Direct Injection Molding Tooling Inserts from the SLS Process with Copper Polyamide

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The "RapidTool" Short Run (SR) Tooling Process using the Copper Polyamide material provides a route to mold inserts for injection molding made directly in the Selective Laser Sintering machine. The STL files for the mold inserts are shelled and conformal cooling lines and ejector pin guides are added before SLS processing. Sintering of the material in the SLS machine provides quick metal/plastic tooling with good thermal conductivity. Final preparation of the tooling inserts includes sealing the surface with epoxy, final finishing using sandpaper, and backing up the shells with a metal alloy. The Copper Polyamide SR Tooling inserts are used to mold several hundred parts with common plastics with injection cycle times similar to conventional molding cycle times.

Rapid Prototyping and Rapid Tooling continue to change how products are designed and tested. Prototyping equipment used to make plastic models for visualization ten years ago is now used to make investment casting patterns, sand casting cores and molds, patterns for secondary processes, functional prototypes, and mold inserts for injection molding.

Market acceptance of Rapid Tooling continues to grow as designers realize the benefits of molding prototype parts with the actual production material. DTM introduced RapidSteel 1.0 in 1996 for the creation of steel/copper mold inserts [1]. DTM introduced the next generation of metal material in 1998. The RapidSteel 2.0 material provides improvements in processing time, finishing time, and accuracy compared to the original RapidSteel material. 3D Keltool was introduced by 3D Systems as a secondary process to produce steel/copper inserts from a RP pattern [2]. Extrude Hone announced the ProMetal RTS-300 system for creating porous steel inserts using the three-dimensional printing (3DP) technology licensed from MIT [3]. These processes require a furnace to sinter the steel and infiltrate the porous steel part with a copper alloy. The resulting parts are fully dense and can be used to mold over 100,000 plastic parts with most plastics.

Recently, a new breed of Rapid Tooling solutions has emerged to provide short runs of production equivalent plastic parts. These limited runs of molded plastic parts are often used in the product development stage where several hundred parts in the final material are needed. The faster and more economically a manufacturer can get a supply of parts produced in actual production materials, the faster he can perform life testing, make adjustments to the design if necessary, and get the new product on the market.

Methods of creating short run mold inserts available in today's market include direct manufacture using RP, cast metal/epoxy tooling, and CNC machining. Mold inserts made directly in rapid prototyping devices include SLA epoxy, SLS metal/plastic, and SLS direct metals [4]. The metal/plastic material available for processing in the Selective Laser Sintering process is Copper Polyamide introduced in mid-1998.

The Copper Polyamide material is a heat resistant, thermally conductive composite of copper and plastic that was introduced for use with DTM's Sinterstation System. The Copper PA material processes in the Sinterstation at conditions similar to the DuraForm Polyamide material. The Sinterstation builds the mold inserts directly from the geometry described in the STL file. Features like runners, gates, conformal cooling lines, and ejector pin guides are included in the STL file and built directly into the part. Turnaround times for the production of a mold insert are as short as a day. The key is that no furnace process is involved.

The Copper PA composite makes parts that are machinable and easily finished with wet sanding. Heat resistance and thermal conductivity are better than most plastic tooling materials, and it is possible to mold parts with cycle times that approach production rates. Injection mold inserts made with this material are used to mold 100 to 400 parts in polystyrene (PS), polyethylene (PE), polypropylene (PP), glass filled polypropylene (GF PP), ABS, PC/ABS, and other common plastics.

Mold Preparation

Injection molding incorporates a cavity into which hot plasticized material is injected under pressure. Heat is removed from the material in the mold until it is rigid enough to be ejected so that the final part will conform to all of its specifications. Both the design of the part and the design of the mold are critical in insuring the right mold. While the design of the part is not within the scope of this paper, it should nevertheless be thoroughly reviewed by those people directly involved in the design of the mold and in the molding operation [5].

Before an injection mold is built the mold design must be established. Some basic considerations for the mold include the type of gating, the thermal control system, the type of ejection, the type of venting, and anticipated shrinkage. With these items in mind, the designer defines a parting line and adds the necessary features to the mold halves.

When designing a mold for direct manufacture using SLS in the Sinterstation the cooling lines, ejector pin guides, gates, and runners can be included in the CAD design and built directly in the Sinterstation, see Figures 1 and 2. Building these features directly into the mold saves time by reducing the man-hours spent preparing the mold for injection molding.

Adding the cooling lines to the CAD file is an advantage because they can be placed near crucial mold features. The alternative to adding cooling lines to the CAD model is placing copper tubing in the back of the mold-half prior to backfilling. The copper tubing can also be placed near critical mold features. However, placing copper tubing is more difficult and time consuming than the placement of virtual cooling lines in the CAD model.

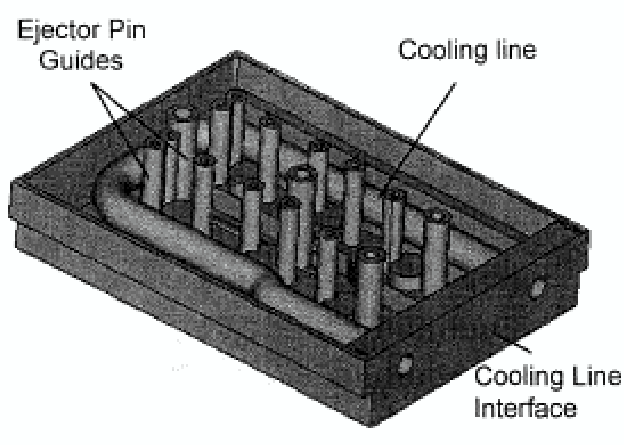

Figure 1. Back surface of a mold core.

Ejector pin location plays a critical role in the success of the mold. A Copper Polyamide mold requires 30 to 40 percent more ejector pins than a standard aluminum tool. Adding more ejector pins makes part ejection easier which extends the life of the mold. When applying ejector pin holes in the CAD file, the holes should be made the size of the ejector pin. These holes are reamed out during the mold-finishing phase. After the shelling operation, extend the ejector pin guides beyond the back surface of the mold to prevent the holes from becoming clogged when the backfill material is added.

Runner and gate designs are important to mold life and part quality. Gates for the Copper Polyamide molds should be larger than gates on an aluminum tool. The larger gate will keep the cavity pressure down. On large molds, fan gates are recommended. On smaller molds, edge gates are used.

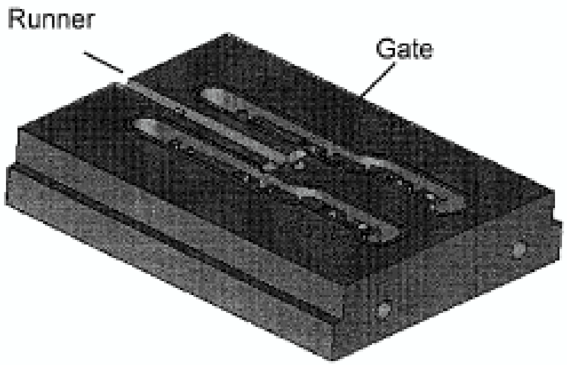

Figure 2. Working surface of a mold core.

When the CAD design of the mold is complete, the mold half is shelled so that a backfill material can be added to aid in the conduction of heat away from the mold surface. The shelling operation is performed either in the CAD package by operating on the solid model, or in a specialized application like Materialise's Magics RP [6] which operates on the STL file. In this step, the mold is hollowed out such that the external surfaces have a wall thickness of 3.8 mm. The bottom surface is then removed to provide access to the back surface of the mold face.

If the cooling lines are added to the CAD file, the wall where the cooling lines enter/exit should be 12.5 mm thick. Since the Copper Polyamide is machinable the cooling line interface can be reamed and tapped for connecting the water source.

When using a low melting metal alloy as a backfill material, include a rib grid in the back of the mold to lock the alloy into the mold, see Figure 3. This rib grid is not necessary if a metal filled epoxy is used as the backfill material, see Figure 5.

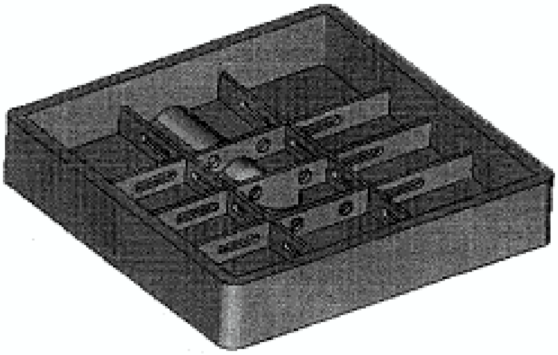
Figure 3. Rib-grid to lock in backfill material.

SLS Processing

After the mold design is complete and a STL file is created, the part is built using the Selective Laser Sintering Process [7]. The Copper Polyamide material is processed with temperatures set points and scan parameters similar to those used to process DTM's other polyamide materials.

The STL file in oriented so that the parting line is facing up with the longest dimension parallel to the x-axis, then rotated 15 degrees around the x-axis. The purpose of angling the part is to add strength to small post features.

Sacrifice geometry is added at the top and bottom of the build to control the cooling rate. The additional layer of scanned material acts as a heat fence reducing the thermal gradient within the part cake. Without this barrier, the mold inserts would cool too quickly because of the good thermal conductivity of the Copper Polyamide material, resulting in curled or warped mold inserts. The sacrifice geometry can be any geometry that covers a majority of the build area and is at least 2 millimeters thick.

Mold finishing

After the mold insert is built in the Sinterstation, it is finished and prepared for molding. The finishing steps include sealing the surface, finishing the surface, casting backfill material, machining ejector pins and cooling line connections, and aligning the insert in the mold base.

The Copper Polyamide parts as built in the Sinterstation are porous. The inserts must be sealed to prevent the molded plastic from adhering to the surface and to prevent the conformal cooling lines from leaking. A low viscosity epoxy or acrylate works well to seal the surface. It is important to select a sealant that can withstand high temperatures during molding. DTM recommends Imprex Superseal 95-1000A, which is a heat cure acrylate.

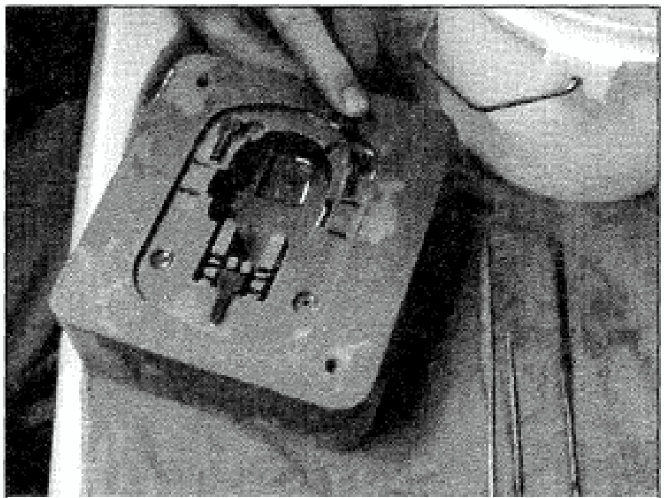

Figure 4. Finishing of the mold surface with sanding cloth.

After sealing the part, the mold surface is finished with a flexible sanding cloth, see Figure 4. Start with 220 grit, then 320 grit, and finally a 400 grit. Either wet or dry sanding techniques can be used. Apply another coat of sealer to the mold surface after sanding.

Figure 5. Backfilling mold inserts with a metal filled epoxy.

The backfill material recommended by DTM is Metspec 217. This material is a metal alloy with a melting temperature of 103°C. The Metspec is poured in layers to avoid softening and deforming the mold insert. When these steps are complete, the mold insert is inserted into the mold base. Different types of mold bases have been used successfully. If using a two-plate type mold base, dowel holes can be added to the CAD model in the corners of the mold insert to aid in alignment. If using a one-plate pocketed base, conventional methods are used to square up the insert before placing the mold insert into the pocketed base.

Molding Trials

The mold inserts are fairly durable allowing a molding house to run the mold without special instructions. The durability of the Copper Polyamide mold inserts is similar to that of cast metal/epoxy tooling. The thermal conductivity of the material is good, 1.28 W/m-K at 40°C, and is also similar to that of cast metal/epoxy tooling. The good thermal conductivity, in combination with the conformal cooling lines and a metal backfill material, allows the mold to be run with normal cycle times, typically 25 to 40 seconds. The mechanical and thermal properties of SLS objects made with the Copper Polyamide are reported in Table 2.

When molding, the mold should be at a consistent molding temperature before injection of the plastic. Try to get a full shot the first time. If there is a short shot, it is more likely to stick in the mold and cause damage. Mold release can be used at the beginning of the molding run. It is not necessary to apply mold release after every shot or late in the molding run. Several different release agents have been used with no problems.

A number of common plastics have been successfully molded in the Copper Polyamide mold inserts. The melting temperatures and processing temperatures for the plastics used in the mold inserts are listed below. In most cases, the mold inserts showed little or no wear and can be used to mold additional parts.

Table 1. Examples of plastics successfully molded in Copper Polyamide mold inserts.

Material	Melting Temperature, °C	Processing Temperature Range, °C (°F)	Parts molded
Polyethylene	T_m 122 – 137	175 – 260 (350 – 500)	50 – 350
Polypropylene (PP)	T_m 160 – 175	190 – 285 (375 – 550)	50 – 200
10-40% talc filled PP	T_m 158 – 168	175 – 285 (350 – 550)	50 – 350
40%GF Polypropylene	T_m 168	230 – 285 (450 – 550)	30 – 150
ABS (medium impact)	T_g 102 – 115	200 – 275 (390 – 525)	40 – 150
ABS/PVC	T_g 175 - 205	185 – 210 (370 – 410)	100 – 200

Case Study #1: Brake fluid reservoir molded in polypropylene [8]

Last spring at BASTECH, Inc [9], an automotive OEM client offered a challenging assignment. It needed 20 to 50 sets of brake reservoir parts produced in the intended production material, polypropylene. The parts had to withstand prolonged contact with brake fluid. Moreover, they had to perform like production parts during functional testing on a prototype vehicle.

BASTECH had faced a similar situation a year ago. Back then, the company had used 3D Systems' AIM Tool process to create prototype tooling. The results were only marginally successful. After 10 shots with the AIM Tool they began to see deformation of the parting line and the mold itself. The run produced only 40 polypropylene parts, with each set becoming slightly more deformed.

Wanting something better for this molding run, BASTECH used the Copper Polyamide material. The brake reservoir consisted of two pieces, which eventually would be welded together. Two tools were required to make these parts. One tool was made up of 13 pieces; the other was made up of 6 pieces. Eight pieces of the thirteen-piece tool were made using the Copper Polyamide (Figure 6), as were five pieces of the six-piece tool. The remaining pieces, very simple inserts or sleeves, were machined out of metal. The final part, after welding, measured approximately 110 mm by 154 mm by 41 mm.

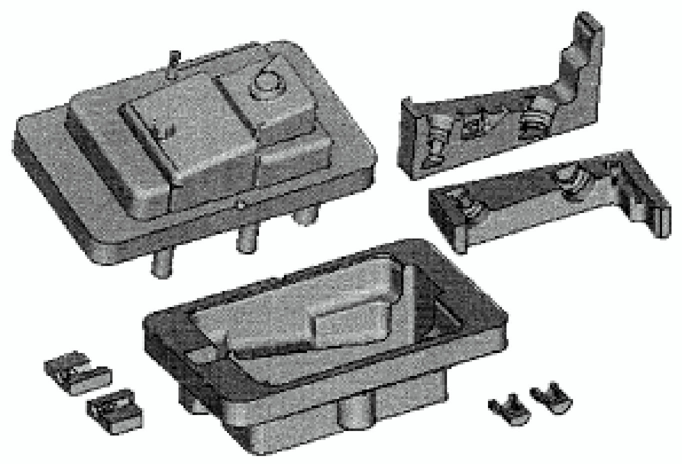

Figure 6. STL files used to build the mold halves and inserts.

BASTECH ran 75 sets of parts on the Copper Polyamide tools and noticed very little wear. They started to see a little degradation in a few areas, but could easily have gotten 100 to 150 sets of parts from the molds. The SLS Copper Polyamide tooling withstood an injection molding pressure of 400 psi and injection molding temperatures of 230°C. They stated that the molds were very sturdy which impressed them the most. Overall, both BASTECH and there customer were very pleased. The molded parts are pictured in Figure 7 next to one of the mold halves.

The SLS Copper Polyamide tooling well outlasted the AIM tooling. It took an extra day to fit, finish, and polish the SLS tooling; but the resulting tools were more stable, not deforming during molding, and the parts produced looked much better. The time and costs for producing tools using Copper Polyamide in the SLS process or Epoxy in the SLA process are roughly the same.

Figure 7. Parts molded by BASTECH in the Copper Polyamide molds pictured next to one of the mold inserts.

Comparing the timing and costs of an SLS Copper Polyamide tool to that of a conventional steel or machined production tool offers more compelling numbers. The SLS molds can be produced at roughly one fourth the cost in only one half the time when compared to steel tooling. These savings are important when only 50 to 500 molded parts are needed.

Case Study #2: Glass guide molded in nylon 6,6 [8]

The Rover Group [10], at their Rapid Prototyping and Tooling Department situated on the campus of the University of Warwick, has participated as a beta test site for the Copper Polyamide material. Rover has studied, among other things, how tooling made via the SLS process with the new Copper Polyamide material compares to alternative low cost tooling routes.

One of the parts selected for Rover's comparison was a glass guide (approximately 90 mm x 60 mm x 25 mm). This part is used to ensure the automobile door window locates in the rubber seal when closing. The intended production material was nylon 6,6. They had already created the tool geometry in cast resin, so when they created a Copper Polyamide tool with the SLS process it was purely for the sake of comparison.

Rover designed the single cavity mold inserts as solid objects on a CATIA workstation. The STL files were then shelled to a wall thickness of 2.5-mm using Materialise Magic RP software. The inserts were produced in one of Rover's two in-house Sinterstation 2500 systems. Once removed from the Sinterstation, the hollow tool inserts were backed with an epoxy resin loaded with aluminum powder and granules. The tool was subsequently machined to fit one of Rover's standard injection molding bolster sets.

To trial the Copper Polyamide mold inserts and to ensure the tool was working properly, Rover shot an initial run of 33 polypropylene parts. Once confident that the tool was working properly, they shot another

117 nylon 6,6 parts into the Copper Polyamide tool. Nylon 6,6 parts molded in the Copper Polyamide tool are pictured in Figure 8.

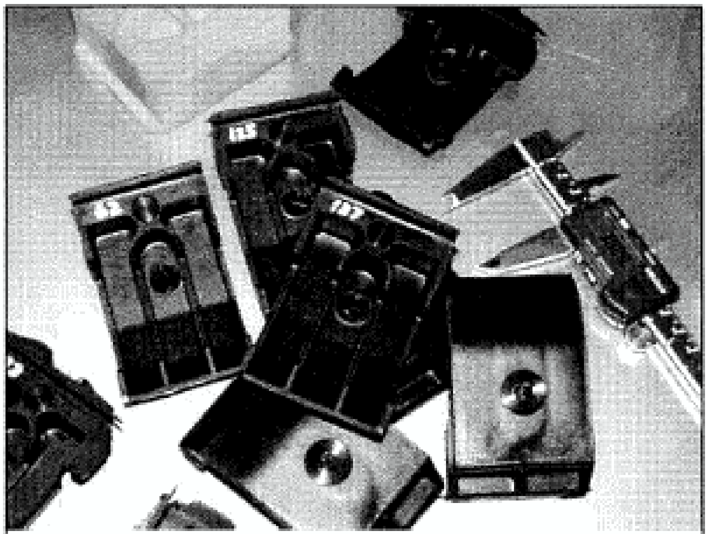

Figure 8. Glass guide parts molded with nylon 6,6 in a Copper Polyamide tool. 117 parts molded.

Rover was pleasantly surprised with the results. They had not expected the Copper Polyamide tooling to withstand the high injection temperature of nylon 6,6 which is 285°C. Some minor degradation of the Copper Polyamide tool began to occur after 20 shots. The degradation was most noticeable around the sprue puller where the sharp edges began to erode. This area was directly across from the injection sprue where the mold reaches the highest temperatures. Dr. Illston at Rover stated that the degradation of the tool was also exaggerated because the part geometry was an early prototype design. The glass guide part featured a section of approximately 1 cm^3 that retained considerable heat during injection molding. Increased localized heat build up resulted in additional erosion of the male part geometry where the small radii were intended.

The final result of this project was that 60 nylon glass guides made from the Copper Polyamide tools have been installed on Rover Group's prototype vehicles. Under the circumstances, the performance of the tool was far better than expected.

Rover has continued to explore the advantages of the SLS-generated Copper Polyamide tooling. Another project resulted in 300 parts molded with 30% talc filled polypropylene. The part is a speaker fret (or speaker cover) which measures 38 mm in diameter and features a complex geometry, see Figure 9. During the production of these parts, the tool showed no wear or part flashing. The injection temperature of the polypropylene material was 240°C.

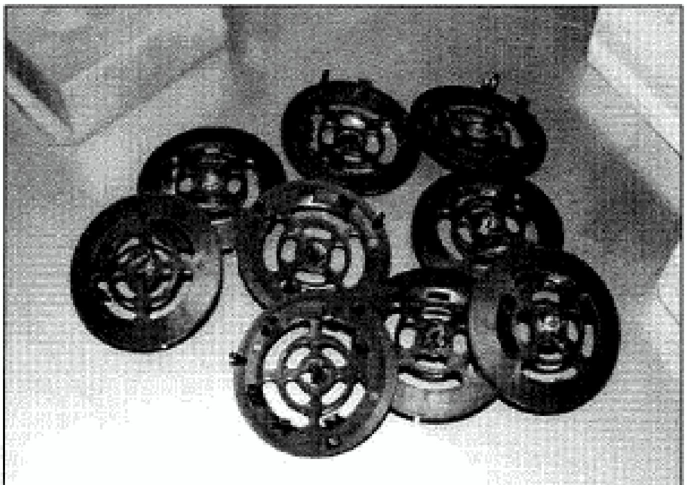

Figure 9. Speaker fret parts molded with 30% talc filled polypropylene. 300 parts molded in the Copper PA tool.

Rover has worked with a number of rapid tooling methods. Their view is that the Copper Polyamide mold inserts compare more favorably to cast resin tools. Although the performance of the Copper Polyamide tools is comparable to cast tools because the thermal conductivity of the two material systems are similar, there are advantages to building the mold inserts directly in the Sinterstation from the CAD data. When asked which method is faster, Dr. Illston says it all depends on the data available. If the CAD data is available for the mold inserts then the Copper Polyamide route is quicker. If the CAD data is only available for the part, then it is quicker to create a RP master pattern and cast the resin tool. Rover is currently evaluating the cost and time comparisons between the two processes.

Conclusion

The Copper Polyamide material and the Sinterstation system can rapidly produce limited life prototype mold inserts. Prototype quantities of production-quality molded plastic parts can be manufactured with these metal-based mold inserts.

The important attributes of a short run tool are durability, molding cycle times, and speed. The durability of the Copper Polyamide tools is comparable to epoxy/metal tooling and is much better than Direct AIM tools. The molding cycle times for Copper PA are similar to metal tooling. This is important because cycle times can affect the mechanical properties of the molded parts. Mold inserts are created relatively quickly with the Copper Polyamide material. Molds can be ready for molding in 5 workdays; this includes all processing steps required to move from a STL file to molded parts.

Table 2. Copper Polyamide product specification

		UNITS	ASTM TEST METHOD	BUILT in Sinterstation	
PHYSICAL PROPERTIES				@15° angle	FLAT
Density	23°C	g/cm^3	D-792	3.45	
THERMAL PROPERTIES					
DTUL, 0.45 MPa (66 psi)		°C	D-648	174	176
DTUL, 1.82 MPa (264 psi)		°C	D-648	122	123
Thermal Conductivity	40° to 150°C	W/m-°C	E-1530	1.28 – 0.92	
Specific Heat	40° to 150°C	J/g-°C	DSC	0.66 – 0.87	
Coefficient Thermal Expansion	30° to 150°C	m/m/°C	E-831	92.6 x 10^{-6}	
MECHANICAL PROPERTIES					
Tensile Strength, ultimate		MPa (lb/in^2)	D-638	33.6 (4,870)	35.9 (5,208)
Flexural Strength, 5% strain		MPa (lb/in^2)	D-790	53.5 (7,760)	58.3 (8,460)
Flexural Modulus		MPa (lb/in^2)	D-790	3,068 (445,000)	3,223 (468,000)
Compressive Strength, 0.2% offset		MPa (lb/in^2)	D-695	88 (12,800)	99 (14,400)
Hardness-Shore "D"			D-2240	75	75
SURFACE FINISH					
As SLS Processed, Ra		µm (µ in.)	-	27.7 (1108)	12.5 (500)
After Finishing, Ra		µm (µ in.)	-	5.2 (208)	2.5 (88)

Data was generated from the testing of SLS™ parts produced with the Copper PA material under typical processing conditions. (New material processed with a laser power of 15 watts, scan speed of 5000 mm/sec, scan spacing of 0.1 mm, and a layer thickness of 0.1 mm in the Sinterstation 2500. Samples infiltrated with Imprex Superseal)

References

1. U. Hejmadi and K. McAlea, "Selective Laser Sintering of Metal Molds: The RapidTool Process", *Solid Freeform Fabrication Symposium Proceedings*, The University of Texas, Texas, pp. 97-104, 1996.
2. R. Connelly, "Rapid Tooling for Medical Products Using 3D Keltool", *Rapid Prototyping and Manufacturing Conference*, Dearborn, Michigan, pp. 89-99, 1997.
3. S. Ashley, "Progress Toward Rapid Tooling; Extrude Hone", *Mechanical Engineering*, **120**, [7], pp. 65-67, 1998.
4. T. Wohlers, *Rapid Prototyping & Tooling, State of the Industry*, Wohlers Associates, Inc.: Fort Collins, Colorado, pp. 71-72, 1997.
5. J. Frados, *Plastics Engineering Handbook of the Society of the Plastics Industry, Inc.*, 4th edition, Van Nostrand Reinhold: New York, pp.131-155, 1976.
6. Materialise, 6111 Jackson Road, Ann Arbor, Michigan, 48103, www.materialise.com.
7. C. Nelson, "Improvements in SLS Part Accuracy", *Solid Freeform Fabrication Symposium Proceedings*, The University of Texas, Texas, pp. 159-169, 1995.
8. "BASTECH and Rover Share Experiences With New Copper Polyamide", *Horizons*, A Publication of DTM Corporation, Austin, Texas, Q3 1998.
9. B. Staub, BASTECH Inc., 3541 Stop Eight Road, Dayton, Ohio, 45414, www.bastech.com.
10. T. Illston, Rover Group, ATC, 3rd Floor, The University of Warwick, Coventry, CV4 7AL.