

Progress on Tooling by 3D Printing; Conformal Cooling, Dimensional Control, Surface Finish and Hardness

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ABSTRACT

Three Dimensional Printing is being applied to the direct fabrication of tooling using metal powders. This paper presents progress updates in four areas: i) thermal management using conformal cooling and related work on enhanced heat transfer using surface textures, ii) data on dimensional control, iii) improvements in surface finish, and iv) harder tooling.

Conformal cooling has demonstrated significantly improved performance in a production part geometry with simultaneous gains in production rate and part quality obtained as measured against conventional tooling. Surface textures printed on cooling channels have demonstrated 8X enhancement of heat transfer over smooth channels.

A set of 18 tooling inserts was fabricated using hardenable stainless steel powder with a resultant tooling hardness of 25-30 Rockwell C. Harder alloy systems are being designed with the aid of computational thermodynamic tools which allow accurate prediction of the interaction of powder and binder. Significant improvements in surface finish were obtained using improved printing technology. Dimensional control of tools conformed well to the expected result of being dominated by control of shrinkage and being predictable to within $\pm 0.25\%$.

INTRODUCTION

Goals

This work explores the fabrication of tooling directly from a CAD model using the Three Dimensional Printing Process. Following a brief review of the status of the technology, progress updates will be presented in 4 areas:

- 1) Data on a production application of conformal cooling
- 2) Data on dimensional control
- 3) Improvements in surface finish
- 4) Harder tooling

THREE DIMENSIONAL PRINTING OF TOOLING; TECHNOLOGY STATUS

Direct Printing of Tooling

Three Dimensional Printing involves the selective joining of powder within a layer by ink-jet printing of a binder material. Through the use of metal powders, 3D Printing can be used to create tooling directly from a computer model. The process has the potential to be scaled using multiple nozzle printing technology (an 8-jet printhead is in routine use at MIT) [Ref. 1: Sachs et al., "High Rate, High Quality 3D Printing through Machine Design, On-line Measurement, and Control", *International Journal of Machine Tools & Manufacture*, to be published].

Direct printing of tooling involves the following steps:

- 1) Print a polymeric binder into stainless or tool-steel powder. This step defines a green part within the powder bed.
- 2) Remove the loose powder, thereby revealing the green part.
- 3) Burn out the polymeric binder in a furnace and lightly sinter the part.
- 4) Infiltrate the part with a copper alloy in a second furnace operation, typically performed at 1100C. At this point, the part is fully dense.
- 5) Finish the tooling to achieve desired surface finish and dimensions as required.

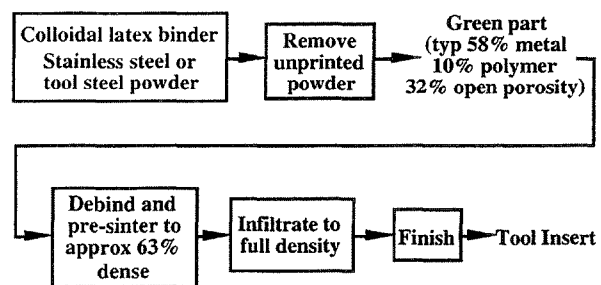


Figure 1. Process sequence for creating tooling directly by 3D Printing.

Recently Fabricated Tool Set

Periodically, a set of tools is fabricated for our industrial sponsors to serve as a benchmark for our process. The project is currently engaged in the fabrication of the third such set of tools. The results presented below and in this paper are derived from the second set of tools made. Figure 2 shows a “family portrait” of 14 of 22 tooling inserts made in the second set of tooling.

The tool inserts in the foreground have been finished and used to inject plastic parts. In materials including glass filled nylon and polycarbonate. Each tool set was designed by a different company and is typically relevant to a different industrial sector. Each company chose to finish the tool set in a different manner ranging from hand polishing to DDM. The tools toward the back of the photo are in earlier stages of processing and some are in the as infiltrated condition. A number of the tool inserts in this photo have conformal cooling channels within them (see section on Conformal Cooling below). All the tools were printed with 420 stainless steel powder and a bronze (90 copper, 10 tin) infiltrant. The hardness of these tool inserts is in the range of 25-30 HRC.



Figure 2. A set of tooling inserts printed for various industrial applications. All tools have been infiltrated and approximately half of the tools have been finished and used to inject parts. For scale, the tool in the lower left hand corner is 6” long.

PERFORMANCE OF CONFORMAL COOLING

In past papers [Ref 2: Sachs et al., “Production of Injection Molding Tooling with Conformal Cooling Channels using The Three Dimensional Printing Process”, *Solid Freeform Fabrication Symposium Proceedings*, August 7-9, 1995, pp. 448-467] we have reported on the use of cooling

channels conformal to the molding cavity to improve the control of mold temperature and part dimensions in a simple mold cavity used to create a split ring part.

Recent work by an industrial sponsor has extended this approach to a high volume commercial product. Figure 3 shows the outline of the mold cavity with a representation of the serpentine conformal cooling channel printed in place (details are absent at the request of the sponsor). This cavity was run in controlled tests against the cavity used in production with the results summarized in bullet form below.

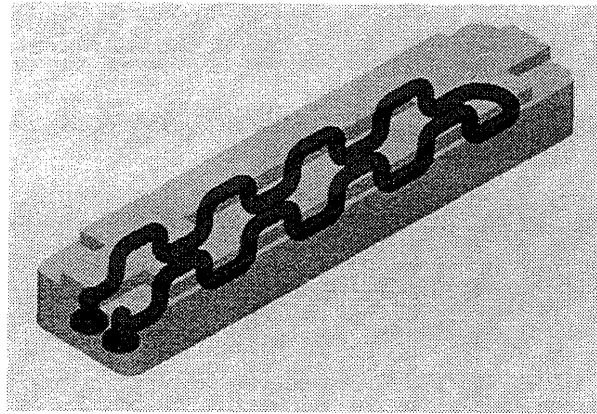


Figure 3. A cavity with a serpentine cooling channel.

- **At one set of molding conditions, a 15% improvement in cycle time was obtained using the 3D Printed cavity with conformal cooling SIMULTANEOUS with a 9% reduction in part distortion.** It was further noted that the factor limiting even further reduction in cycle time in the cavity with conformal cooling was freezing of the sprue and not the cavity itself, thus offering the potential of further cycle time reduction with a runner system redesign.
- **At a second set of molding conditions, a 37% reduction in part distortion was obtained using the 3D Printed cavity with conformal cooling with the same cycle time as the production tool.**

A development related to conformal cooling channels is the use of surface textures for heat transfer augmentation on the inside of channels. A variety of printed patterns were tested. The most successful was the “chevron” shaped ribs shown in Figure 4. It was found that channels printed with the chevron ribs exhibited significant improvements in heat transfer coefficients with water as the working fluid as compared with both as-printed and wire-EDM control channels. Over the full range of 1,500 - 15,000 Reynolds numbers the chevron ribbed showed an 8-fold increase in heat transfer coefficient as compared to the smooth EDM channel and a 4-fold increase as compared to the as-printed channel without ribs. This result is of significance as it would allow for effective cooling of a tool with flow in the laminar regime (with lower pumping requirements and pressures), whereas conventional wisdom dictates that turbulent flow must be maintained.

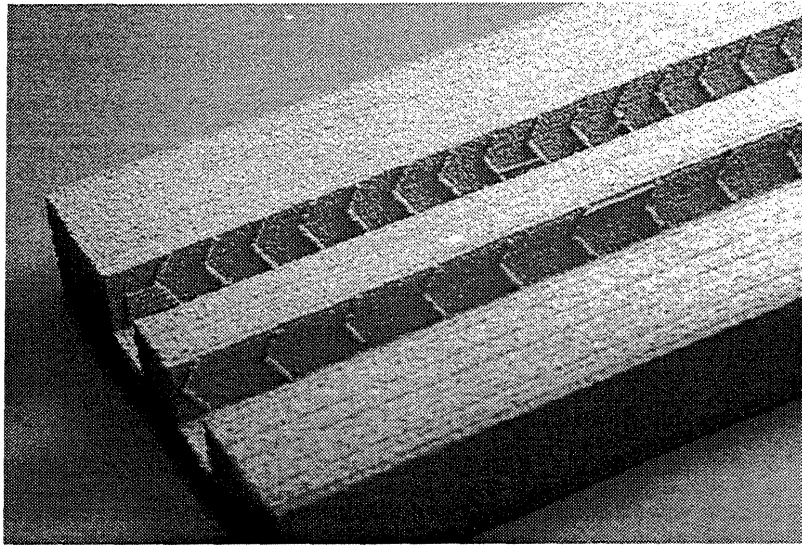


Figure 4. Printed ribs on the interior of 8 mm x 8mm channels for heat transfer augmentation. The ribs are approx. 200 microns high and 500 microns wide.

DIMENSIONAL CONTROL

The dimensional control of tooling made by 3D Printing is governed by the furnace processing steps and in particular by uncertainty in the shrinkage during the sintering operation. During the sintering operation there is some shrinkage of the part which is associated with the formation of a skeleton which can subsequently be infiltrated. The CAD file is “prestretched” by the amount of anticipated shrinkage. A green part is then printed and these green parts have been found to conform quite closely to the “prestretched” CAD dimensions. At the present time, the shrinkage during the sintering step is $1.8 \pm .25 \%$ (linear), which represents a nominal shrinkage of 1.8% and an uncertainty in shrinkage of .25%. While the nominal shrinkage can be anticipated by “prestretching” the CAD file, the uncertainty in shrinkage dictates a loss of dimensional control which scales with part dimension.

Based on previous observations, a specification range was created which contemplates a multiplicative error which is expected to scale with part size and an additive error which reflects uncertainty in the location of the edges of the part which is not expected to scale with part size. This spec range is illustrated as the trapezoidal shaded region in Figure 5 where the vertical axis is the error in linear dimension (deviation from desired dimension) of the infiltrated tool and the horizontal axis is the length of a particular dimension. The vertical intercepts represent the additive error while the slope of the top and bottom of the spec range represent the multiplicative error.

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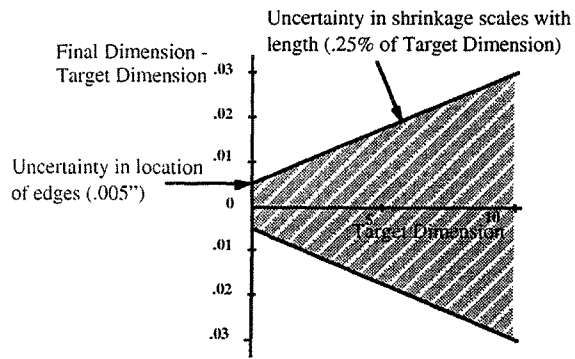


Figure 5. Illustration of the specification range for 3D Printed Tooling.

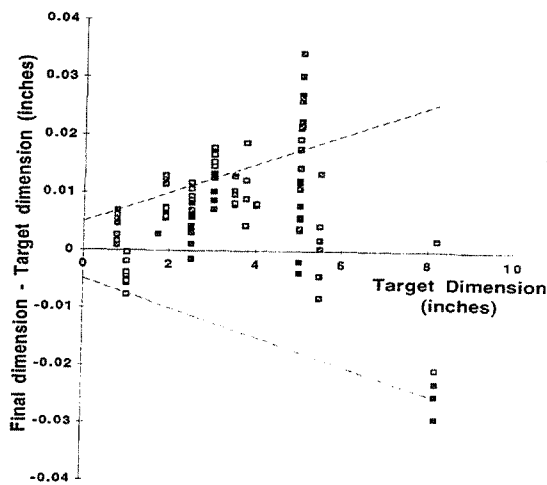


Figure 6. Data on dimensional control of 3D Printed tooling within the print plane.

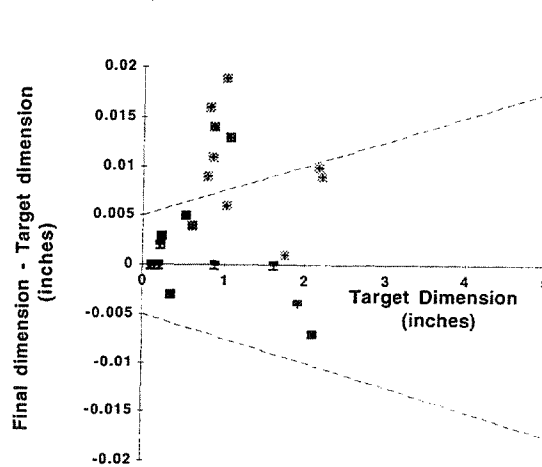


Figure 7. Data on dimensional control of 3D Printed tooling in the vertical axis.

Figure 6 shows data taken on 18 tools in both the fast and slow axes within the print plane. As can be seen, 81 of the 107 data points lie within the anticipated spec range. Figure 7 shows analogous data for the vertical axis. In this case less data is available but the ratio of 15 out of 21 points (on 6 tools) within the spec range is roughly comparable to the in plane print data. While the results were not quite as good as expected, it does seem that we have come close to defining a proper specification range which anticipates the dimensional control of our tooling. Further, it can

be noted that most of the data of Figures 6 and 7 has a positive bias, and so correction of this bias would further improve the results. Nonetheless, the dimensional control of our tooling is not sufficient for net shape tooling inserts (perhaps by a full order of magnitude). Thus, materials systems with substantially improved dimensional control are a major thrust for this project.

SURFACE FINISH

Figure 9 shows a detail area of the cavity geometry of Figure 8 created with two different printing approaches. The detail on the left was created 15 months ago, while the detail to the right was created more recently. The detail to the right illustrates a significant improvement in surface finish which has been achieved by control of the droplet landing position with 10 micron resolution in each of the two in-layer axes (contrast this with 10 micron x 150 micron resolution in the detail at the left). This achievement represents a combination of new printhead hardware, new software used to create the printing instructions from an .STL model and the integration of on-line measurement used to characterize and adapt to changes in the performance of the printhead [Ref. 1].

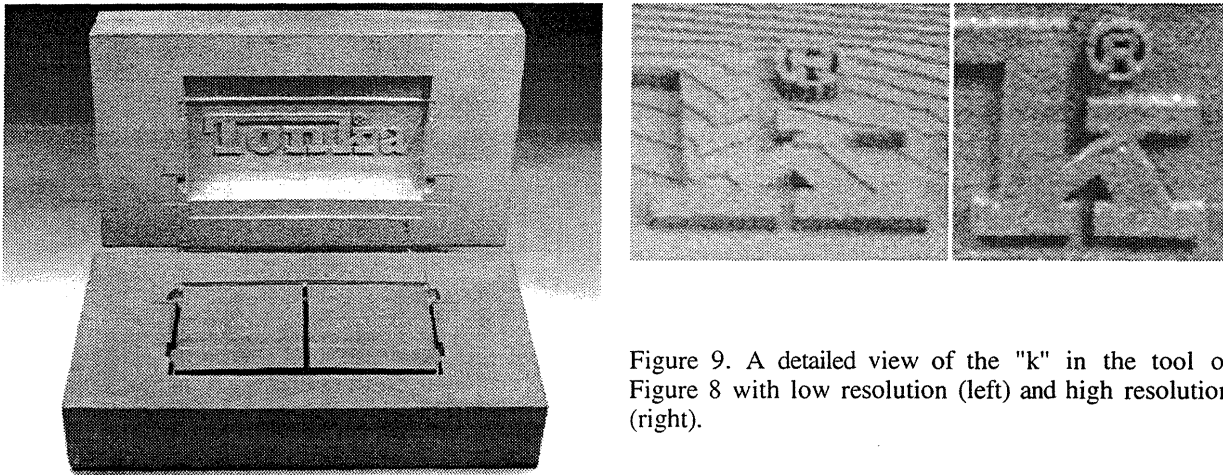


Figure 8. An infiltrated core and cavity set.

HARDER TOOLING

As noted earlier, the current tooling materials system is 420 stainless powder, infiltrated with bronze, a system which produces a Hardness of 25-30 on the Rockwell C scale. However, this hardness is actually the result of a composite system which has particles which are quite hard (HRC 50+) and infiltrant which is much softer (HRB scale).

A goal of the project is to develop materials systems with higher hardness and with greater uniformity of hardness between powder and infiltrant though the use of hardenable infiltrants. However, when the molten infiltrant contacts the powder, mutual solubility and fast the inter-diffusion at the infiltration temperatures can lead to changes in the composition of both powder and

infiltrant resulting in a loss of hardenability of both (as well as possible distortion). Thus, an important goal of the project is to understand the interaction of powder and infiltrant, design materials systems which minimize this interaction, and manage any remaining interaction. Toward this end, a computer-aided alloy design has been used in the 3DP material system selection. The computer modeling can simulate the thermodynamic interaction of the multi-component 3DP system at any temperature. The simulation results show the mole fraction of each phase and the composition of each phase at equilibrium state. In addition, the simulation can also show the melting point of the infiltrant, the phase transformation temperature and the effect of an additive element on the thermodynamic equilibrium.

Good agreement between the computer calculation and experimental result for the interaction of the 420 stainless/bronze system can be seen in the following tables. The tables show the composition of powder and infiltrant before furnace processing, and the changes in composition which are predicted and measured. This tool will now be used to design alloy systems.

Composition of the 420 stainless powder (wt%)

	Fe	Cr	C	Si	Mn	Cu	Ni	Sn
Before infiltration	85	14	0.47	0.37	0.29	----	----	----
After infiltration (measured)	80	13	----	----	----	2.5	3.5	0.15
After infiltration (calculated)	79	12	0.35	----	----	5.8	3.4	0.03

Composition of the bronze (Cu-10Sn) infiltrant (wt%)

	Fe	Cr	C	Si	Mn	Cu	Ni	Sn
Before infiltration	----	----	----	----	----	85	9	6
After infiltration (measured)	2	0.3	----	----	0.2	88	2	7
After infiltration (calculated)	2.5	0.4	----	----	----	89	0.7	7.5

CONCLUSIONS

Three Dimensional Printing is being applied to the fabrication of tooling directly from a computer model using metal powders. This paper presents progress updates in four areas: i) harder tooling, ii) improvements in surface finish, iii) data on dimensional control, and iv) production application of conformal cooling. A set of 18 tooling inserts was fabricated using hardenable stainless steel powder with a resultant tooling hardness of 25-30 Rockwell C. Significant improvements in dimensional control were obtained using improved printing technology. Dimensional control of tools conformed well to the expected result of being dominated by control of shrinkage and being predictable to within $\pm 0.25\%$. Conformal cooling has demonstrated significantly improved performance in a production part geometry with simultaneous gains in production rate and part quality obtained. In one case, a simultaneous improvement of 15% in production rate and reduction of part distortion by 9% were obtained. Surface textures fabricated in channels show the potential for 8x improvement of heat transfer over smooth channels. Thermodynamic tools are being used to model the interaction of powder and binder and provide a method for the design of new, harder materials systems.

ACKNOWLEDGMENTS

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