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FABRICATION OF CERAMIC PARTS FOR A MINIATURE JET ENGINE APPLICATION USING MOLD SDM

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ABSTRACT

This paper describes recent progress towards using the Mold Shape Deposition Manufacturing (Mold SDM) process for the fabrication of structural ceramic parts for a miniature jet engine application. The goal is to improve the engine's thrust to weight ratio by increasing operating temperature and reducing weight. Mold SDM is an additive-subtractive layered manufacturing process for building fugitive wax molds which can be used to make ceramic parts by gelcasting. Monolithic casting eliminates layer boundaries which may be sources of weakness in the final part. Other advantages of Mold SDM for this application are the ability to produce smooth accurate surfaces for use in the engine's flow path and the fine features required for these small parts. Example parts and material property measurements will be presented.

INTRODUCTION

Mold SDM is an additive-subtractive layered manufacturing process for fabricating fugitive molds which can then be used to make parts using castable materials such as ceramic gelcasting[1] slurries and thermoset polymers[2]. Figure 1 is an example process sequence for the fabrication of a simple part using Mold SDM. Molds are currently fabricated from a variety of waxes. These are deposited by casting and are shaped by either 3- or 5-axis CNC milling. The mold is constructed layer by layer in steps 1 through 4. Each step represents one material deposition and shaping cycle. The support material is removed in step 5 and the part material is cast in step 6. After removal of the mold in step 7 finishing operations, such as casting feature removal, are performed leaving the finished part in step 8. Processes such as sintering can be performed at any time after mold removal.

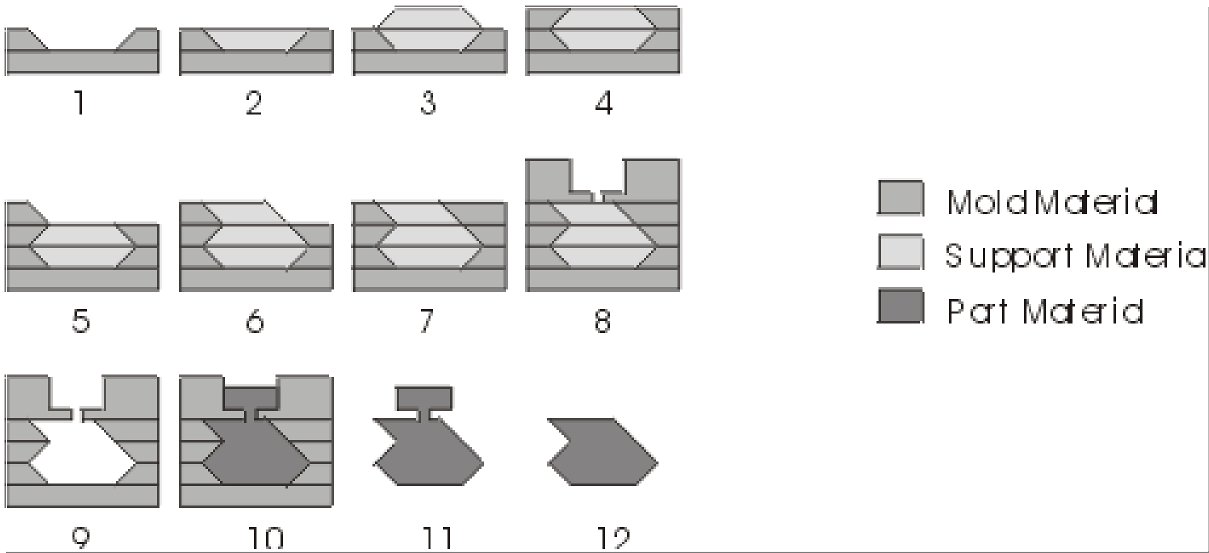

Figure 1: Example Mold SDM process sequence

Two features of the Mold SDM process are advantageous for the fabrication of complex structural ceramic components: 1) all surfaces are either machined or replicated from machined surfaces resulting in smooth accurate geometry, and 2) the part material is cast monolithically so there will be no layer boundaries, which are potential sources of defects, in the final part. Defects can arise from incomplete bonding between layers, or foreign particles or voids trapped at the layer boundaries. Both of these advantages are particularly important for flaw sensitive materials where surface roughness and internal defects can significantly reduce part strength.

Two examples of the types of part that can be produced using Mold SDM are shown in Figures 2 and 3. The sintered alumina turbine shown in Figure 2 consists of a rotor with eight curved blades that is free to spin about the captive shaft that passes through its center. This part was built pre-assembled and demonstrates the capability of Mold SDM to build ceramic components without any assembly. The pitch shaft shown in Figure 3 is a component from a missile guidance system. It is a sintered silicon nitride part. This part shows the ability of Mold SDM to produce complex parts with smooth surved curfaces.

MINIATURE TURBINE ENGINE APPLICATION

This paper focuses on one particular application of Mold SDM, the fabrication of ceramic components to replace metal parts in a prototype miniature turbine engine developed by M-DOT Inc., of Phoenix, AZ. The engine is a radial flow turbine engine that is 76 mm long, 41 mm in diameter and weights 85 grams. It is being developed as a power source for unmanned vehicles.

The goal is to improve the thrust to weight ratio of the engine by replacing parts currently made of metal with redesigned silicon nitride parts. Thrust to weight ratio will be increased both by reducing weight and by increasing engine operating temperatures to increase thrust. Two parts are currently being fabricated: the center seal and the turbine inlet nozzle.

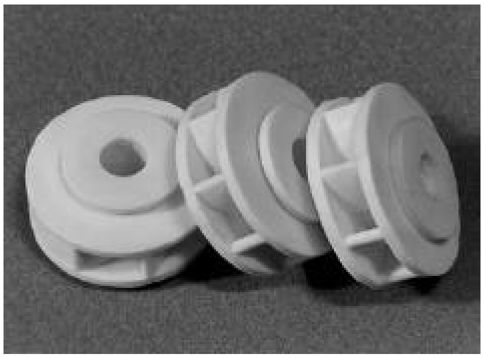

Figure 2: Alumina turbine

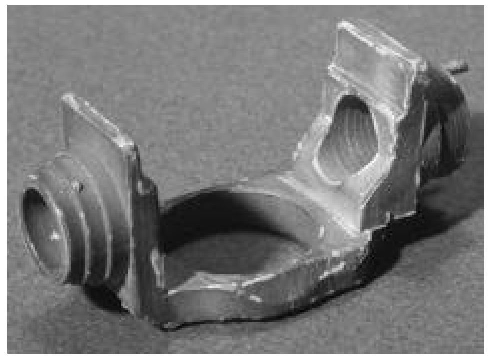

Figure 3: Silicon nitride pitch shaft

The first part is the center seal, shown in Figure 4. This part is about 2 mm thick and 31 mm in diameter. The complete center seal consists of two of these parts fitted together. This part forms the seal that prevents gas leakage between the hot turbine side of the engine from the cold compressor side. It also maintains a thermal gradient between the two sections. Making this a ceramic part will enable increased engine operating temperature and will also reduce the weight.

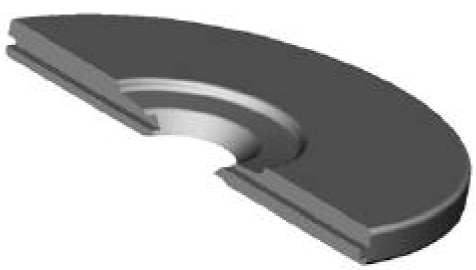

Figure 4: CAD model of the center seal

Figure 5: CAD model of the inlet nozzle

The turbine inlet nozzle, shown in Figure 5, is a non-rotating part that channels the hot gasses from the combustion chamber into the turbine. This part is about 35 mm in diameter and 9 mm tall. It experiences the highest static temperatures in the engine. Estimates indicate that a ceramic inlet nozzle could increase performance by 7%.

Because both of these parts were intended to be fabricated from superalloys they are currently being redesigned and optimized to take advantage of the different properties of silicon nitride. Despite the non-optimal design it was decided that these parts should be fabricated as is in silicon nitride as first run test parts. The information gathered from this initial fabrication run, as well as subsequent runs, will be used to iteratively refine the new ceramic part designs.

PART FABRICATION ISSUES

The ultimate goal is to use the ceramic parts fabricated using Mold SDM in an actual turbine engine. For the parts to be usable they must meet stringent requirements in terms of material strength, dimensional accuracy and surface finish. In addition, since the engine is so small it is critical that small detailed features be manufacturable and that the required shape complexity be achievable.

In terms of meeting these requirements the Mold SDM fabrication process can be divided into two stages. The first is the fabrication of the mold, the second is the production of a sintered ceramic part from the mold.

In the mold fabrication stage quality is primarily dependent on materials issues[3]. Material shrinkage during deposition, due to phase and temperature changes, results in distortion of the mold geometry. In extreme cases this can result in cracking or overall warping of the mold. With the current materials combinations the principal effect is to cause a slight discontinuity, or step, at layer boundaries. This is known as the Christmas Tree effect. The Christmas Tree effect can be reduced by using materials with lower shrinkages, by reducing casting temperatures and by using planning strategies that minimize the number of layer boundaries that lie in the middle of part faces.

High temperatures caused by casting and exothermic curing can also cause remelting of previously made geometry. This typically causes rounding of sharp edges and slumping surfaces. These effects can be minimized in a number of ways. Materials can be cast at lower temperatures, although this may result in insufficient interlayer bonding. When large amounts of material must be deposited, this can be done incrementally as a series of thinner coatings such that there is never a large amount of hot material in direct contact with machined features. Materials that cure exothermically can be cured in several stages, with cooling periods in between.

Machinability is also important for achieving part quality. Since features are either machined directly or replicated from machined surfaces, both the mold and support materials must be machinable. Materials that are too brittle will tend to chip along edges and those that are too soft will tend to clog the cutting tools resulting in rough surfaces. These effects can usually be minimized by machining less aggressively, by using higher pressure air to clear chips, or in the case of soft materials, by using cooled air to clear the chips. The use of cold air tends to decrease the stickiness of the waxes used in Mold SDM and thus reduces the chance of them clogging the cutter.

The main issues in the part fabrication stage relate to the casting, demolding and sintering steps.

The casting step consists of mold filling and then curing of the gelcasting slurry in the mold. The ease with which the mold can be completely filled depends on the design of the mold, the viscosity of the slurry and its working time. Molds are designed with a number of vents and are cast in an orientation such that they can be filled completely without trapping gasses inside. The slurry formulations have been optimized to reduce viscosity and their cure conditions allow working times on the order of half an hour. Full cure can be achieved in 1 hour at 60 °C or overnight at room temperature. Initially many of the cured parts exhibited flaking on the surface which resulted in poor surface quality. This is believed to be due to cure inhibition due to adsorbed oxygen on mold surfaces. This problem can be solved by using different mold waxes or by avoiding the presence of oxygen when casting and curing the slurry.

The main issue during demolding is avoiding damage to the green part. Currently demolding is performed by heating the mold and cured part until most of the wax mold material has melted off. Any remaining wax is then cleaned off the part using a heated organic solvent. For parts cured at room temperature the melting step can break the parts due to the thermal expansion of the wax mold material before it begins to soften. This effect is more pronounced on parts with cavities or hoops which surround sections of wax. Currently this problem is avoided by curing the part at a temperature close to the softening temperature of the mold wax. Improvements to the gelcasting slurries should be able to increase green part strength to minimize this effect.

Sintering shrinkage is a major issue for geometrical part accuracy. Gelcast parts tend to shrink very uniformly during sintering but if parts are not correctly supported they will tend to sag and warp. Silicon nitride parts are currently sintered in a powder bed to provide support. For some parts, such as the pitch shaft shown above, a complementary green ceramic fixture is made to support the part during sintering. Because the support is made from the same green ceramic as the part both pieces will shrink together and maintain alignment.

In addition, there are a number factors that affect the part fabrication rate but do not directly affect part quality. These include the cooling time required after material deposition, the time required to cure materials, machining time and the time required to remove the support and then mold materials.

CENTER SEAL FABRICATION

The center seal part shown in Figure 4 is relatively simple geometrically. It is basically one half of a washer shape with a rounded outside edge, tapered inside edge and a tongue and groove on the ends to allow two of these parts to fit together. In order for pairs of these parts to fit together the small features of the tongue and groove must be made very accurately. These features are about 0.5 mm thick with 40 µm clearances.

For fabrication the center seal parts were decomposed into two layers, as shown in Figure 6. A large casting hole can be used on top since the top surface can easily be machined flat after casting. The larger the casting hole the easier it is to remove the support materials and then fill the mold.

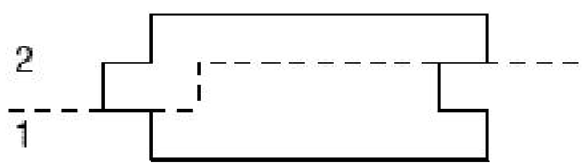

Figure 6: Centerseal decomposition

The center seal parts were fabricated using Kindt-Collins Master Protowax as the mold material and Kindt-Collins KC1665 water soluble wax as the support material. Both of these materials are deposited by casting from the melt and since both are thermoplastic materials with similar melting points it is likely that features will be damaged by remelting. If the melting points are very different then features created in the lower melting point material will be damaged during casting of the higher melting point material. Features in the higher melting point material will not be damaged much, if at all, during casting of the lower melting point material. To minimize the risk of feature damage the best compromise is to use materials with similar melting points.

With the materials used to fabricate the center seal parts it was found that casting at 10°C above the melting point produced negligible remelting and feature damage. However because of the low casting temperatures the cast material tends to solidify very rapidly when it contacts the surface and does not always have sufficient time in the liquid state to fully and accurately replicate the surface details. Mild preheating of the surfaces prior to casting overcomes this effect. Excessive preheating can cause feature damage either during preheating by melting or during casting if the material has softened too much.

The support material was removed by dissolving it in water. This operation took approximately 4 hours in room temperature water with gentle agitation.

Parts were then cast using the proprietary non-aqueous silicon nitride gelcasting formulation developed by Advanced Ceramics Research of Tucson, AZ. The casting operation was performed under nitrogen and degassing was used to eliminate bubbles during casting.

Mold removal was performed by first melting off most of the wax in an oven in air. Temperatures are typically between 90 and 120°C. Any remaining wax was then removed using heated BioAct 280 organic solvent. The solvent bath is usually operated at 90°C.

The green parts were then dried in ambient air at 90°C for 2 hours followed by 12 hours at 160°C. No humidity control was used. Burn out was also performed in air at temperatures up to 600°C over 36 hours. To ensure that the center seal parts would fit together after sintering pairs of green parts were fitted together during sintering. The sintered silicon nitride parts, shown in Figure 7, exhibited smooth surfaces and fit together after a slight de-buring process on the tongue and groove.

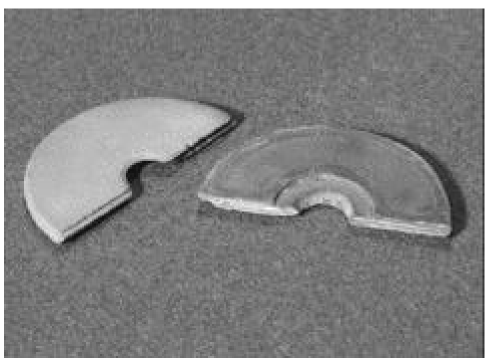

Figure 7: Sintered silicon nitride center seals

INLET NOZZLE FABRICATION

The inlet nozzle part shown in Figure 5 is much more complex geometrically than the center seal. Many of the features have sharp edges and corners and one of the goals of the fabrication was to see how well these features could be produced.

The decomposition produced 4 layers as shown in Figure 8. Each layer required several deposition and machining cycles to build because of the technique required to produce sharp corners.

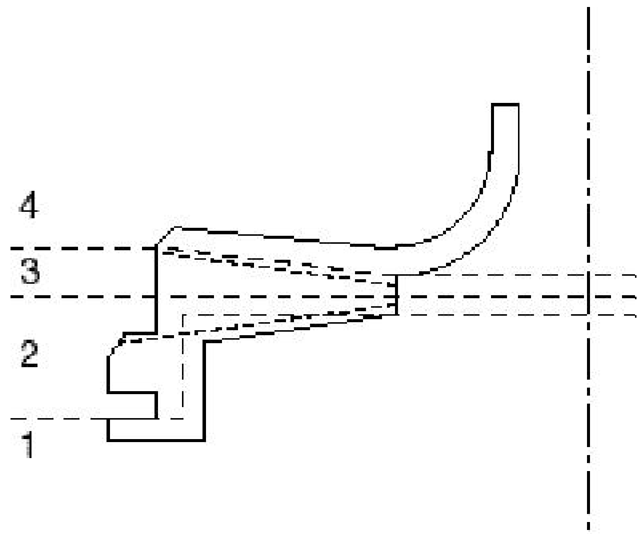

Figure 8: Inlet nozzle decomposition

Because Mold SDM uses conventional machining to create geometry it is not possible to produce sharp internal corners directly. Using smaller diameter milling cutters will produce better approximations to a sharp corner but because the cutter diameter is finite a perfectly sharp corner can't be made. To produce sharp corners the procedure illustrated in Figure 9 in top view is used. The desired geometry in shown in step 1 by the dashed line. When machining a cavity that requires a sharp corner one side adjacent to the corner is overcut by at least the tool radius (step 2). Material is deposited into the cavity (step 3) and then the excess material is trimmed back to the desired final shape (step 4), producing the sharp corner geometry. The last step is to backfill the slot left from trimming (step 5).

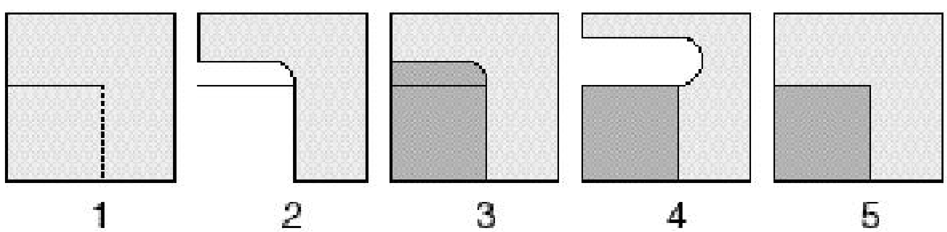

Figure 9: Sharp corner fabrication technique

The inlet nozzle parts were fabricated using a mixture of 25% Kindt-Collins Master File-a-wax and 75% Kindt-Collins Master Protowax as the mold material and a mixture of 80% Electro-lite ELC4497 and 20% Dymax 9-20311-F UV-curing water soluble soldermasks as the support material. The addition of 25% File-a-wax to the Protowax increases the machinability of the wax making it easier to machine the fine features required for this part. The soldermask mix was also created to improve the machinability. When cured the ELC4497 is very brittle and chips easily. The 9-20311-F is a much more rubbery material and this increases the toughness of the mix making it more machinable.

The use of soldermask instead of the water soluble wax as support material has both advantages and disadvantages. The principal advantage is that the soldermask is more temperature resistant than the water soluble wax. There is therefore less likelihood of features in the support material being damaged during deposition of the mold material. The principal disadvantage of the soldermask is that it has a cure depth of only about 1 mm so that thick sections must be build up using multiple deposition and curing cycles. It is also a fairly viscous material which increases the chances of bubbles becoming trapped in the material during deposition. These voids can cause geometrical defects if they are located on surfaces.

Once the molds were completed the soldermask was dissolved in water. The soldermask dissolves more slowly than the water soluble wax, and since these molds contained much more intricate cavities it took approximately one week to fully etch the molds in gently agitated water. The water was changed several times during the process to help speed the dissolution.

Subsequent process steps were identical to those used for the center seal parts. Figures 10 and 11 show a finished silicon nitride inlet nozzle.

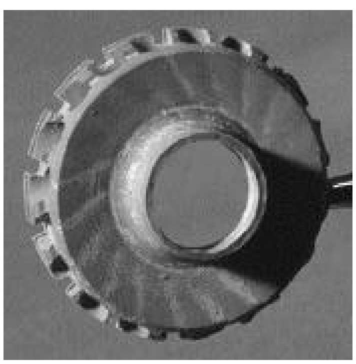

Figure 10: Sintered inlet nozzle

Figure 11: Sintered inlet nozzle

RESULTS

The flexural strength of sintered silicon nitride test bars was measured in four point bending. The test bars were fabricated using the same procedure as is used for part fabrication. Bars were tested as made and were not ground or polished.

The average strength was calculated to be 414 ± 70 MPa with a Weibull Modulus of 9.6. The strongest test bars had strengths of approximately 590 MPa.

Sintering shrinkage was measured on the test bars as well as the center seal and inlet nozzle parts. Shrinkage of the test bars was measured to be about 16% linear and was measured relative to the demolded and dried part size. Shrinkage for the center seal and inlet nozzle parts was measured to be 16-18% linear. These values were measured relative to the mold cavity dimensions and may be slightly higher than for the test bars due to a small amount of shrinkage during drying. These shrinkage numbers will be used to scale up future part designs such that they shrink to the correct final size.

The surface roughness of the faces of the center seal parts was measured using a profilometer over distances of approximately 6 mm. The lower surfaces, where the geometry was replicated from a machined surface, had RMS roughnesses of 0.5-0.7 µm. The upper surfaces, where the casting features were cut off by manual machining of the green part, had RMS roughnesses of 1.3-1.8 µm. These values compare favorably with values of 4 µm reported for ceramic parts produced by stereolithography[4].

These surface roughness values are for horizontal surfaces only, but even for inclined surfaces Mold SDM should be able to produce good quality surfaces. The use of 5-axis milling should produce surface finishes that are independent of surface orientation. In the worst case ball endmills would be used with 3-axis machining to produce inclined surfaces. Even in this case surface convergence will be more rapid than with stacking of 2.5D layers.

Comparisons between the soldermask and water soluble wax support materials indicate that there is a potential to increase process rate by switching to the water soluble wax. Soldermask deposition tends to be time consuming due to the low cure depth which requires thick sections to be built up as a series of thin layers. The water soluble wax also dissolves much more rapidly. The only drawback of the water soluble wax is its lower temperature resistance which can result in poorer surface quality.

CONCLUSIONS

Mold SDM has been successfully used to make complex silicon nitride parts for a miniature jet engine application. These parts demonstrated the capability of Mold SDM to produce complex shapes with fine accurate features and smooth surfaces.

Flexural strength measurements indicate that the parts have a slightly lower than expected strength. Improvements to the gelcasting slurries as well as processing parameters are expected to increase the strength in the future.

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