shown in Table 3 below and ball milled in a tungsten carbide container. The composition of the cobalt braze was varied to determine its effect on the final properties of the sintered composite, providing an optimized composition with respect to braze content. The amount of cermet grit remained constant in all mixtures. All grit except the grit used in Mixture 5 was coated with titanium.

Material	Composition 1	Composition 2	Composition 3	Composition 4	Composition 5	Composition 6
Alloy	Bal	Bal	Bal	Bal	Bal	Bal
Braze	24.3 wt.%	21 wt.%	18 wt.%	15 wt.%	24.3 wt.%	24.3 wt.%
Grit	Ti Coated	Ti Coated	Ti Coated	Ti Coated	Uncoated	Ti Coated
Binder	2.0 wt.%	2.0 wt.%	2.0 wt.%	2.0 wt.%	2.0 wt.%	2.0 wt.%

Table 3. Indirect SLS compositions

Initial trials indicated that there was a sporadic problem with grit segregation. To eliminate this problem, a slurry was created by adding acetone. The slurry was mixed in a motor driven stirrer. During mixing, the acetone evaporated leaving a highly viscous slurry paste which was pressed to form a thin cake and dried to volatilize the remaining solvent. The cake was crushed using a mortar and pestle to form a coarse powder composed of roughly 500 μm particle agglomerates. SEM micrographs are provided in Figure 2.

The agglomerate powder was placed in the stainless steel mold of a compression molding press. The platens of the molding machine were preheated above the binder softening temperature. Pressure was maintained during heat up and cool down. The fractional density of the bound and pressed preform was measured, using the linear intercept method, at 60%.

Indirect SLS processing

SLS processing included cutting the desired shape from the pressed preform using a 25 Watt CO_2 laser. Several passes were necessary at this laser power to completely penetrate the 0.060" preform thickness. Use of higher laser power of the order of 100 Watts would facilitate cutting the shape in a single pass. Other process trials addressed the volatilization of the binder utilizing low power scanning to facilitate direct SLS processing.

Direct SLS material preparation

Material preparation for the direct SLS method was simpler. The metal alloy and ceramic constituents were combined according to mixture 3 shown in Table 3 above and blended for 4-6 hours prior to loading in the SLS chamber.

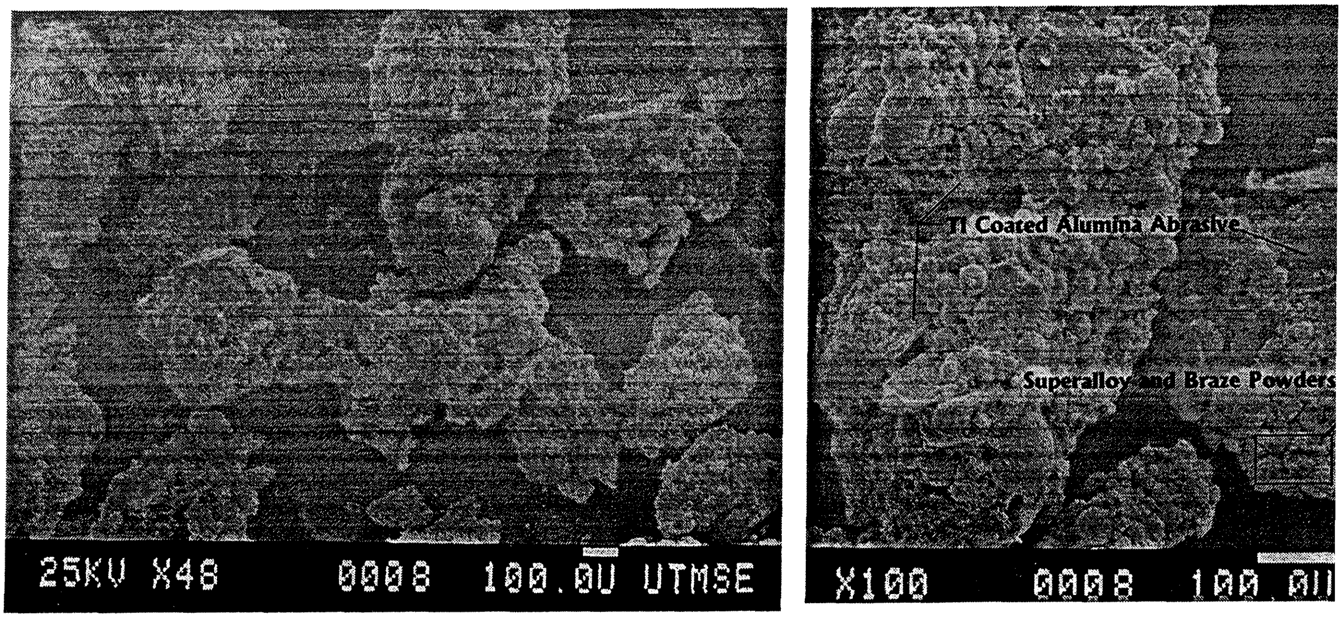

Figure 2. SEM micrographs of Agglomerates

Direct SLS processing

To characterize the behavior of the metallic constituents of this material system with respect to laser irradiation, the superalloy and the cobalt braze were individually processed by SLS. These initial screening trials indicated that structurally sound monolithic single layers could be produced. Typical microstructures from these trials are shown in Figures 3 through 5. However when the metal alloys were blended together the material exhibited severe balling. The balling of the alloy mixture is demonstrated by the photomicrograph of the sample in Figure 5. The uniform dendritic microstructure is indicative of thorough melting and mixing.

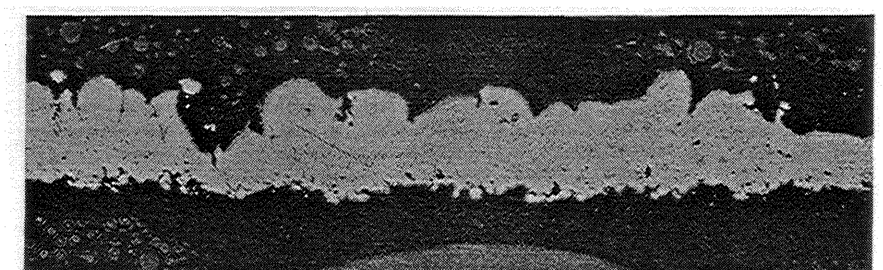

Figure 3. Direct SLS Mar-M-247, no etch, magnification 50X

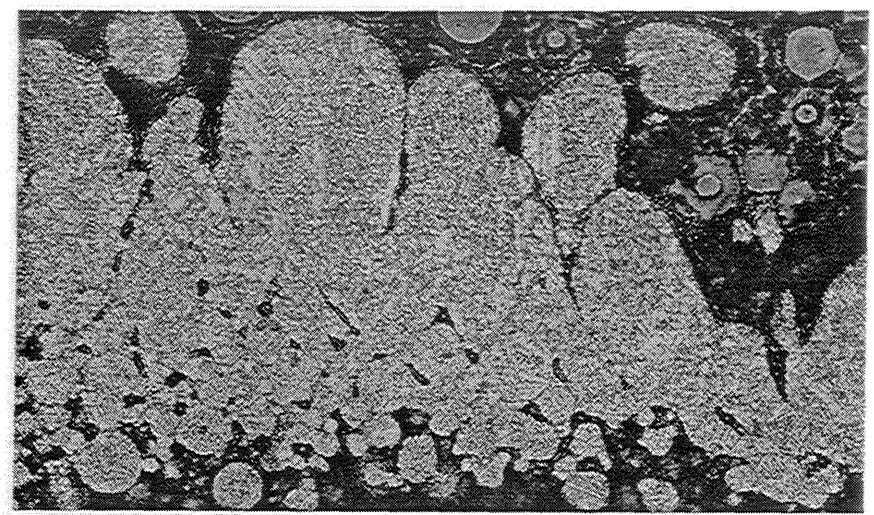

Figure 4. Direct SLS cobalt braze, no etch, magnification 200 X

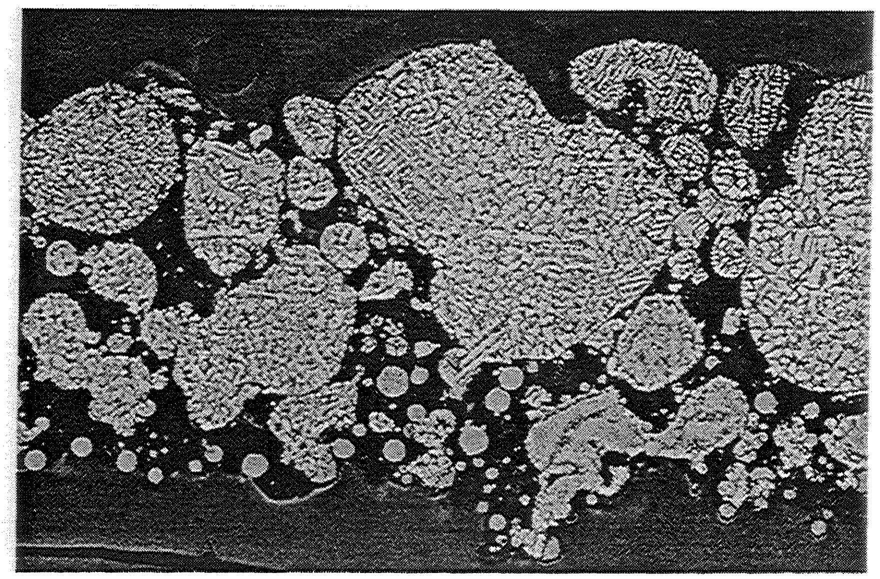

Figure 5. Direct SLS Mar-M-247 & braze alloy, magnification 200 X

As stated earlier, one of the goals of this research was to investigate the elimination of the cobalt braze alloy from the material system. Due to the severe balling exhibited by the standard mixture recipe, direct SLS of a brazeless cermet composition was pursued. This composition was formulated by replacing the weight fraction of the cobalt braze by the nickel base superalloy. This composition was utilized in all direct SLS experiments conducted for the remainder of the program.