

Manufacture Of Injection Molds Using SLS

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Abstract

This paper describes the use of SLS technology for the fabrication of injection mold cavities. Green shapes were made from metal - copolymer powder mixtures by SLS. The copolymer was gradually burnt out and the metal was oxidized in an air furnace. The porous oxidized metal part was subsequently infiltrated with an epoxy resin and cured. Effect of process variables in SLS, effect of oxidation cycle, dimensional changes on oxidation and epoxy infiltration of the oxidized metal part are discussed.

Introduction

Selective Laser Sintering comes under the class of Solid Freeform Processes for Rapid Manufacture of parts directly from a CAD model without part specific tooling or human intervention[1,2]. This technology has been developed at the University of Texas at Austin to produce polymer parts as well as indirect metal and ceramic parts that have polymer as an intermediate binder. We have adapted SLS to manufacture indirect oxidized metal molds for injection molding applications. The traditional method for manufacturing injection molds involves precision machining of cast metals. This fabrication process is usually very complex, time intensive, expensive and also requires highly skilled labor. Rapid Prototyping using SLS offers the solution to the problem of fabricating prototypes at low costs and high speed. Time savings due to design refinements are enormous since the prototype can be fabricated in hours as compared to months and changes required can easily be made on the computer and the part rebuilt quickly. The suitability of the material system for mold manufacture has been demonstrated in an earlier paper[3].

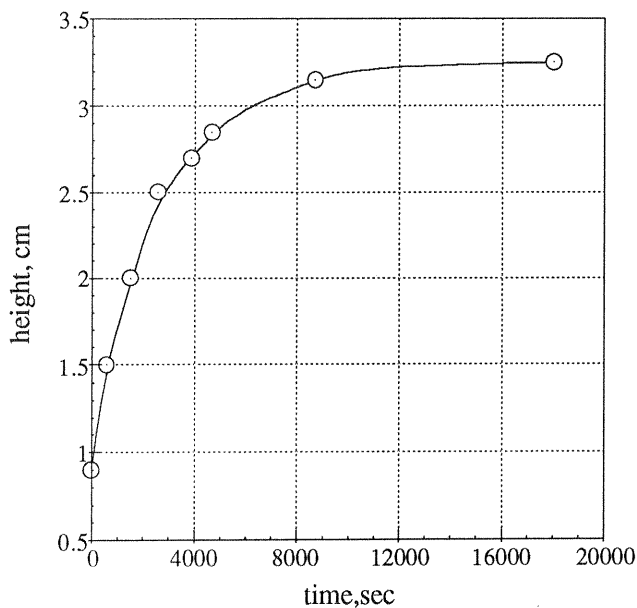
Experimental Work

Processing and Post-Processing : The raw material for the SLS process consists of a metal powder and a polymer powder that acts an intermediate binder. Iron powder, -325 mesh in size, was used as the metal and was obtained from Hoeganaes, Riverton, New Jersey. The polymer binder is a copolymer of poly(methylmethacrylate-co-butylmethacrylate) and has an average melt flow index of 28.9g/10min at 75 psi and 200°C[4]. The polymer powder is obtained by spray drying polymer emulsion in a Anhydro Spray Dryer. The iron powder is mixed with polymer and used in SLS for making the green shape. The polymer composition in the mixture was 40 vol % (9.16 wt %). SLS was used to make the green molds as well as bars for strength tests and density cups for measurement of bed density. The mold design was provided by Golden, Colorado. The surface bed temperature in SLS was maintained at 103 °C to prevent powder from caking and also to keep the part from curling. The green part made by SLS was then processed in an air furnace to remove the polymer and oxidize the metal. The effect of firing conditions on oxidized metal part were studied. The effects of processing variables on part strength are described in the following section.

Epoxy Infiltration : The porous oxidized metal preforms were infiltrated with a liquid epoxy resin to increase density and strength of parts. Epoxy resins contain a reactive oxirane structure which is commonly referred to as an "epoxy" functionality. Liquid epoxy resins are converted through these reactive epoxy sites into tough, insoluble, and infusible solids. The main issues in choosing an epoxy infiltration system are :

- (i) The epoxy should have low viscosity (of the order of 100 cp) at the operating temperature.
- (ii) The epoxy should have good mechanical properties and high heat distortion temperature.
- (iii) The gel time of the epoxy at the operating temperature should be large to allow sufficient time for infiltration of parts. If the gel time is short (< 1hr) the epoxy starts crosslinking during infiltration and this increases the viscosity and prevents infiltration. This becomes especially important when one has to infiltrate large parts.

There is usually a compromise between properties. Some of the epoxy infiltration systems that were tried out were : D.E.R. 331 with DEH 24 and D.E.R. 331 with Ac-methyl (anhydride curing agent) from DOW Chemical Company, CGL 1310 resin with RP1520 hardener from Ciba Giegy, and Casting resin CR 00183 from ETI Inc. Typically, the viscosity of the resin drops with temperature. The part to be infiltrated is usually heated to 60 °C and the epoxy system which is also heated to approximately the same temperature is used for infiltration. Infiltration is carried out either by applying the epoxy with a paint brush or by soaking the part in epoxy till all the porosity is filled. Figure 1. shows a resin uptake curve for infiltration of a 68% porous cylindrical oxidized iron preform with D.E.R. 331 resin, Ac-methyl curing agent, and BDMA as cure accelerator at 75 °C. This infiltration was carried out by placing the part in a pond of the epoxy.



Epoxy System : DER 331 - Ac methyl - BDMA
Infiltration Temperature = 75°C

Figure 1. Resin Uptake Curve For Porous Oxidized Iron Preform

The maximum infiltration height was 3.25 cm. Copper and iron were used as materials for making bars to evaluate strengths.

Results and Discussion

The first task was to select a suitable epoxy infiltration system for infiltration of porous oxidized metal preforms. Three different epoxy resins were evaluated for infiltration using porous oxidized copper preforms fired under the same conditions. The infiltrated strengths are shown in Table 1. Even though the Ciba Giegy system shows higher strength the DOW epoxy with anhydride cure was eventually chosen because of lower viscosity and greater pot life at the operating temperature. Two different metal powders, copper and iron, were used in SLS to make bars to evaluate final strengths of the mold material. Comparison of strengths of epoxy infiltrated oxidized copper and oxidized iron bars are shown in Figure 2. All the bars were processed with identical firing cycles and a maximum firing temperature of 300°C for 15.25 hrs. Epoxy infiltrated oxidized iron bars show much higher strengths than epoxy infiltrated oxidized copper bars and hence iron was chosen as the raw material in SLS for making the mold.

| Infiltrant | Avg.preform density (%) | Avg Infiltrated Density (%) | Avg. MOR (psi) |
|------------|-------------------------|-----------------------------|----------------|
| D.E.R. 331 | 32 | 98 | 3841 |
| CGL 1310 | 32 | 83 | 4045 |
| CR 00183 | 37 | 89 | 3103 |

Table 1. Comparison Of Epoxy Infiltrants

The SLS of iron-copolymer mixture was carried out in a full size DTM Model 125 commercial SLS machine supplied to the University by DTM Corporation. Nitrogen was used as an inert gas during the runs. The variables in SLS manufacture of green parts are the Laser Power, the Scan spacing, the step size and step period, which determine the beam speed, and the layer thickness. These can be coupled together to form an energy term known as the scan density or Andrew number which signifies the amount of heat put in per unit area [5]. Shown below is the equation for Andrew number, A_n :

$$A_n = P \cdot f / (BS \cdot SCSP)$$

| | | | |
|-------|-------|---|-----------------------------------|
| Where | A_n | = | scan density, cal/cm ² |
| | P | = | Power, Watts |
| | f | = | conversion factor |
| | BS | = | Beam Speed, inch/sec |
| | SCSP | = | Scan Spacing, mils |

The scan density was varied by changing the beam speed between 24 and 67 in/sec while keeping the other parameters fixed. The plot of strength with scan density is shown in Figure 2. The effect of density on strength is shown in Figure 4. The strength of a material usually varies as a power law function of the density as given by the equation below :

$$\sigma = A \rho^n$$

The plot of $\log(\sigma)$ with $\log(\rho)$ yields the slope "n" and intercept "A". The value of A is $7.025e-03$ and n is 11.023 for the iron - copolymer SLS parts.

The effect of Firing cycle on oxidized bar strength was carried out on bars made at a scan density of 3.0. The polymer decomposition and oxidation of the metal preforms were carried out in a conventional air oven . Figure 5 shows the effect of maximum firing temperature on oxidized part strength. Table 2 shows the oxidation cycle used to study the effect of temperature on oxidized part strength.

| Furnace Set Point (°C) | Time (Hrs) |
|------------------------|-------------|
| 200 | 5 |
| 300 | 1 |
| 400 | 1 |
| 500 | 1 |
| Max Temp | 4 |

Table 2. Oxidation Cycle To Study Effect Of Maximum Firing Temperature on Part Strength.

* Note : For maximum temperatures less than 500°C similar firing cycle is used and the ramp rates are the same.

The effect of firing cycle on strength of epoxy infiltrated oxidized iron bars is shown in Table 3. We see that there is dramatic increase in infiltrated strength as we go from bars oxidized at 300°C to those oxidized at 450°C. This could be a result of higher oxidized strength of the preform fired at 450°C. The epoxy used was D.E.R. 331 with Ac-Methyl as the anhydride curing agent and BDMA as the accelerator. The parts were cured at 100°C for 2hrs and then postcured at 150°C for 6hrs. The tensile strength of the anhydride cured D.E.R. 331 epoxy is reported to be 10,000 psi[6].

| Max. Oxidation Temp (°C) | Time (Hours) | MOR (Oxidized part) psi | MOR (Infiltrated Part) psi |
|--------------------------|--------------|-------------------------|----------------------------|
| 300 | 15.25 | 1480 | 5575 |
| 450 | 4.0 | 2500 | 9515 |

Table 3. Effect of Firing Cycle on Infiltrated Part Strength

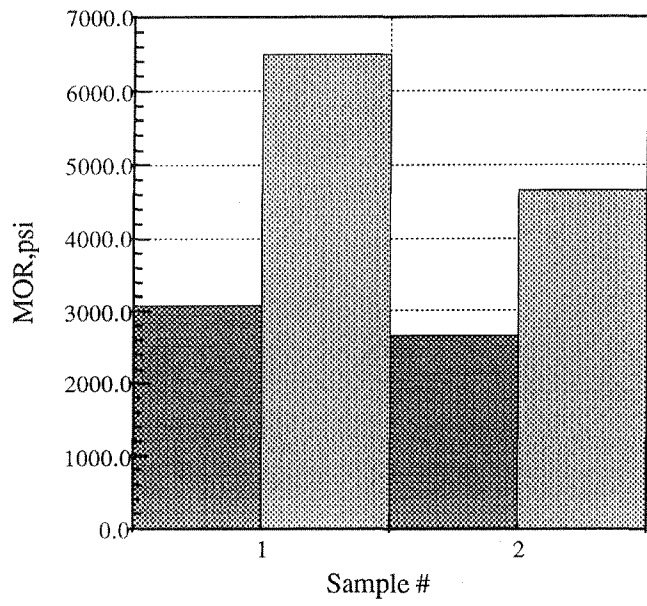


Figure 2. Comparison of Infiltrated Strengths for Oxidized Copper and Oxidized Iron Preforms

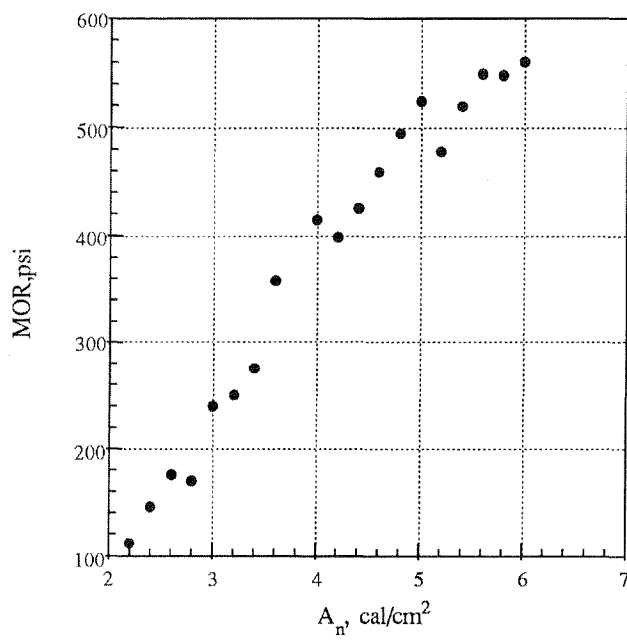


Figure 3. Effect of Scan density on green strength of Fe-copolymer parts.

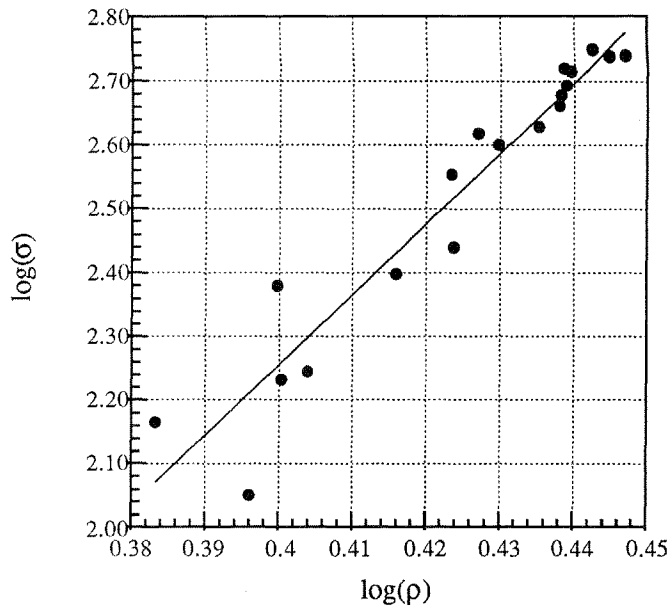


Figure 4. Variation of Part Strength with Part Density

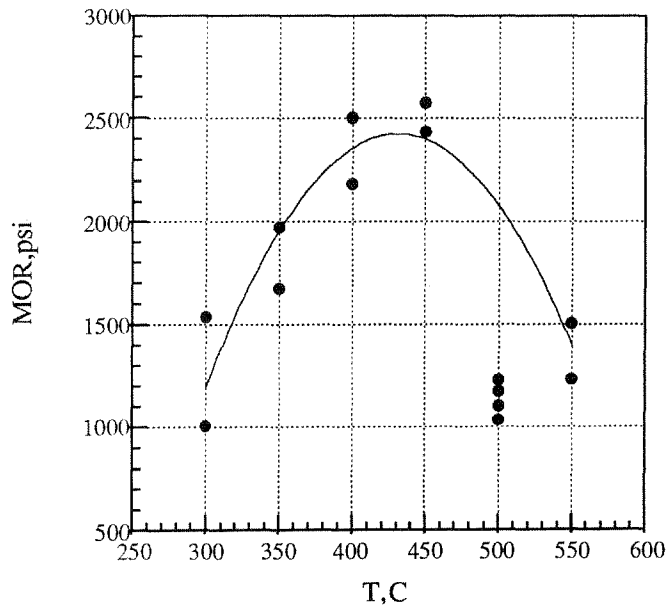


Figure 5. Effect of Maximum Firing Temperature on Oxidized Part Strength

An injection mold for Golden, Colorado, was made using iron-copolymer powder mixture by SLS. The build time for one mold was approximately 10hrs. The mold pieces were fired in an air oven to remove the polymer and oxidize the metal. The porous mold preform was infiltrated with D.E.R. 331 epoxy with Ac-Methyl as the curing agent and BDMA as the accelerator. The dimensional change in going from the drawing to the green part and from the green part to the final infiltrated part is shown in Figure 6. Figure 7 shows the green and infiltrated mold parts. The biggest changes are the associated with going from the drawing to the green part. The difference in dimensionality between the drawing and the green part can be removed using a beam compensating software. Most of the dimensional shrinkages on firing and post-curing are below 4%. The negative value for shrinkage, when going from the green to the infiltrated part, is the result of "growth" due to oxidation of iron during the firing cycle in air.

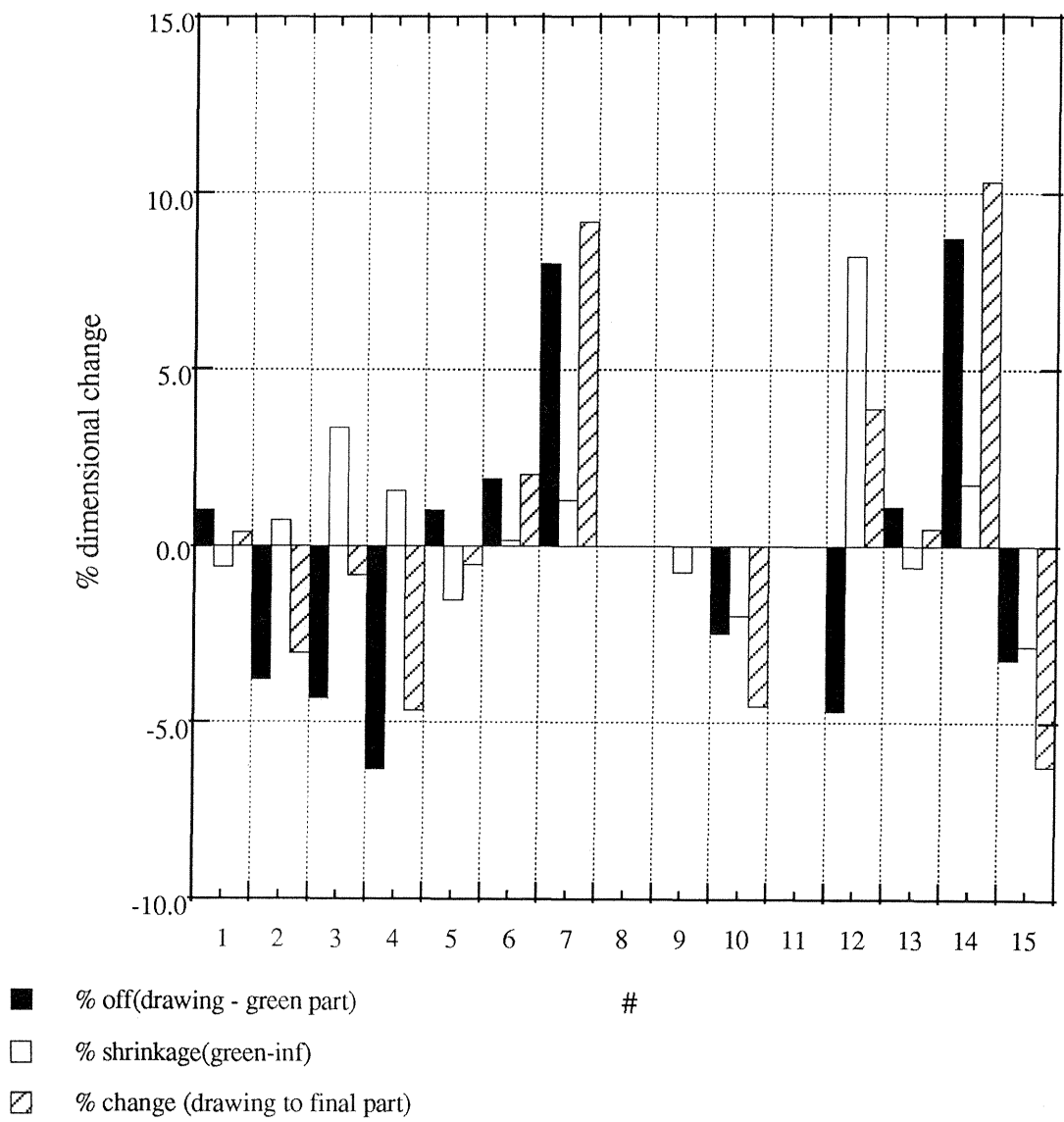


Figure 6. Dimensional Change For Mold Parts

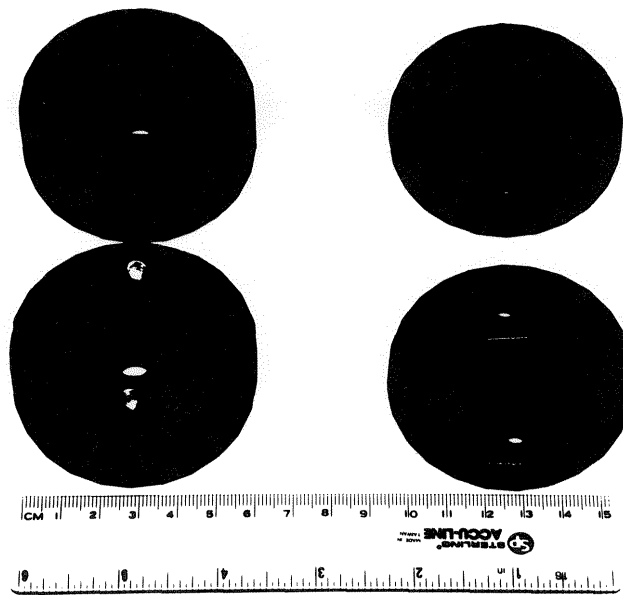


Figure 7. Green And Epoxy Infiltrated Oxidized Metal Molds

Conclusions

Selective Laser Sintering has been used to prepare indirect metal parts that have reasonable strengths. This material system can be used to make injection molds for small scale production runs. Optimization of binder burnout and metal oxidation cycle holds the key to accurate dimensional control which is critical in production of injection molds.

Acknowledgment

The authors gratefully acknowledge support for this work by DARPA / ONR Grant N00014-92-J-1394. The authors also thank N.K.Vail for his invaluable assistance in design of the mold from line drawings and in the machine operation.

References

1. Carl Deckard and Joseph Beaman, *15th Conference on Production Research and Technology*, University of California at Berkeley, p 623 - 630, (1989).
2. Harris L. Marcus, Joseph Beaman, Joel W. Barlow and David L. Bourell, *JOM*, **42**(2), p 8-10, (1990).
3. James R. Tobin, B. Badrinarayan, J. W. Barlow, J. J. Beaman and D. L. Bourell, *Proc. of the Solid Freeform Fabrication Symp.*, p 303 - 307, (1993).
4. N. K. Vail, J. W. Barlow, J. J. Beamean, H. L. Marcus, and D. L. Bourell, " Development of Poly(Methyl Methacrylate - co - n Butyl Methacrylate) Copolymer Binder System," *J.Appl. Polym. Sci.*, **52**, p 789 - 812, (1994).
5. Christian J. Nelson, "Selective Laser Sintering : A Definition Of The Process And An Empirical Sintering Model " Ph.D Dissertation, (1993).
6. "Dow Liquid Epoxy Resins", The Dow Chemical Company, p 26, (1990).