Rapid Steel Tooling Via Solid Freeform Fabrication

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ABSTRACT

With increasing part complexity and requirements for long production runs, tooling has become an expensive process that requires long lead times to manufacture. This lengthens the amount of time from "art to part". Rapid tooling via stereolithography (SLA), filled epoxies, etc. have been stopgap measures to produce limited prototyping runs from (10 to 500 parts). This gives poor dimensional analysis and does not allow for limited production runs of 1000+ parts. The method of producing prototype tooling with a powdered metal process has been developed that produces tooling with a hardness greater than 35 HRC and total shrinkage less than 0.5%. This tooling process manufactures production ready tooling that will perform extended cycle runs (100,000+). Manufacturing of this tooling takes 1 to 2 weeks and will compare favorably with production grade steel tooling. Originals drawn in 3D CAD can be used to prototype the master that will allow for the production of the rapid metal tool set.

This process starts with a rapid prototyped model made by whatever process is desired or a machined master. For this paper a Sander's Model Maker II® rapid prototyping machine was used to fabricate the model. After the model of the tool set is made, a silicone rubber negative is cast around that model. After the silicone rubber model is made, a heated slurry of metal powders and polymers is poured into the mold to create the green tool set. The tool set is left to cool, and then removed from the silicone rubber mold. The tool set is then debound and sintered to produce a final tool set with properties approaching hardened tool steel.

INTRODUCTION

Rapid tooling has many different forms for various applications. Tooling from silicone rubber, epoxies, aluminum, powder metal, and prehardened tool steel could all fall under the category of rapid tooling. Each method of rapid tooling has its applications and shortcomings. Therefore the defined application of the tooling is required to determine the properties that the tooling needs to exhibit.

As the race to get a product to market increases in speed, the drive for tooling lead times to decrease will become higher. This drive in time compression in the manufacturing sector leads to unique opportunities to create tooling via non traditional methods that dramatically reduce lead times while not sacrificing mechanical properties. Therefore the goal of this paper was to develop tooling quickly (< 2 weeks) with mechanical properties comparable to hardened tool steel. This tooling was fabricated using a powder metallurgy process combining the processing of various metals and or ceramic powders to form a tool set with tailored mechanical properties. This in turn leads to a decrease in lead-time with no sacrifice in properties.

BACKGROUND

Rapid tooling is a growing technology that is currently moving from temporary tooling silicone rubber, epoxies, etc. to a more robust tooling that can still be made in a rapid fashion. DTM® selective laser sintering has been making tooling inserts for injection molding for a number of years. [1] Keltool has been using a casting process to make inserts since patenting the technology in 1980. [2] Most current techniques that produce metal tooling fail in one of the following ways:

1. Rough Surface
2. Low mechanical properties
3. Poor wear resistance
4. Poor thermal conductivity
5. Difficult or complex process
6. Needs excessive finishing or post processing

These reasons have allowed traditional tooling to continue to have an advantage over the current rapid tooling processes. In order for rapid tooling to have a significant impact on the industry these problems need to be overcome and the final product must not only be delivered quicker, but with either a cheaper price or better mechanical responses. The process that is described in this paper provides a potential processing route to overcome these issues, except low impact strength.

PROCESS DESCRIPTION

To make a rapid tool mold or part you must first design the part in a 3 dimension (3D) computer aided design (CAD) software package or fabricate a model of the part by hand. There are many software programs available to design the part or tool mold. [3] The particular program used for this paper was Solidworks 97 Plus. The part or tool mold is designed in the software program in 3D, to the dimensions or size required for that part or tool mold. The software in the (stereolithography) .STL format saves the design.

The next step is to actually build a model of the part or tool mold using the computer design. Once again this can be accomplished on a variety of machines, but care must be given to obtain a good surface finish and closed surface model. For this processing step a Sanders Model Maker II prototyping machine was used. [4] Before actually building the model of the part or tool mold, the .STL file is loaded into the software program provided by the manufacturer of the prototyping machine to generate sections or slices of the 3D designed part into very thin layers on the computer. The Model Works software, provided by Sanders, allows the user to take the 3D .STL file and divide it into very thin layers with thicknesses ranging from 0.0005 to 0.005 inches. For reference, the thickness of a sheet of paper is 0.0015 inches. The user chooses the layer thickness, and how the modeling material is to be deposited to form the model of the part. The Model Works software program incorporates the user's choices and slices or sections the computer design into the appropriate layer thickness and determines the way the modeling material will be deposited to form the model of the part. This slicing data of the 3D.STL file is saved in a separate file that will be downloaded by the machine to fabricate or build the model of the part.

The next step is building the model of the part or tool mold. The file with the layer or slice data is fed into the machine and the machine begins to build the model, layer by layer, until the entire model has been finished. This process can take from hours to days depending on the size, complexity, and layer thickness that was chosen by the user. Figure 1 shows the final model.

After the model has been fabricated, the next step is to make a silicone rubber negative of the model. A frame is built around the model to contain the resin mixture. This resin is poured over the model contained inside the walls to create a negative or reverse impression of the final part or tool mold, as shown in Figure 2. The rubber is then left to cure until solid. After the rubber has cured, the model that was built on the rapid prototyping machine is removed from the silicone rubber. The silicone rubber mold is now ready to create the final tool mold or part. The silicone rubber was selected due to its ability to hold tolerances, pick up fine surface detail, and it's elasticity to facilitate part release.

The next step is to prepare molten slurry of molten polymers and a blend of powdered metal or ceramic materials. The molten polymers are used as a carrier to allow the powdered material to flow and conform to the details of the silicone rubber mold. The slurry is poured into the silicone rubber mold, and is allowed to cool to room temperature as shown in Figure 3. Once the slurry has solidified, it is removed from the silicone rubber mold by flexing the rubber and releasing the part of polymer-metal and or ceramic powder. The part should now be the exact replica of the 3D-computer design and the model that was built on the Sanders rapid prototyping machine, as shown in Figure 4. The final part is now ready to be processed to form a finished product.

To process the cast part the next step is to remove the remaining polymers from the final part. Once the binder is removed, the tool set is sintered to fuse the metal or ceramic powders together and eliminate porosity that is developed during the debinding process. For the tooling material the process has been developed such that shrinkage is limited to approximately 0.4%. For other materials like stainless steels, ceramics, etc. typical powder injection molding linear shrinkage values of 15 to 18%, would be expected. Final finishing and polishing is performed on the final part as shown in Figure 5. Once the finishing process is done, the final part is complete and ready for use as a part or tool mold to make the desired geometry, as shown in Figure 6.

MECHANICAL PROPERTIES

The mechanical properties of the tool sets made are listed in Table 1 below. As can be seen from Table 1 some of the mechanical properties are comparable to hardened tool steel, and the tooling material has a very good wear resistance. The impact properties of the material are particularly low, and improvements will need to be made to produce a satisfactory final material. The surface roughness is also a little high, but with polishing a surface finish of 0.25-0.3μm average roughness can be achieved. This is comparable to polished tool steel with a surface finish of 0.2μm average roughness. The hardness of the tooling material is dependent on powder loading and the actual blend of powders used. It is envisioned that optimizing the blend of powders the hardness of the material will increase to 50+HRC.

Table 1. Mechanical Properties of Tool Sets

Mechanical Property	Recorded Value
Strength	950 MPa – transverse rupture strength (TRS)
Hardness	30 to 35 HRC
Impact Strength	5 J/cm^2
Wear Resistance – ASTM G65 Procedure A	0.052cm^3 (hardened tool steel 0.059cm^3)
Surface Roughness	1.75 to 2.25μm average roughness
Surface Roughness (after polishing)	0.3μm (polished tool steel ~0.2μm)
Shrinkage	~ 0.4%

A comparison of different types of tooling is shown in Table 2 below. This tooling material has some properties higher than prehard steel like P20, and some of the properties are similar to hardened tool steel. It is envisioned that the life of the tool set would be similar to tool steel. Further life cycle testing will be done to evaluate this claim.

Table 2. Comparison of Various Types of Tooling for Powder Injection Molding

Type of Tooling	Hardness	Cycle Time	Life Cycle
Rubber Mold	15-65 Shore "A"	5-30 minutes	1-100
Epoxy	80-110 RM	3-5 minutes	100-1,000
Filled Epoxy	85 RM	3-5 minutes	250-2,500
Aluminum	60-95 BHN	10 to 60s	2,500-10,000
Prehard Steel	28-32 HRC	10 to 60s	10,000-100,000
Hard Tooling	60's HRC	10 to 60s	100,000+

CONCLUSIONS

The goal of this research was to develop a tool set or specific geometry rapidly from a machined master or prototyped component. This goal has been realized by fabrication techniques that allow for the production of a tool set or geometry in less than two weeks. Another goal was to make it a simplistic technology that could be practiced by anyone (with limited capital investment) that is currently practicing powder injection molding. [5] The processing steps are very simple with less than a $5,000 investment needed if currently practicing powder injection molding. Finally the ability with the same process to make limited components is possible. This allows the first real components to be placed in the customer's hand or used for marketing studies without the expenses and time associated with conventional tooling.

FUTURE WORK

The need to replicate the process to determine the absolute dimensional shrinkage and reproducibility is still required. The ability to reproduce dimensions accurately will be one of the main focuses of future research. The size envelope that this technology will allow is still under evaluation, but is probably limited to the debinding technology developed and thermal conductivity of the metal powder system over large cross-sections. Experimental work to reduce the shrinkage of the tooling material to net zero shrinkage is underway. This is needed for exact reproduction of a master that cannot be oversized for shrinkage. Also, further focus on the binder rheology and it's ability to form the tool set or part at low viscosities while retaining good green strength is being investigated. Finally, optimizing the debinding conditions to allow the processing of thicker parts is necessary.

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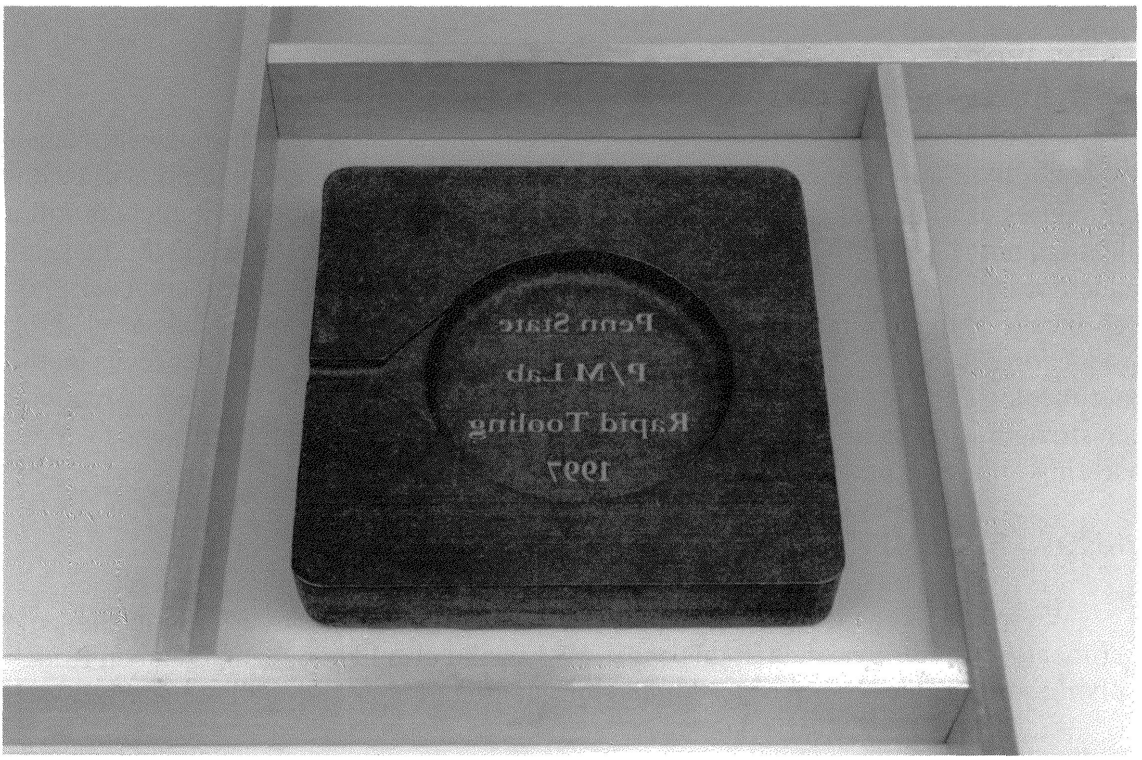

Figure 1. Picture of the Final Green Model in Mold Frame.

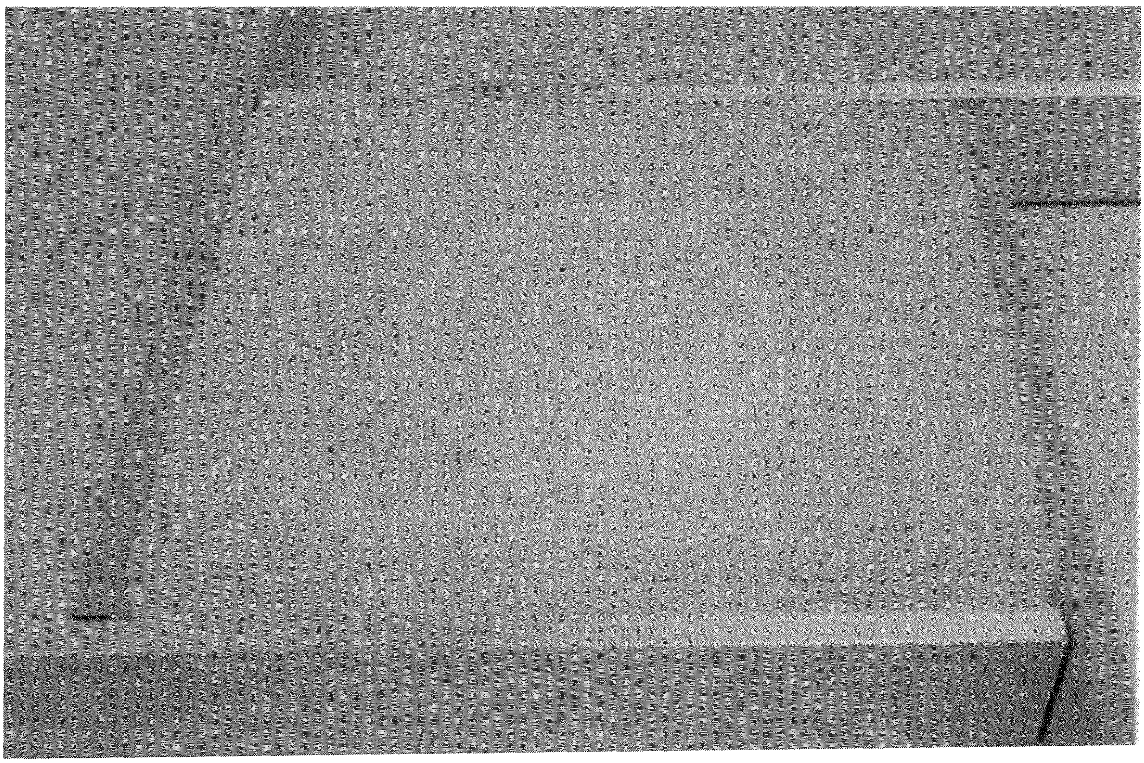

Figure 2. Picture of Silicone Rubber Negative Mold Setup.

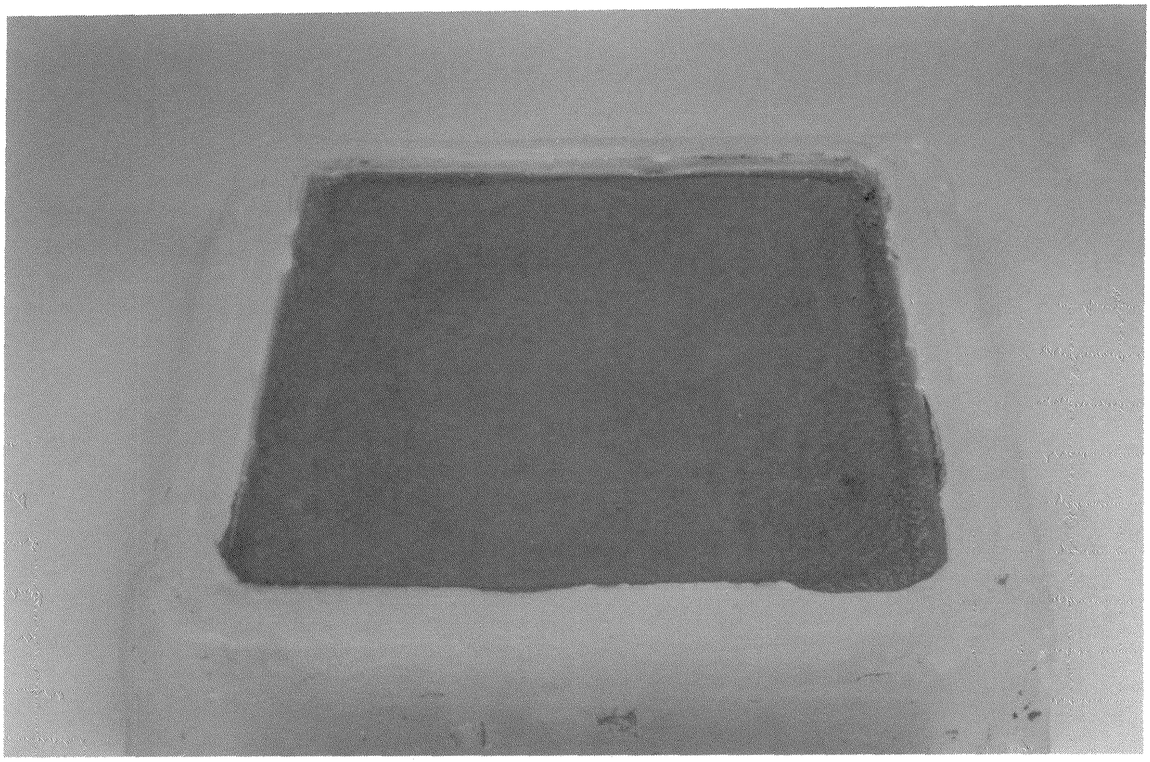

Figure 3. Picture of Metal Slurry in the Silicone Rubber Mold.

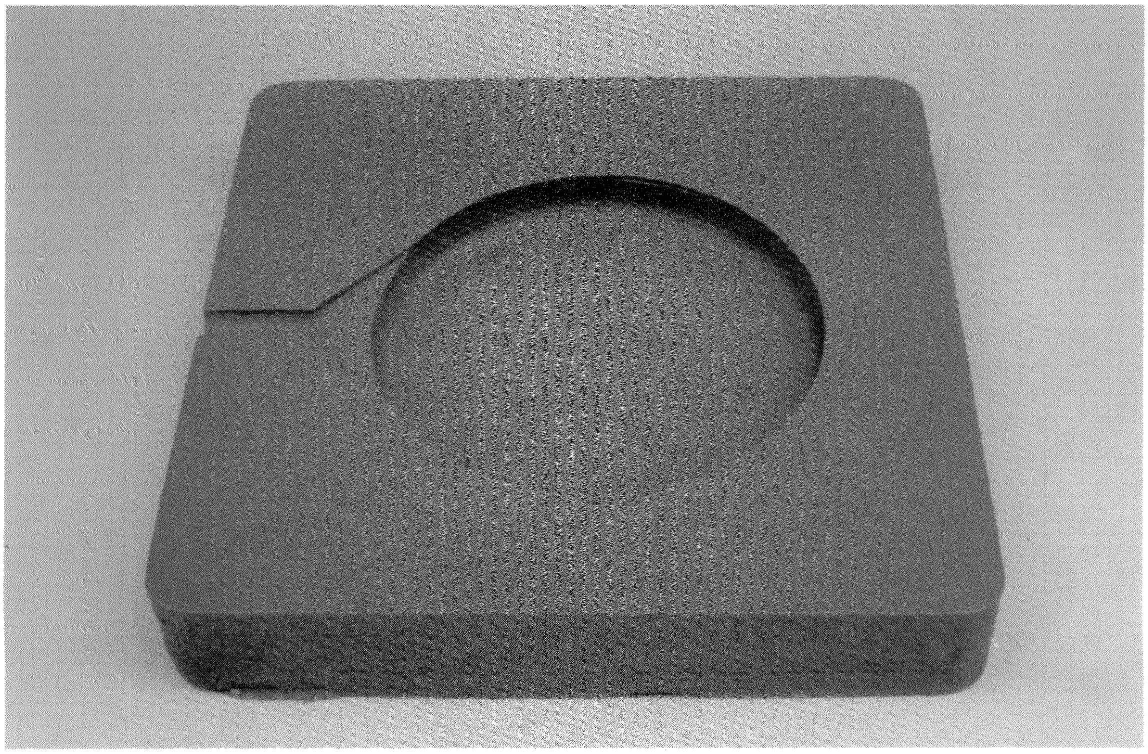

Figure 4. Picture of the Green Part Removed From the Silicone Rubber Mold.

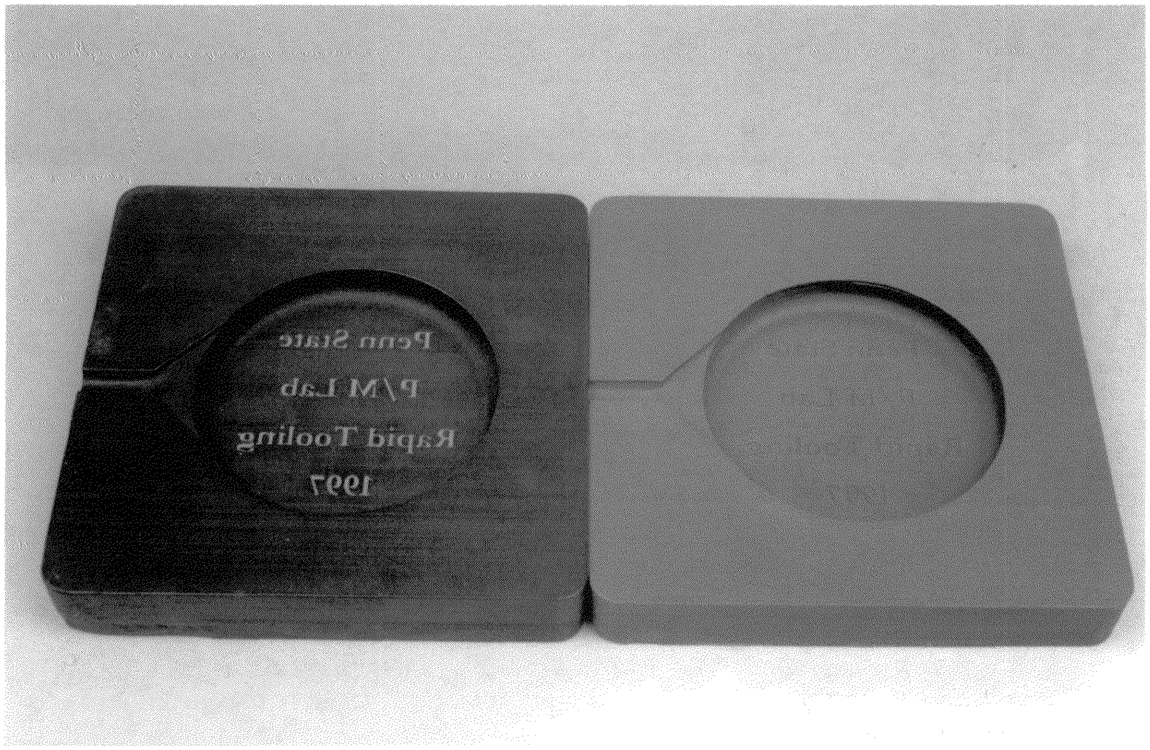

Figure 5. Picture of the Green Part Compared to Original Model.

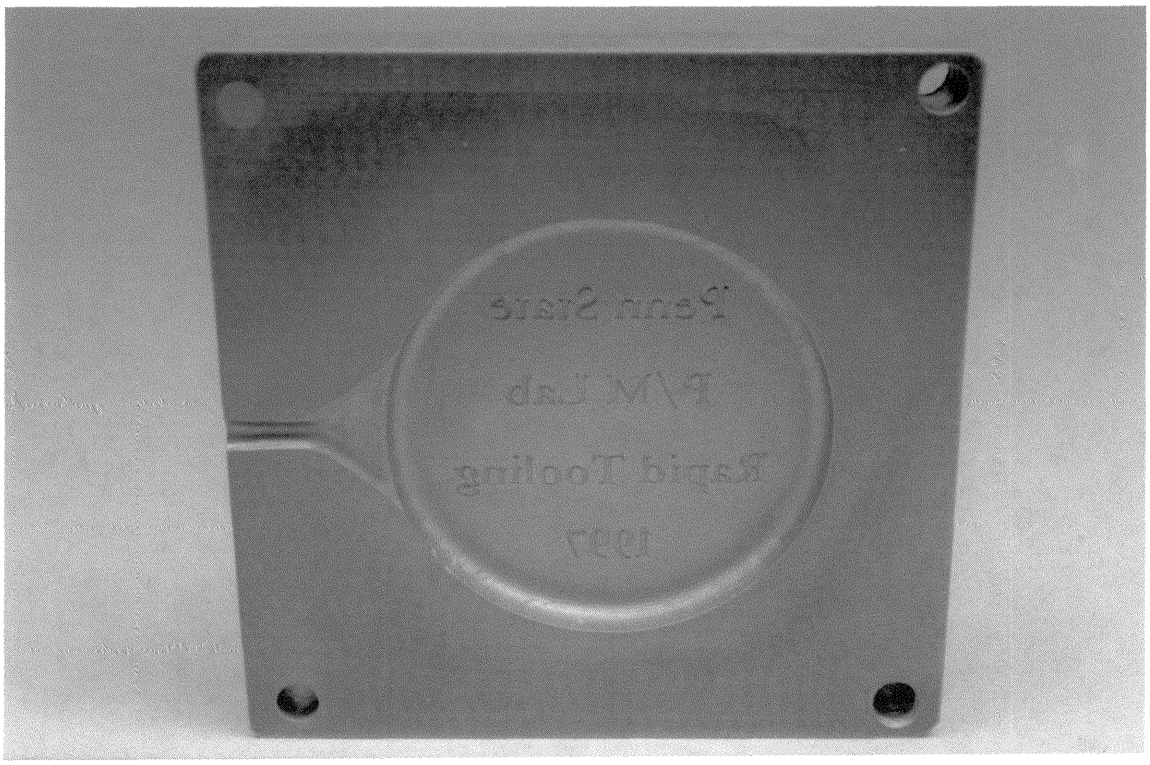

Figure 6. Picture of Final Tool Set Ready for Injection Molding.