SELECTIVE LASER SINTERING OF METAL MOLDS: THE RAPIDTOOL™ PROCESS

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ABSTRACT

Complex three dimensional parts can be manufactured directly from CAD data using rapid prototyping processes. SLS® Selective Laser Sintering is a rapid prototyping process developed at the University of Texas at Austin and commercialized by DTM Corporation. SLS parts are constructed layer by layer from powdered materials using laser energy to melt CAD specified cross sections. Polymer, metal, and ceramic powders are all potential candidate materials for this process. In this paper, a commercial SLS process - the RapidTool Process - which allows metal molds to be rapidly manufactured is described. With this process, a polymer coated carbon steel powder is used to fabricate a "green part" in the SLS machine. The green part is then placed in a furnace with blocks of copper and, in a single furnace cycle, the polymer coating is removed and the steel skeleton is infiltrated with the copper. The resulting steel/copper composite material has durability and thermal conductivity similar to aluminum and can be hand finished using standard techniques. A finished mold core and cavity set which can be used to mold at least 50,000 parts with most plastics can be prepared in approximately ten days. The cost to produce most mold geometries with the RapidTool Process is also competitive with traditional mold-making methods .

INTRODUCTION

Since 1989, when the first stereolithography [1] machine was commercialized, Rapid Prototyping (RP) has been used primarily to produce plastic parts. Improvements to the materials and the processes have led to extensive use of rapid prototyping in a number of applications such as concept modeling, functional testing and patterns for investment casting and soft tooling. However, one of the drawbacks of RP parts especially for concept modeling and functional testing application is that they do not reflect all the characteristics of the final production parts. First, the range of materials currently available is limited to nylon, nylon / glass composites [2], Trueform™ PM [3], polycarbonate, ABS [4], wax and photopolymers based on acrylate and epoxy chemistries Therefore, the user is limited to these materials even though the production parts may be of a different material. Second, even if the RP material is acceptable, RP processes may not reflect all the properties of production processes. For instance, injection molding, a common plastic shaping process, introduces anisotropy in properties due to material flow which cannot be reproduced in any RP process. Therefore, there is a need to rapidly manufacture prototypes or small scale production parts with materials and properties similar to that of production parts.

The RapidTool process is a method to fabricate near net shape injection molding inserts using a combination of SLS and traditional powder metallurgy techniques. With the RapidTool process, the user can produce prototype plastic parts in the material of choice with the characteristics of injection molded parts.

OVERVIEW OF RAPIDTOOL PROCESS

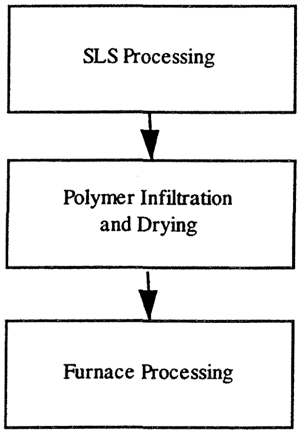

Figure 1: Process flow diagram for RapidTool process

The various steps in the RapidTool process are shown in Figure 1. First, polymer coated steel powder is processed in a SLS machine (Sinterstation™ 2000). The porous parts (commonly referred to as "green" parts) produced in the SLS equipment are then infiltrated with an aqueous emulsion of a polymer and a hardener and dried. The parts are then processed in a furnace to remove the organic binder and impregnate the voids with copper.

SLS PROCESS

The strength of the green parts, an indication of the handling durability in the green stage, is an important characteristic when choosing the material system and the SLS process conditions.
The green strength of the parts depends on the extent of polymer to polymer bonding as reflected in the size of the polymer bonds between the iron particles (Figure 2). Green strength increases with an increase in either the total laser energy delivered to the powder (defined in equation 1) or the binder level in the feed material [5]. However, there are practical limitations to both variables. Excessive laser energy causes a reduction in strength due to thermal degradation of the binder. In addition, as the binder level in the feed material increases, shrinkage during furnace processing increases. Therefore, it is preferable to minimize binder content in the feed material.

$$\text{Laser energy (J/sq. cm)} = \frac{\text{Laser power (W)}}{\text{Scan speed (cm/s)} * \text{scan spacing (cm)}} \qquad \text{---------} \; (1)$$

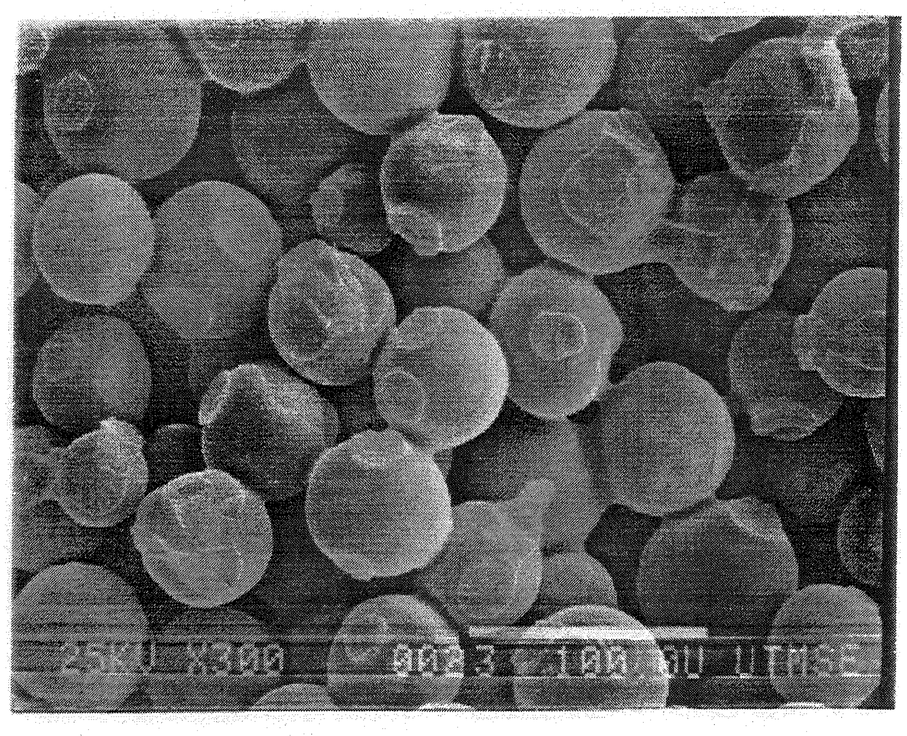

Figure 2: Fracture surface of green part showing the polymer necks between the iron particles.

The second important attribute of a green part is its density. A high green density is desirable since shrinkage and distortion during the furnace cycle increase with decreasing part density. Although it is possible to compensate for the shrinkage in the SLS process, it is still desirable to minimize distortion by maximizing density. The green density of the parts depends on the packing efficiency of the material in the powder bed. Since there is no pressure or vibration applied during the SLS process, the packing density of the powder in the bed is typically between its apparent density and the tap density values. Packing efficiency depends on a number of factors including particle size, particle size distribution and particle shape [6]. Interparticular friction and agglomeration cause finer particles to pack less efficiently than coarser particles. Similarly, irregular particles do not pack as efficiently as spherical particles. Hence, large spherical particles are preferable to fine irregular particles for efficient packing. However, the particle size sets a lower limit on the layer thickness during the SLS process.

The feed material for the selective laser sintering process is spherical steel powder (0.8% carbon) coated with an organic binder. The binder content is 0.8% by weight. The mean particle size is 55 micron. As indicated in Table 1, the feed material has a narrow particle size distribution. The apparent and tap densities of the feed material are also shown in Table 1.

Typical SLS processing conditions are indicated in Table 2. These SLS parameters yield green parts with the highest strength while maintaining the accuracy of the green parts. The strength of the green parts (3 point bend strength standard MPIF B312) under the optimum conditions shown in Table 2 is 400 psi (2 MPa). The density of the parts in the green stage is 4.3 gms/cc.

Table 1 Particle size distribution and packing densities of polymer coated steel powder.

Particle size	d10 d50 d90	43 microns 55 microns 65 microns
Particle shape		Spherical
Apparent packing density		4.1 gms/cc
Tap density		4.3 gms/cc

Table 2: Optimum SLS processing conditions

Processing Condition	Value
Laser power	30 W
Scan speed	155 cm/s
Distance between scans	50 - 100 microns (0.002' - 0.004")
Layer thickness	125 - 250 microns (0.005" - 0.010")
Part bed temperature	Room temperature
Feed bed temperature	Room temperature

After SLS processing, excess powder next to the parts is brushed away using fine brushes and compressed air. Since, there is no significant change in the properties of the excess powder in the build volume, it can be reused for subsequent builds.

The green parts are infiltrated with an aqueous emulsion of a polymer and a hardener. Infiltration occurs by capillary action when the parts are placed in the emulsion. After infiltration, the parts are dried in a convection oven at 50°C. After drying, the polymer and hardener react to form a crosslinked material.

If the parts from the SLS machine are processed in a furnace, without the polymer infiltration step, they would exhibit shrinkage in the direction of gravity due to a "creep-like" phenomenon. Above the glass transition point of the binder, the polymer coating on the metal powder softens allowing the metal particles to slide past each other. The amount of settling in the direction of gravity depends on the height of the features. As Figure 3 indicates, the uninfiltrated parts exhibit linear shrinkage varying from about 1.5% to 4.5% as the feature height varies from 0.5" (1.25 cm) to 2.0" (5.0 cm). Variable shrinkages cannot be easily compensated by scaling the dimensions of the computer model used in the SLS process. In contrast, the crosslinked material in the polymer infiltrated parts does not soften during the furnace cycle. Hence, they exhibit a uniform linear shrinkage of 2.5% and computer model can be scaled to compensate for it.

FURNACE PROCESSING

After the polymer infiltration and drying stage, the parts are subjected to a thermal cycle in a retort type furnace. The various stages of the furnace cycle are shown in a time - temperature plot (Figure 4). Between 350°C and 450°C, the organic binder is removed from the parts by thermal decomposition. The porous nature of the parts helps in the easy removal of the binder without any defects such as blisters or cracks. At temperatures above 750°C, the steel particles sinter to develop a porous skeleton. The steel skeleton has to be strong enough to withstand capillary forces during the copper infiltration stage. Therefore, sintering is done at 1000°C for 8 hours. After sintering, the furnace temperature is increased to 1120°C. At this temperature, the copper melts and infiltrates the part. Since liquid copper has excellent wetting characteristics with respect to iron surfaces (contact angle =0°) [7], infiltration occurs by capillary forces and no external pressures are required. A reducing atmosphere (70% nitrogen - 30% hydrogen) is maintained inside the furnace to ensure reduction of iron oxides on the powder prior to copper infiltration.

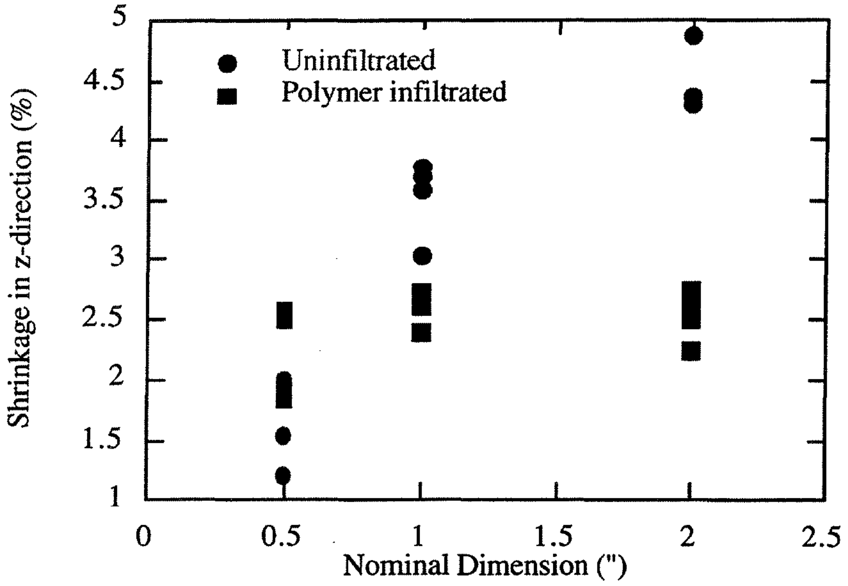

Figure 3: Vertical shrinkage of features with varying masses

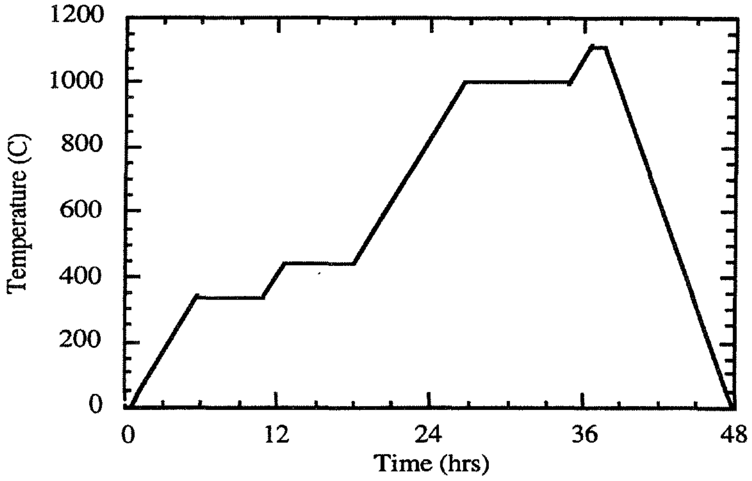

Figure 4: Time - temperature plot for the furnace treatment of green metal parts.

Parts are arranged in a graphite crucible as shown in Figure 5 and then placed inside the furnace. Inside the crucible, the parts are laid on an flat alumina plate. The alumina plate acts as a barrier for the diffusion of carbon from the crucible into the parts. In addition, the ceramic plate minimizes distortion in the parts by supporting them during the furnace cycle.

Infiltrant grade copper pressed into pellets is used for infiltration. The copper infiltrant contains about 2 percent by weight iron which prevents part erosion due to dissolution of the iron matrix in liquid copper. The copper pellets are placed on a graphite incline about 0.25" (6.4 mm) in front of the parts. When the copper melts, it flows towards the parts due to gravity and ensures part-to-part consistency in infiltration. It has been determined that consistent infiltration efficiency improves the dimensional accuracy of the final parts.

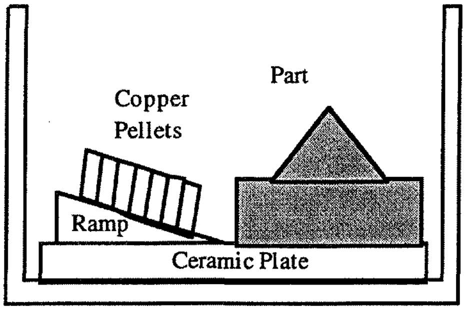

Figure 5: Arrangement of part in a graphite crucible prior to the furnace cycle.

Table 3: Mechanical and Thermal Properties of steel-copper composite material.

Property	Test Standard	RapidTool Material	Al 7075 T6	P20 steel
Yield Stress (0.2%elongation)	ASTM E8	255	505	750
Tensile Strength (MPa)	ASTM E8	475	570	950
Elongation (%)	ASTM E8	15	11	20
Elastic Modulus (GPa)	ASTM E8	210	72	207
Hardness (HRB)	ASTM E18	75	81	180 - 210
Thermal Expn. Coeff (mm/m°C)	ASTM E831	14.4	23.6	1.7
Thermal Cond. (w/mK)	ASTM E831	91	130	29

The parts exhibit a shrinkage of 2.5% in the horizontal direction and 4.0% in the vertical direction. The shrinkage of the parts during the furnace cycle is anisotropic due to settling of the material after debinding.

The mechanical and thermal properties of the steel-copper composite system made by SLS is compared against that of other common prototype mold materials such as Al 7075-T6 and P20 steel (Table 3).

RAPIDTOOL APPLICATION PERFORMANCE

The surface finish (Ra) of RapidTool inserts after the furnace process is 10 microns. While this surface finish is adequate under certain circumstances, in most cases a better surface finish is desired. Conventional mold finishing techniques such as grinding, polishing and electrical discharge machining (EDM) can improve the surface roughness to 0.6 micron Ra.

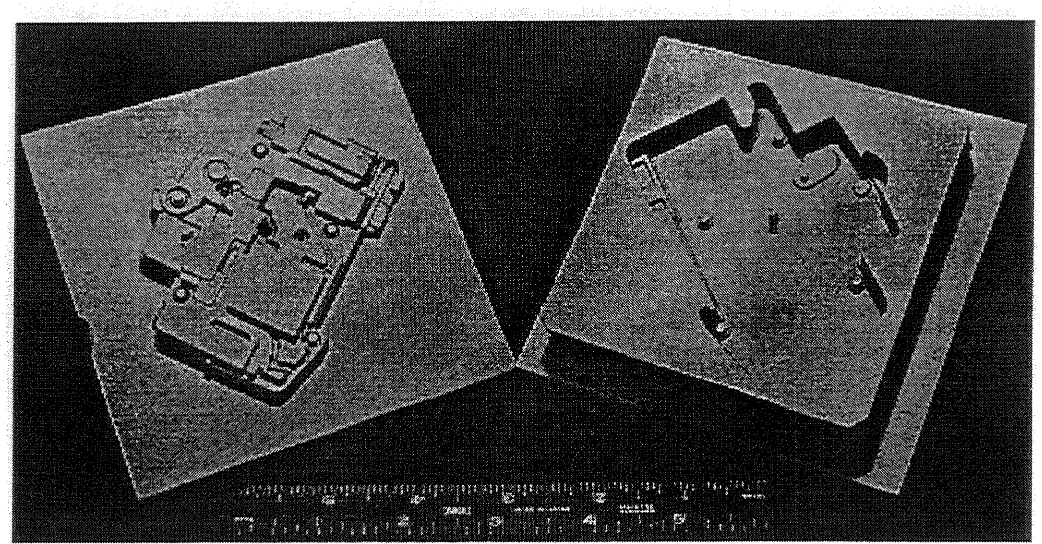

Figure 6: Steel-copper core and cavity inserts produced by the RapidTool process.

Table 4: Cost comparison for core and cavity inserts shown in Figure 6 produced by RapidTool process and by conventional processes

Item	RapidTool Process	Conventional Process
Material Cost ($)	419	80
Processing Cost ($)	1,331	
Finishing Cost ($)	5,175	28,125
Total Cost ($)	6,925	28,205
Total Time (hrs)	202	625

Total processing time for a core and cavity insert set, each measuring 6"x6"x1.5", is about 100 hours. The time estimate includes SLS processing and furnace processing but does not include any mold finishing time. Mold finishing time depends on the complexity of the mold and the skill of the mold maker. An economic analysis comparing the processing costs for the parts shown Figure 6 is shown in Table 4. The finishing costs for the RapidTool inserts and the costs for fabricating a set by conventional processes was quoted by a external vendor. It can be seen that although the raw material for the RapidTool process costs more than that of conventional processes, the total costs for the RapidTool process is lower compared to conventional processes.

RAPIDTOOL MATERIAL AND PROCESS ENHANCEMENTS

Several enhancements to the RapidTool process are being investigated. As described in the previous sections, the polymer infiltration and drying steps are designed to minimize gravity induced creep during the furnace cycle. Changes to the steel powder morphology and binder chemistries are being examined to eliminate the polymer infiltration step completely resulting in a reduction in processing time and an improvement in part accuracy.

An alternate method to fabricate molds for plastic injection molding is being investigated. In this method, porous core and cavity inserts would be fabricated by SLS using a polymer / metal feed material. However, the green parts will not be infiltrated with copper as in the RapidTool process. Instead, the green parts will be infiltrated with a crosslinkable liquid epoxy and cured. It is expected that these steel/epoxy mold inserts can be processed faster compared to the RapidTool process since no furnace processing is required. However, these inserts will be less durable than the steel / copper molds produced by the RapidTool process.

SUMMARY

The RapidTool process is a method to make near net shape parts using a combination of SLS and conventional powder metallurgy techniques. The primary application for the steel copper composite material produced by this process is in the fabrication of prototype molds for plastic injection molding. Mechanical and thermal properties of the steel-copper composite is similar to that of aluminum 7075 used in conventional mold making process. Total SLS and furnace processing time for a core and cavity insert set is about 100 hours. Fabricating molds via the RapidTool process can result in significant time and cost saving when compared to traditional mold making methods.

REFERENCES

1. P.F.Jacobs, Rapid Prototyping and Manufacturing: Fundamentals of Stereolithography, Society of Manufacturing Engineers, Dearborn, MI 1992.
2. P.Forderhase and R.Corden,"SLS Prototypes from Nylon", *Solid Freeform Fabrication Symposium Proceedings*, University of Texas, TX, 1994, p 102-109.
3. K.McAlea, "SLS Technology Advances", Proceedings of the Rapid Prototyping and Manufacturing Conference, Dearborn MI, 1996
4. J.W.Combs, W.R.Priedman, P.W.Turley, "FDM® Technology Process Improvements", *Solid Freeform Fabrication Symposium Proceedings*, University of Texas, TX, 1994, p 42-49.
5. U.Lakshminarayan and K.McAlea, "Advances in Manufacturing Metal Objects by Selective Laser Sintering (SLS™)", Proceedings of the 1996 World Powder Metallurgy Conference, Washington D.C., 1996.
6. R.M.German, *Particle Packing Characteristics*, Metal Powder Industries Federation, Princeton NJ 1989.
7. R.M.German, Liquid Phase Sintering, Plenum Press, New York, 1985.