FREEFORM POWDER MOLDING FOR RAPID TOOLING

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ABSTRACT

Tooling development can be quite time consuming and costly. Several iterations may be required, and later product or process modifications may necessitate tooling redesign. Rapid prototyping techniques capable of meeting the structural requirements of short-run and end-use tooling will have a significant impact on the product development cycle. This paper presents a technique for producing tooling using the Freeform Powder Molding process. Resulting tooling can be made from a wide variety of readily available metal powders, and mechanical properties can be tailored for customized tool design and fabrication. The example presented in this paper focuses on the rapid production of tooling for sheet metal forming.

1. INTRODUCTION

Since the emergence of the first commercial Solid Freeform Fabrication (SFF) processes, SFF system production rates have been unable to match the rates of conventional high-volume manufacturing operations such as injection molding, die casting, and stamping. While substantial progress has been made toward producing SFF components from engineering materials, throughput limitations continue to remain a formidable obstacle to the deployment of SFF systems in production. If these systems can be used to produce tooling for high-volume manufacturing processes, then throughput limitations can be surmounted while realizing many of the benefits associated with SFF, and more generally with Rapid Prototyping (RP). This use of RP to make tooling offers one means for realizing Rapid Tooling (RT). Rapid tooling allows early implementation of production manufacturing techniques and materials to evaluate product designs earlier in the development cycle than is possible where conventional techniques are used to fabricate tooling.

This paper introduces a technique for quickly producing tooling based on the two-material Freeform Powder Molding (FPM) concept [1], and the notion of freeze molding [2]. While much work has been published on the use of RP parts as patterns [3-5], particularly for casting applications [6-8], this work describes the *direct* use of an RP part as a mold for shaping metal powder. The resulting molded metal object then serves as tooling for sheet metal forming. Before discussing details of tooling production, a brief introduction to FPM and freeze molding are provided.

1.1 Freeform Powder Molding

The FPM process relies on material behavior differences to selectively define component shape [1]. By arranging powders with different diffusion kinetics within some confining volume, it is possible to process the entire volume and cause only one of the materials to consolidate while the other remains a loose powder. This is illustrated in Figure 1, where material that consolidates is termed *part powder* and material which does not consolidate is termed *tool powder*. In this example, the part powder represents a part which will become the tooling used for metal forming.

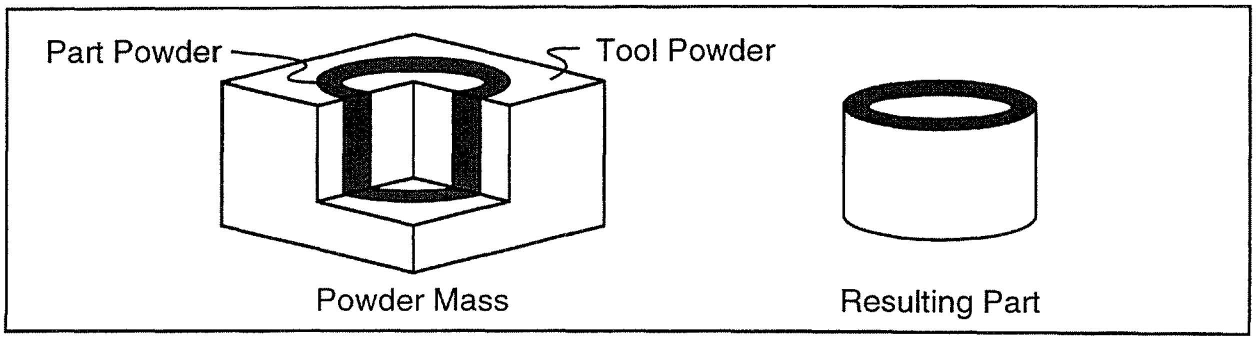

Figure 1 - Freeform Powder Molding Two Material Concept [1]

The tool powder essentially forms soft tooling which both supports, and in conjunction with the part powder, defines the shape of the resulting component.

Although originally envisioned as a layer-wise SFF process, the underlying process concept can be applied when alternative shape defining techniques such as freeze molding are employed. Powder can be shaped by molding, and then surrounded with tool powder to preserve its shape during carrier melting and subsequent removal.

1.2 Freeze Molding

Freeze molding, also referred to as freeze casting, presents a low-cost alternative to powder processing techniques requiring costly tool sets. Freeze molding was originally explored to bring concurrency to FPM process development and distortion compensation research [9]; however, the results of this work suggest it has merit as a secondary material conversion alternative for RP. A slurry of powder and carrier is introduced into a mold at low (or no) pressure and the mixture is frozen [2]. Molds can be fabricated from a variety of inexpensive materials which can be easily machined or they can be produced by a variety of commercial RP processes. Since the powder slurry is not injected into the molds under high pressure, the geometric complexity of the molds may be limited.

Aqueous carriers are used because they can be easily frozen. Carriers may contain additional constituents which support the development of green strength after shaping of the powder compact and sublimation of the principal carrier component. The presence of some organic binder is particularly important if the compact is dried rapidly, as this can cause cracks within the compact [10]. Unfortunately, carrier sublimation takes a long time and this disadvantage is similar to the debinding operation necessary with powder injection molding [2].

While typical freeze molding requires carrier sublimation and compact green strength development, these are not required when coupling freeze molding with FPM.

2. Rapid Tooling Production Procedure

The following procedure is used to produce tooling. A mold is created by RP and used to shape a powder mass. This powder is subsequently sintered to realize a solid component which has the physical properties required of tooling. The resulting tooling is used to make the final desired component, which in this application is formed sheet metal. Figure 2 depicts the sequence of operations used for rapid tooling production. While oversimplified by this depiction, this procedure was quite straight-forward and efficient to implement. The complete rapid tooling sequence from die design to sheet metal forming could be completed in only four days given this simple forming geometry.

2.1 Powder Selection & Preparation

Rapid tooling was fabricated using both Anval 316 stainless steel powder with a particle size of -325 mesh/+16 μm and Novamet 4SP elemental nickel powder with a particle size of -20 μm/+10 μm. Both powders are chemically compatible with the carrier used during freeze molding. Both powders also have relatively small particles to promote rapid sintering to maximum density given loose powder preforms. The small particles help to develop a fine grained microstructure in the resulting sinter-body which leads to improved mechanical properties. Both powders have particles of spherical morphology so they pack to a high initial density, relative to irregularly shaped powder, in the absence of external compaction pressure.

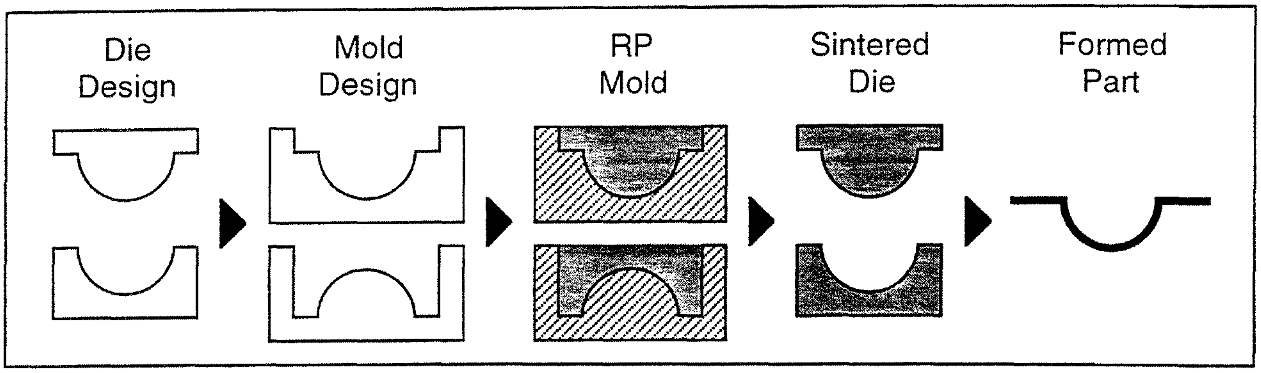

Figure 2 - FPM Rapid Tooling Procedure

An aqueous carrier comprized of water with 10% by volume ethyl alcohol to facilitate particle wetting was used in this work. This carrier was selected because it was easily frozen and later removed from the powder. No additional organic binding constituents were necessary since the modified freeze molding procedure does not require that the compact develop green strength or that it withstand sublimation which may lead to crack formation. Each powder was manually stirred into the carrier, and sufficient carrier was used to ensure the powder remained completely saturated.

The powder used to support the rapid tooling in the frozen state and during sintering, known as *tool powder* given the FPM process definition, was Norton #204 yttria zirconia. Also spherical in shape, this powder has a broad powder size distribution below 180 µm. It is important that this powder have sufficiently different diffusion kinetics such that it will not sinter at the given processing conditions.

2.2 Mold Fabrication & Filling

Molds suitable for shaping the powder slurry described previously can be made in a variety of ways provided the mold material can withstand the temperatures required to freeze the powder slurry and is compatible with slurry chemistry. To realize the many benefits of rapid prototyping which contribute to this rapid tooling process, the molds should be produced using manufacturing automation guided by CAD model information. A major goal of this effort was to show that RP parts can be used directly to cast the powder slurry. Molds were produced both by the Stereolithography process and by NC machining. These are shown in Figures 3 and 4, respectively. Relatively simple die shapes were selected for the sheet metal forming example in this paper to simplify mold design and fabrication.

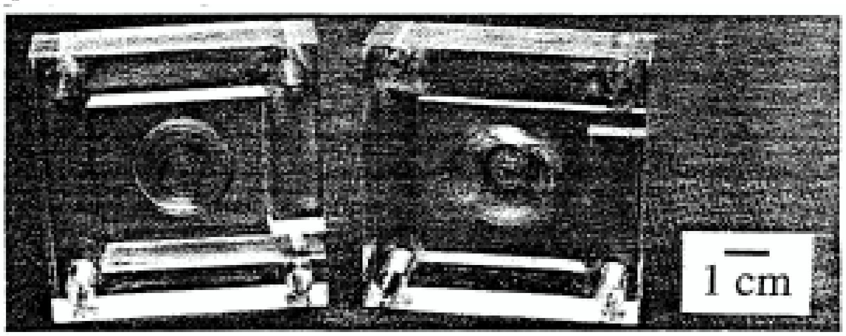

Figure 3 - SOMOS 6110™ SLA Mold Set

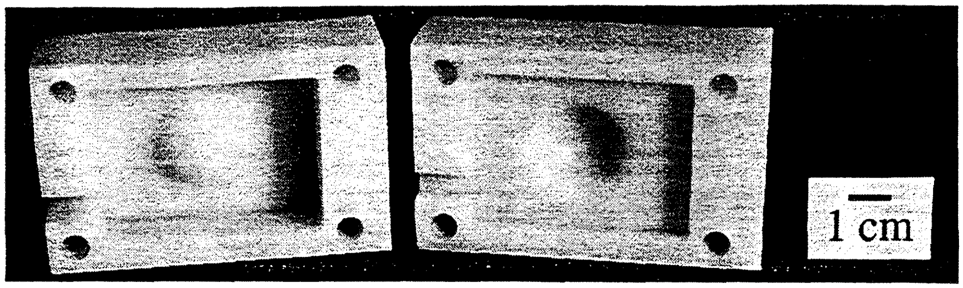

Figure 4 - Acetal Resin NC Machined Mold Set

This tooling geometry is similar to the ball punch deformation test specified by ASTM E643 [11]. Sintering furnace size also restricted the tooling size.

The molds were designed to produce dies with a suitable clearance to accommodate the 0.033" sheet metal thickness. A draft angle of 3° was designed into the vertical walls of the mold to facilitate part ejection. Each mold is designed to attach to a backing plate (not shown) which provides a flat surface on the back of each metal forming tool necessary for attachment to press equipment. Molds are filled from one side via a rectangular gate. Mold filling is performed manually under the influence of gravity. The molds are lightly tapped as the powder slurry is added to facilitate the powder fill.

2.2.1 Stereolithography Molds

One set of molds was fabricated directly by Stereolithography (SLA) using a 3D Systems SLA-250/40. The molds were fabricated from the recently introduced DuPont SOMOS™ 6110 epoxy photopolymer resin using 0.006" thick build layers.

Geometry for these molds was designed using Pro/Engineer and exported as an STL facet file with a chordal deviation set to 0.0004" to minimize tessellated surface artifacts. Such artifacts were nearly impossible to observe in the manufactured parts; however, the well-documented spatial aliasing (stair-stepping) caused by layer-wise fabrication was evident. The molds were used in as-manufactured condition without manual post-processing (e.g. sanding, polishing, etc.), with exception of the manual filling of a small hole added for trapped-volume pressure equalization during resin recoating [12]. Prior to slurry filling a silicone-based molding release agent was applied to the SOMOS 6110 material.

2.2.2 NC Machined Molds

Another set of molds was fabricated by NC machining using an acetal resin (DuPont Delrin™). This material machines easily and yields a high quality surface finish without subsequent hand finishing. It has been used extensively in other freeze molding shaping applications [9].

Molds were fabricated by NC machining to illustrate the potential role that more conventional manufacturing processes hold for rapid tooling. The benefits of solid modeling and ease with which information is handled by SFF processes became painfully clear during the 2D mold design and CAM path planning steps leading to cutting the molds. These activities accounted for much greater delay than actually cutting the plastic mold material. However, for a fair comparison to be made between SFF and NC machining RP approaches, both processes should be driven from a 3D solid model.

2.3 Modified Freeze Molding

A variant of the freeze molding procedure described in section 1.2 was used to shape the powder which ultimately becomes the rapid tooling of interest. Molds filled with the powder/carrier slurry were frozen using dry ice, with both the SOMOS 6110 and acetal molds first cooled to in a refrigerator freezer to reduce the potential for mold damage due to thermal shock [12].

After 30 minutes in the dry ice, the molds were returned to room temperature (~20° C) and allowed to warm for approximately 4 minutes. The molds are inverted and taped gently until the still-frozen powder mass is released from the mold. The frozen powder mass is placed in a furnace boat on a layer of FPM tool powder and then subsequently surrounded with more tool powder before slurry melting begins.

The frozen powder slurry is allowed to melt, as the furnace boat remains at room temperature throughout storage and transport to the sintering furnace. The FPM tool powder is sufficient to retain tool powder shape during carrier melting. The presence of the tool powder may also facilitate carrier removal through capillary action by wicking the carrier away from the part powder as has been demonstrated for debinding powder injection molded components [2]. Since sublimation is not required for carrier removal and since the part does not need to develop green strength to be self-supporting, no organic binder constituents are used in the carrier mixture.

2.4 Carrier Removal & Sintering

The carrier used for freeze molding must be evaporated and the powder used for rapid tooling must be sintered. This is accomplished using a sintering furnace under protective atmosphere. Tooling was produced in both 316 stainless steel and nickel. For both powders, the sintering process was begun by heating the furnace to 85° C. This temperature was held for 1.5 hours. Then, the furnace temperature was increased to 115° C. This temperature was held for 1.5 hours to remove the carrier. Lengthy debinding times required for freeze drying sublimation are cited as a potential disadvantage of freeze molding [2]; however, it is unclear if the three hours used here is comparable to these times. Furnace temperature was then increased at 10° C/min. to a maximum sintering temperature of 1200° C for both 316 stainless steel and nickel powders. The powder was held at these temperatures for 45 minutes. The furnace cool-down commences at a rate no faster than 5° C/min. Sintering time is selected to minimize grain growth and is consistent with that recommended in the literature [13]. The nickel powder is sintered in an inert atmosphere of argon. The 316 stainless steel powder is sintered in a reducing atmosphere of dry hydrogen. The sintering cycles and atmospheres have not been optimized for the specific powders used.

3. Experimental Results & Discussion

The procedure described above was used to sinter dies for the example application of sheet metal forming. Fully dense material was not required for this demonstration; however, infiltration may be used in applications where improved mechanical properties or non-permeable tooling is required. This procedure should be suitable for producing prototype and short-run production tooling for a variety of other manufacturing processes such as injection molding, composite lay-up, sink-type EDM, extrusion, and thermoforming. The results presented below illustrate the potential utility of the FPM rapid tooling technique described here.

3.1 Part Ejection

Part ejection from the NC machined molds was relatively straight-forward. After allowing a short period for mold warming following freeze molding, gentle tapping is used to eject the resulting part. The part surface appeared quite smooth and even fine features on the molds, such as the marks from cutter rotation along tool paths, were visible on the molded part.

Part ejection from the SLA molds was slightly more difficult. Despite the use of mold release, a significantly longer duration was required to allow the molds to warm before parts could be ejected. While this may be due to different thermal conductivity of the mold materials or different geometries of the molds, inspection of the mold suggests that many of the 0.006" layers comprising the SLA part create undercuts which hinder part ejection. Figure 5 shows a magnified view of the near vertical mold walls. Despite the presence of a 3° draft angle on these walls, it is thought that significant thermal expansion of the frozen mold must occur before the part can be ejected.

Upon ejection, many small fragments of the molded powder slurry (still frozen) are found resting loose on the top surface of the mold. This suggests that even thermal expansion of the mold does not fully release the frozen mass in all locations. These fragments can be removed by suction before they melt, and their breakage from the molded part does not appear to significantly impact tooling performance for the example application.

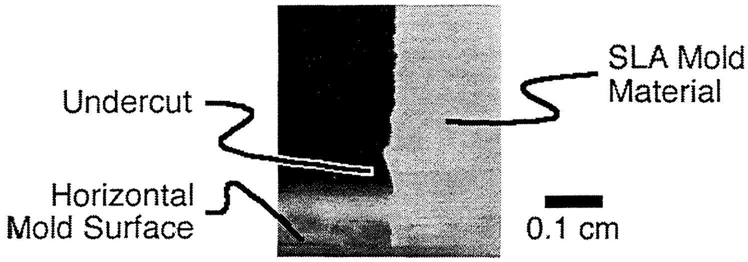

Figure 5 - SLA Mold Wall Undercuts

Similar artifacts likely exist with other layer-based SFF processes, and this illustration is not intended to suggest that the SLA process is unsuitable for this application. In fact, the SOMOS 6110 epoxy resin molds withstood both the thermal cycle of molding and impact required for part ejection without damage. In contrast to past experience with fragile parts made from early SLA resins, the SOMOS™ 6110 parts appeared to be quite tough. Constructing parts from finer resin layers or employing some additional finishing operation(s) may improve part ejection.

3.2 Sintered Dies

After sintering as described in section 2.4, the dies must be removed from the FPM tool powder in which they were embedded. This is accomplished simply by brushing the loose tool powder from the dies. Figure 6 shows the resulting nickel die set (left) produced by the SLA molds and the 316 stainless steel die set (right) produced by the NC machined molds.

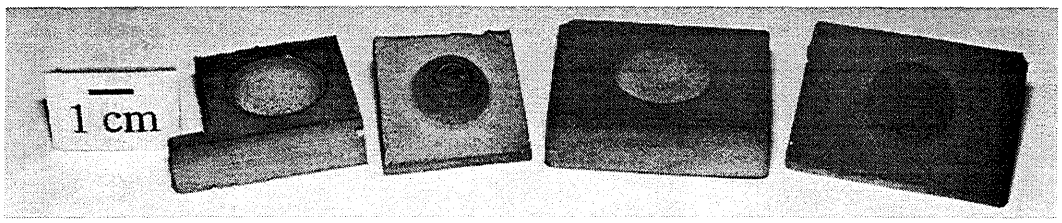

Figure 6 - Sintered Nickel Die Set from SLA Molds (left), and
Sintered SS316 Die Set From NC Machined Molds (right)

The layer-wise stair-stepping of the SLA molds transfers to the die-set, with some evidence of sharp corners of the stair-steps being damaged during mold ejection. Although not clearly visible in Figure 6, the NC machined dies pick-up fine detail from the mold surface showing the concentric paths of the ball mill used to fabricate the mold protrusion.

3.2.1 Dimensional Change

Material shrinkage resulting during consolidation caused dimensional reduction of both die sets. On average, the nickel shrunk 15.4% when measured linearly. The 316 stainless steel shrunk 3.4% when measured linearly. When material shrinkage is uniform it is possible to account for it simply by model scaling. Shrinkage experienced at prescribed processing conditions would typically be determined prior to mold design, and this shrinkage taken into account to over-size the mold geometries by an appropriate dimension. In this experiment, the additional steps of shrinkage compensation were not performed and a smaller-than-designed mold geometry was accepted for demonstration purposes.

Some non-uniform shrinkage was observed along the die axis held vertical during mold filling. This is believed to be caused by the development of density gradients in the compact as a result of mold filling. Deviations of 0.3% and 0.4% were observed on the female 316SS and nickel dies; however, the male dies exhibited deviations of 1.2% and 3% for the respective die material. This increased error is throught to result from poor mold filling due to the small mold gate in the male die molds, as shown in Figures 3 and 4 above. Alternate gate geometries or improved mold filling techniques will likely eliminate this non-uniformity.

3.2.2 Microstructure

Analysis of the microstructure confirms the expected — tooling sintered from loose powder is rather porous. Figure 7 shows the microstructures of the sintered nickel and 316 stainless steel die materials.

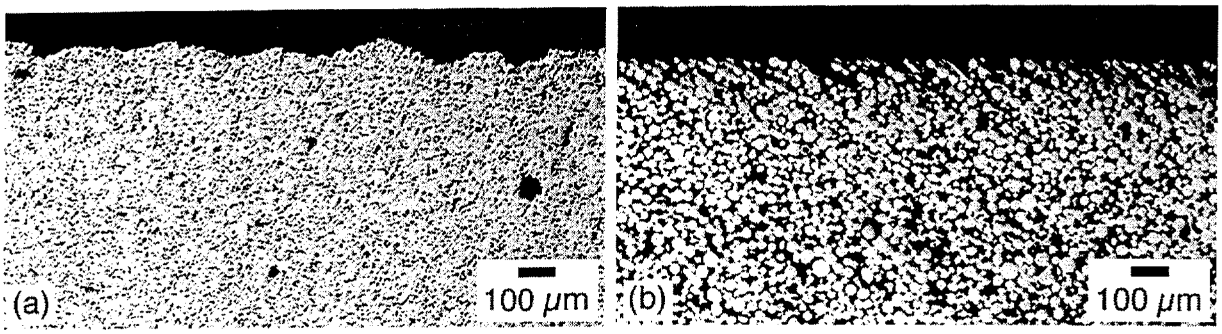

Figure 7 - Microstructure and Edge of (a)Nickel and (b)316 Stainless Steel FPM Rapid Tooling

Optical density measurements using image processing techniques indicate densities of 80% of theoretical for the nickel dies and 60% of theoretical for the 316 stainless steel dies. However, density improvement should be possible with an optimized sintering schedule.

These micrographs also illustrate the surface quality obtained on the near vertical edges (shown horizontally in this figure) of the tooling made by the SLA molds (a) and by the NC machined molds (b). The rougher surface finish of the SLA molds transfers to the tooling. However, surface roughness as related to particle size must also be considered. The internal microstructure of the parts reflects the spherical morphology of the powders used to produce them. Note that both parts are porous and appear to be only stage one sintered. This enables application of infiltration or impregnation to realize fully-dense tooling, and either of these operations would serve to somewhat smooth the surface finish of the tooling. Pores resulting from gas entrapment during molding have been observed in some sintered material, and measures must be taken to eliminate these in practical situations.

3.3 Metal Forming

The sintered dies were installed on a press and forming was attempted on 0.033" low-carbon mild sheet steel. This steel fractured during pressing on the unlubricated dies. Examination of the metal flow of the sheet after forming suggests that high die friction near the fillet between the female die parting plane and the hemispherical depression is probably responsible for this forming failure. Instead of attempting to improve die surface finish manually, as is common even with production tooling, a 0.005" teflon film was used as an interpolator between both dies and the sheet metal during a second forming trial as suggested by [14]. This time the material did not fracture and forming was successful. Figure 8 illustrates both the failed (a) and successful (b) forming trials using the SLA molded die set and the successful (c) forming trial using the NC machined molded die set.

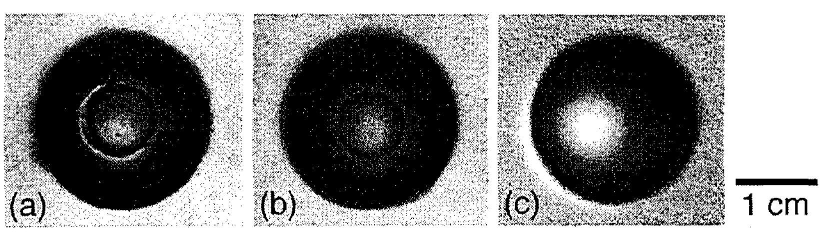

Figure 8 - Metal Forming Results on 0.033" Sheet using (a) Unlubricated Dies from SLA Molds, (b) Dies from SLA Molds with Teflon Interpolator, and (c) SS316 Dies from NC Machined Molds

Although applying an interpolator sheet to the die surface instead of manual finishing may not be an economically viable alternative for high-volume part production, it is suitable for prototyping and low-volume work where minimizing die fabrication time is advantageous. Analyzing the affect of additional forming variables, such as pressing rate or binder tension were beyond the scope of this research effort.

4. CONCLUSION

The preceding results indicate that FPM/freeze molding is a useful secondary material conversion option for RP. This conversion route uses RP parts directly as tooling for powder shaping. This method can be used to quicly fabricate tooling from conventional materials as well as a number of high performance materials that can only be processed using powder metallurgy. This paper focused on sheet metal forming, however, a variety of other tooling such as injection molding cores and cavities, composite lay-up forms, EDM electrodes, extrusion dies, and thermoforming tooling may also be produced using this approach.

Turn-around-time for the tooling featured in this report was relatively short. In an ideal case, in-process time breaks down as follows:

- Day 1: Design formed part geometry and die geometry, fabricate RP molds that evening;
- Day 2: RP molds in transit;
- Day 3: Prepare powder slurry, fill & freeze molds, eject parts and embed in FPM tool powder, remove carrier and sinter over-night;
- Day 4: Remove solid tooling from embedding powder; use dies to press and form sample.

Since mold filling and ejection are manual operations, and the resulting powder compact is fragile, more than one molding attempt may be required to realize a preform of suitable quality. If full density tools are required, additional time must be allocated for infiltrating, impregnating, or hot isostatic pressing.

Additional investigation is certainly required to determine how the FPM/freeze molding approach described in this paper compares with alternative secondary material conversion options for RP and alternative rapid tooling methods. It must also be contrast with direct methods for tooling production. The FPM rapid tooling procedure eliminates the need for the production of molds from RP patterns by directly creating the mold. This removes one shape conversion operation which reduces delay and may increase tooling precision. If layer-based SFF parts are used as molds, this technique still suffers the delay associated with layer-wise additive material build-up; however, this delay must only be incurred once during mold production. The resulting molds can be used to shape powder multiple times. Consequently, the "cost" of layer-wise fabrication may be amortized across multiple parts — whether these parts represent rapid tooling or end-use components. Alternatively, when relatively simple geometries are involved, NC machining can be performed quite efficiently on plastic mold material. Driven by appropriate CAM software, this is an RP/RT path which should not be overlooked.

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