Rapid Tooling via Stereolithography

Moving SL Closer towards Rapid Manufacturing

Montgomery, Eva; DSM Somos®, Elgin Illinois

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Abstract

Approximately three years ago, composite stereolithography (SL) resins were introduced to the marketplace, offering performance features beyond what traditional SL resins could offer. In particular, the high heat deflection temperatures (>250°C) and high stiffness of these highly filled resins have opened the door to several new rapid prototyping (RP) applications, including wind tunnel test modelling and, more recently, rapid tooling. While traditional SL resins of the past couldn't offer the mould life necessary for the effort, the commercial successes of new Somos® ProtoComposites™ materials such as ProtoTool™ 20L and NanoForm™ are demonstrating new potential for time and cost savings.

In rapid tooling applications, molds made from these resins have been able to successfully produce hundreds of injection molded parts at a time from such plastic materials as ABS, polypropylene, polyethylene, polycarbonate, thermoplastic elastomer and 33 percent glass-filled nylon. Depending upon part geometry, the use of these composite molds can provide time savings compared to machined metal molds as evidenced by the Paramount Industries case study described in the paper. As more handling experience is gained, composite molds can also provide cost savings.

To address the learning curve and to begin answering the many questions regarding SL composite tool size and geometry limitations, tool life expectancy and dimensional stability, key players in the rapid prototyping and rapid tooling industries from the United States formed a working group initiated by DSM Somos. The working group completed the first phase of their controlled study to better assess the technology for its reliability, initial Phase 1 findings are reported in the paper.

Background

The concept of working with stereolithography (SL) for manufacturing rapid tools for the injection molding of thermoplastic parts is not new. Initial attempts to build tools were largely unsuccessful, leaving in its wake an underlying resistance within the rapid prototyping and.

tooling industries to even consider SL for rapid tooling applications.

There are a multitude of reasons for the initial lack of success. DSM Somos identified the most important ones as being

- An absence of materials with adequate strength, temperature resistance, modulus and dimensional stability
- Insufficient understanding as to how mold designs need to be modified to accommodate specific characteristics of SL technology
- A lack of experience with injection molding in tools made from composite materials rather than alloys.

Given DSM Somos central strategy of growth through SL applications development, we were not prepared to give up so easily on these challenges. We were convinced that the accuracy and speed inherent in SL technology, combined with targeted materials and applications development could yield positive results. Our approach has been four-fold:

- Rapid Tooling materials development and optimisation
- Support of fully commercial tooling projects with industry partners
- The sponsoring of a rapid tooling Working Group which draws together experts from the complete development and supply chain
- Support of academic graduate and PhD research

Materials Development

In the last 4 years, DSM Somos has commercialised two SL materials that exhibit step-change characteristics from standard epoxy SL materials.

- ProtoTool™ 20L
- NanoForm™ 15120

Both are based on composite technology not used in stereolithography until the introduction of ProtoTool™ in 2002. The combination of a high performance resin and non-crystalline silica reinforcement produces a composite material that has excellent properties for use in injection molds as well as allowing the mold finisher to more safely finish the mold. These properties include high strength, modulus, heat deflection temperature, and accuracy, as well as excellent dimensional stability when compared to neat SL resins (Table 1).

Property	Typical Unreinforced SL Resins (UV cure only)	NanoForm™ 15120 (UV + thermal post-cure)	ProtoTool™ 20L Composite Resin (UV cure only)
Tensile Strength, MPa	41-55	53	72-79
Modulus of Elasticity MPa	690-3100	5900	10,100-11,200
Elongation at break (%)	4-30	1.2	1.2-1.3
Flexural strength, MPa	41-103	129	118-123
Flexural Modulus MPa	690-3450	4450	9240-9600
Compressive strength, MPa	N/A	234	153
Compressive modulus, MPa	N/A	4680	10,130
Tg, °C		80	49
Heat Deflection Temperature, °C @ 0.46MPa @ 1.81MPa		 269 115	 257-259 83-94
KtA (100-150°C), µm/m-°C	170-190	129	81-91
Water Absorbtion (%)	1.0-1.25	0.26	0.24-0.30

Table 1. Physical and mechanical properties NanoForm™ 15120, ProtoTool™ 20L and unreinforced SL resins.

From the table it can be seen that the property differences are significant. The higher strengths and moduli of both NanoForm™ and ProtoTool™ enable molds made of made of these resins to withstand high injection pressures (>35 Bar). Compressive properties are not normally measured for unreinforced resins, but the high compressive strength and modulus of ProtoTool™ 20L and NanoForm™ 15120 enable molds made of these materials to withstand the clamping pressures of an injection molding machine. In addition, the high heat deflection temperature and low coefficient of thermal expansion of the DSM Somos composite resins provide assurance that the molds will not deform or become dimensionally inaccurate over the injection molding temperature range of the most common thermoplastics.

Over the past two years, molds made from these materials have been used to make a series of fully commercial injection molded parts ranging from polypropylene to glass filled nylon in both Europe and the United States. The number of parts produced has ranged from ‘just a few’ to several thousand, depending upon the requirements of each specific project.

This paper will present the research and findings of two groups who over the past year have investigated the commercial feasibility of using stereolithography and composite SL resins for rapid tooling: 1) a commercial design and product development house and 2) an industry working group. The findings to date are proving that rapid tooling via SL technology is a viable and cost effective alternative to CNC machining for short runs.

Commercial Applications Experience: Paramount Industries

Paramount Industries is a full service product development design house located in Pennsylvania, USA. Their clients include those from the consumer products and medical device markets. Like most design and product development houses, High speed (HS) CNC machining is their rapid tooling standard, however, over the last 30 years they had investigated other rapid tooling methods such as cast epoxy composites, cast aluminum, cast S7, spray-metal, cast beryllium, KelTool and SLS RapidSteel', however, none of these methods proved to be as useful and reliable to them as CNC machining.

When SL users and injection molders first began investigating rapid tooling (several years prior to the introduction of ProtoTool™ 20L), Paramount Industries was not interested in investigating yet another RT method, until DSM Somos showed them the potential with ProtoTool™ 20L. The advanced material properties such as HDT of 258°C, coupled with reliable machine accuracy (due to the advent of 3D system's Viper) was enough to warrant a first look for Paramount, they believed that if the SL-ProtoTool™ routing proved successful, the technology could be used to make parts with approximately 75% of the engineering grade molding resins, possible exceptions being polyether, polysulfone and similar resin classes which have processing temperatures in excess of 310°C.

Paramount had clear business goals: accurate parts produced within one week from receipt of initial drawings, and at much lower cost compared to machined metal tools.

The first opportunity to investigate a new approach to Rapid Tooling came in the form of a project from a division of Ingersoll Rand. Paramount had been working with a product development team for nearly a year on a new line of high-speed hand-held air grinders. The new air grinders were being engineered to include more reduced cost injection molded thermoplastic components rather than machined metal.

The predominant resin used was a type 6 Nylon with 33% glass filler (BASF Capron 8333G-HI). This material is typical for robust and abusive industrial environments. Recommended injection pressure for this particular grade of Capron is relatively low, 35-125 Bar with a processing temperature of 270-291°C and molding temperature of between 94 and 105°C.

The production tooling was near completion and the first articles were beginning to arrive from Ingersoll's Chinese supplier when errors became apparent. The part's surface geometry had been interpreted incorrectly from the CAD data and translated to the inside of the body housing. Requesting a correction to the body housing would put the team 4-5 weeks behind schedule. The IR engineering team thought they might be able to modify an internal part called a 'Cage' to compensate for the error however, the theory needed to be tested, but therein lay a dilemma:

- A new part needed to be made, but using anything other than Capron was not an option, motor speeds of 30,000 rpm and accelerated air velocities which can create elevated part temperatures excluded SL materials as well as cast urethane.

The team needed at least two Capron parts to verify their design concept. If the design change worked, Ingersoll would request their Chinese supplier to modify the Cage tool. However even this routing would still leave Ingersoll 2-3 weeks behind schedule. Using the SL-ProtoTool™ RT route, Paramount modified the tool design to include a steel gating area because of concern that the composite tooling would not stand up to the injection forces of the glass filled nylon. It turns out adding the steel gating was the right decision because after the second full shot, the pressures of the Capron broke off a piece of the ProtoTool™ directly opposite the gate area. Even allowing for modifications to the tooling, Paramount was able to deliver molded parts in less than two weeks.

At a later time, this same tooling trial was attempted unsuccessfully with NanoForm™, in this case, the NanoForm™ could not withstand the injection forces even with steel inserts in the gating an rib area.

Keen to monitor the commercial feasibility of the new SL-ProtoTool ™ approach to Rapid Tooling, Paramount also ran a bench with their standard HS-CNC route. The bench, as well as that of a second project, a run of 1000 Polypropylene molded parts, indicated that the SL-ProtoTool™ routing generated fairly significant time savings (Figure 2).

	Cage SL RT#1		**SL RT#2**	
Phase Description	**PT20L**	**HSM AL**	**PT20L**	**HSM AL**
	Hrs	**Hrs**	**Hrs**	**Hrs**
Tool design	4	4	12	12
CAM Programming	-	8	-	13
Net Shape	28	24	75	36
Bench-work	50	40	36	37
Sample tool	8	8	8	8
Labour & Machine Hrs:	90	84	131	106
SL Resin Cost	$ 450	$ -	$ 1,050	$ -
Purchased Materials:	$ 250	$ 250	$ 350	$ 485
Lead time	1.5 weeks	3 weeks	1.5 weeks	3 weeks

Table 2. Time/cost comparison of ProtoTool™20L tooling versus HS-CNC

Comparing the total labour and machine hours of SL-ProtoTool™ 20L versus HS-CNC Al, it appears in both cases that it cost more to build the tools out of the SL process than machining, however, the benefit for rapid tooling in each of these cases was time where SL delivered the injection molded parts in half the time as evidenced by lead time. In addition, Paramount Industries has indicated that in both cases RT#1 and RT#2, if repeated, would show SL rapid tooling providing a significant time and cost savings presumably due to the knowledge gained in handling composite tooling from these and three other trials.2 This knowledge includes, techniques for finishing and properly fitting the composite tools into the injection molding frames and layer thickness required to build the mold. Both molds were built in high-resolution mode on the Viper in 0.05mm layers. The resolution in both cases could have been reduced to 0.10mm layers thus saving even more time.

Sponsoring of A Working Group

Paramount completed 5 successful RT projects using the SL-ProtoTool™ routing, while these projects, as well as others elsewhere in the US and Europe, have been a commercial success, a number of questions were raised, mainly with respect to optimising tooling design, tool life, difference between NanoForm™ 15120 and ProtoTool ™ 20L and optimisation of injection molding parameters.

The need to address these questions in order to further open the window for SL technology in the RT world, prompted DSM Somos to form a US based working group which has been in operation since June 2005 and includes several RP service bureaus with either NanoForm™ or ProtoTool ™ processing capabilities, RP service bureaus with injection molding capabilities, consumer products companies and one university. Phase one began with the design of a simple, non-proprietary part that measured 63mm x 44mm and included features such as tall ribs (8mm) and sharp corners. These features, although simple, would require a secondary machining step after CNC machining to produce the sharp edges but yet would not be an issue with stereolithography since the features would be grown directly along with the rest

Using this part design, molds were made via several tooling methods each by a different working group member, including stereolithography (both NanoForm™ and ProtoTool™), CNC machining, cast epoxy and nickel-plated ProtoTool ™ 20L. All tool sets were then sent to the Center for Manufacturing Excellence at the University of Kentucky, where they were used to injection mold parts out of ABS on a Cincinnati Milacron 100 ton press (goal was to produce 100 parts from each tool set), attention was paid to injection mold parameters, part quality, cycle times and factors effecting tool life. Several key learnings were gained from the study and are shared in this paper however, the full report will be presented at SME's Rapid Prototyping 2006.

Gate design

The gate design was created with an aluminum tool in mind and a MoldFlow program determined the optimum position. The original size of the gate was 6mm(w) x

1mm(d)x2mm(l), which was not problematic with any of the tools except those built with NanoForm™ (Table 3). The flexural modulus (ability of a material to resist deformation under load) of NanoForm™ is approximately half the value of ProtoTool™. It is believed the NanoForm™ could not stand up to the forces exerted on the gate area as evidenced by NanoForm™ 1 tool. A piece of the gate area cracked off after the second ABS shot, however, the injection molder continued with the trial until full failure (when the face of the mold was removed). After inspecting the cracked gate area of the first NanoForm™ tool, it was determined the gate was too small for this resin, therefore the next set of NanoForm™ tools were widened and deepened to produce a gate area that was four times as large as the original. In the second and third trials with NanoForm™ 2, the gate area did not crack.

In comparing NanoForm™ with ProtoTool™ 20L, the gate area of the ProtoTool™ inserts were left the original size according to the tool design, but did not exhibit the same cracking problems seen with the NanoForm™ tools. Between this study, the trial with Paramount Industries and other industry accounts, several conclusions can be made with regards to SL composite tooling.

1) Special considerations must be taken in regards to the gating area for both ProtoTool™ and NanoForm™.

2) Due to it's lower flexural modulus, more care needs to be taken with NanoForm™ tooling versus ProtoTool™ tooling.

3) The tool designer should consider either enlarging the gate area (especially in the case of NanoForm™), moving the gate position or even adding a metal insert if very abrasive thermoplastics are to be molded.

Tooling method	SL Build style	Gate Size	Visible wear on gate area	# parts molded
NanoForm 1	Flat, 0.10mm layers	original	Large piece cracked off after 2nd shot	40
NanoForm 2	On edge, 0.15mm layers	4x larger	None	35
NanoForm 3	Flat, 0.10mm layers	4x larger	None	110*
ProtoTool 20L	Flat, 0.05mm layers	original	None	115*
Cast Epoxy	NA	original	None	115*
CNC Aluminum	NA	original	None	50*
Ni plated ProtoTool	Flat, 0.13mm Cu/Ni plating	original	None	110*

Table 3. Results of injecting molding trial with different rapid tooling methods and mold insert materials.

*** Note: Injection molder stopped the trial, tools were still in good condition.**

Cycle time

Both ProtoTool™ and NanoForm™ are fairly nonconductive materials, as such it was more difficult to remove heat from the tools than it was from either the aluminum or the aluminum filled cast epoxy tools (Table 4). For the injection molding trial, 9.5mm cooling channels were drilled through the Multi Unit Die (MUD) base 3mm from its surface to affect cooling.

Cycle times were judged based on the appearance of the parts coming of the press. The cycle began at 60 seconds and was either adjusted up or down depending on whether the part was warped. For this particular part, the two legs tended to warped and twist inward if the part was ejected too soon, therefore, based on this "test" cycle times were increased to >/= 130 seconds for NanoForm™ tooling. Adding external cooling via a Vortex cooling gun, reduced the cycle time by approximately 20 seconds to 111 seconds, ProtoTool™ had an even lower cycle time (75 seconds) using external cooling. It is not entirely understood why ProtoTool™ presumably has a higher thermal conductivity except that the composite resin contains a higher concentration of silica reinforcement than NanoForm™.

Tooling method	Gate Size	Injection Pressures (ksi)	Cycle Time	Vortex Cooling
NanoForm 1	original	5,2	138	No
NanoForm 2	4x larger	5,1	130	No
NanoForm 3	4x larger	4,7	111	Yes (10sec between shots)
ProtoTool 20L	original	5,5	75	Yes (10sec between shots)
Cast Epoxy	original	6,5	47	No
CNC Aluminum	original	8,0	35	No
Ni plated ProtoTool	original	5,75	81	No

Table 4. Cycle time comparison

Conclusion

SL composite rapid tooling continues to prove a viable alternative to CNC machined aluminum tooling or cast epoxy tooling for short-runs (less than 500). While the mold material cost may be greater in some cases than it is with Aluminum tooling, the benefit of SL composite tooling comes in the form of lead time as seen in the Paramount Industries example, especially when multiple machining steps would be required, however, the smaller the tool, the less significant the SL resin cost becomes. Also, the composite tooling needs to be treated differently than one would an aluminum tool. Careful consideration of the gate design and cooling methods needs to be taken into account. By adding SL composite tooling to the available tooling methods, the tool designer can increase the capabilities of the service bureau and perhaps deliver real injection molded parts in less time than its competition providing a real competitive edge in the marketplace.

References

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Contact

Eva Montgomery
DSM Somos®
1122 St. Charles Street
60120 Elgin, Illinois, USA
WEB: www.dsm.com