StereoLithography 1993:

QuickCast ™

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Abstract

Previously, StereoLithography (SL) generated solid patterns had limited success in highly accurate shell investment casting applications. The majority of the failures involved the cracking of the ceramic investment casting shell. However, the recent invention of the QuickCast ™ build-style and the development of a new epoxy resin, XB 5170, led to an unprecedented level of success in the burnout process of SL patterns from investment casting shells. Unlike conventional SL building techniques, QuickCast involves the building of SL patterns with essentially hollow structures. When the low viscosity liquid epoxy resin is drained from the interior of the pattern, voids are formed, allowing the cured resin to collapse inwards during the autoclave and burn-out stages. This effectively prevents the shells from cracking as the result of outward thermal expansion. 3D Systems formed QuickCast teams with three respected foundries to test shell investment casting using SL patterns. A test part having relatively complex geometries (i.e. a Boeing 737 cargo door bracket) was selected. To date, this SL part has been successfully cast in aluminum, titanium, beryllium-copper, and stainless steel, with RMS surface finish as low as 1 micrometer, without any subsequent finishing operations.

Background

Recently, one of the authors visited a large foundry that has specialized in investment casting for decades. Until just a few years ago, typical projects involved highly complex geometries in hundred to multi-thousand lot quantities for various aerospace applications. On such projects, the development of the tooling typically cost from $ 30,000 to as much as $ 200,000. Obviously, this was a lot of money. However, considering the critical characteristics of the final components, investment casting was often the least expensive production method capable of satisfying the specifications and was commonly the preferred approach. Furthermore, the amortized cost of the tooling, on a per part basis, was quite reasonable.

As a consequence of the profound changes in the aerospace business within the past two years, the situation has altered significantly. This foundry is now receiving hundreds of requests for quotation (RFQs) on projects involving one, two, or three prototype parts. Obviously, if traditional methods were used, the amortized cost of the tooling could be tens to hundreds of thousands of dollars per component. This is clearly not very economical. It is also not especially competitive. As a result, the company has been forced to no-bid hundreds of RFQs. Under the best of conditions this would not be desirable, but in a serious recession, sustained non-responsiveness could be critical to their future viability.

An economical means to produce accurate patterns with a smooth surface finish was clearly needed. Further, these patterns must be sufficiently robust to allow handling, assembly, and ceramic shell investing without breakage. Also, the pattern material must have characteristics that allow for excellent burnout without damage to the shell. And finally, prototype quantities should require minimal initial pattern generation expense. Stereolithography can be a solution if a process can be developed to address all these elements. While definitely ambitious, 3D Systems has advanced considerably towards this goal. Much of the progress has been led by improved photopolymers working in concert with still newer part building methods discussed below.

New Epoxy Resin XB 5170

Ciba-Geigy (Switzerland) and the Research and Development Department at 3D Systems have been involved in a program of joint SL photopolymer research and development since 1988. Ciba-Geigy, one of the leading chemical companies in the area of epoxy chemistry, had been looking at SL epoxy resins for sometime. In July, 1993, Ciba-Geigy released a new resin for the SLA-250 based on epoxy chemistry. The epoxy resin has an excellent set of physical, mechanical, and dimensional properties that exceed those of acrylate resins in almost every single category.[1] Namely, XB 5170 has

1) very low viscosity
2) high laser-cured (green) modulus
3) high postcured modulus
4) good elongation at break
5) good impact strength
6) substantially reduced thin flat slab distortion
7) almost twice the overall UserPart accuracy compared to XB 5081-1 acrylate resin (Note: XB 5081-1 was formerly the most accurate SL resin until XB 5170 was introduced.)
8) negligible curl during the SL building process
9) superb dimensional stability in the laser-cured state.

It is clear that XB 5170 possesses many of the key stereolithography characteristics needed for the generation of substantially more accurate parts. The combined properties make this epoxy resin, XB 5170, the resin of choice, especially for the new QuickCast ™ build style.

QuickCast ™

Previously, stereolithography generated patterns were successfully used for so-called flask investment casting, as shown by the results of Texas Instruments working with two foundries: Cercast Group and Shellcast Foundries, Inc., both of Montreal, Quebec, Canada. [2] In this method the stresses generated as a result of the thermal expansion of the resin during burnout are resisted by the solid metal flask as well as the considerable thickness of the ceramic material. However, this technique can only be used efficiently for a limited range of part geometries.

Unfortunately, attempts to use solid SL parts as patterns for the more general ***shell*** investment casting technique had achieved only modest success.[3] In numerous cases the heating of the pattern during burnout would cause significant thermal expansion of the resin, in excess of that of the ceramic material. This would lead to the development of substantial internal stresses and possible cracking of the shell. Special purpose Investment Casting Resins were also only marginally successful. The concept involved the addition to the resin formulation of a non-reactive volatile diluent. In principle, subsequent to polymer crosslinking, the volatile diluent would escape from the pattern upon heating, resulting in a loss of mass and a corresponding shrinkage that would hopefully offset the thermal expansion of the polymer.

Since this process hinges upon the diffusion of the volatile component to the surface, its effectiveness clearly depends upon the local surface to volume ratio. While thin sections might work well, thick sections could become diffusion limited, with the effects of thermal expansion occurring before those of mass loss. This was indeed what was observed. Parts having section thicknesses less than 2.5 mm worked well, with little or no tendency to generate shell cracks. For parts with section thicknesses between 2.5 and 4 mm, the method was marginal, showing occasional shell cracking. However, for parts with section thicknesses in excess of 4 mm, major shell cracking was observed.[4] Thus, despite some initial positive results, it became clear that solid patterns would not work in all cases.

Recognizing that the problem involved the thermal expansion of thick, solid sections of cured resin, it was reasoned that *quasi-hollow* patterns generated from a resin with good burnout characteristics might well allow the shell to survive. The key idea was that if the pattern was mostly hollow and made from a resin that softened at a relatively low temperature, it might collapse inward upon itself before sufficient stress had been developed to crack the ceramic shell. However, in order to generate quasi-hollow patterns, it became essential to devise a means by which the residual uncured liquid resin could be drained from within.

The heart of the QuickCast ™ method depends upon a novel interior part structure capable of providing effective resin drainage. Mathematically, QuickCast ™ involves building patterns in a *topologically simply connected* manner. Subject only to the limitations of viscous and surface tension forces, in principle no matter how complicated the pattern geometry, the resin should be able to flow from any location within the part to any other location within the part.

Clearly, if the second location is an opening, then the pattern could be drained of uncured liquid resin. In addition to the small openings for resin drainage, known appropriately as *drains*, other small openings known as *vents* are also required. The vents enable air to enter the evacuated volumes, thereby avoiding any flow retardation due to the creation of reduced pressure regions.

The vents and drains are later sealed with investment casting wax, at the foundry, to insure that the ceramic slurry will not invade the interior of the pattern. Experience with QuickCast ™ has shown that the time required to thoroughly drain a part is a function of:

- The part geometry
- The resin viscosity
- The resin surface tension
- The spacing of the QuickCast™ interior hatch vectors.

Extremely convoluted parts will take longer to drain than simple cubes. Resins with lower viscosity drain faster. Smaller resin surface tension reduces capillary effects. Finally, larger interior triangles greatly speed drainage. However, if the triangles are made too large, upfacing and downfacing surfaces may sag, leading to reduced pattern accuracy. Clearly, optimum parameters must be established for each resin. Figure 1 is a photomicrograph of an interior portion from a QuickCast™ part, showing the quasi-hollow, triangular hatch structure characteristic of this build style.

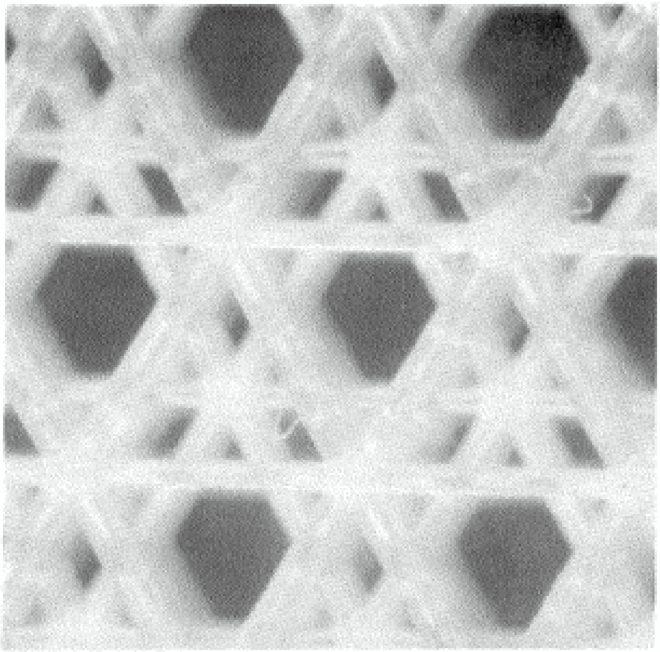

Figure 1. The interior hatch pattern used in the QuickCast™ build style.

A CAD model of the pattern is initially developed in the usual manner. Next, the part is sliced using the new QuickCast™ software proprietary to 3D Systems. This software provides instructions for the SLA system to generate the appropriate interior topology that is fundamental to the QuickCast™ method.

Upon completion of the SLA building process, the pattern is allowed to drain under the influence of gravity. With the new epoxy resin, XB 5170, simple parts drain within 30 minutes, while even the extremely complicated geometries require only a few hours. Subsequent to drainage, the part is simply wiped clean. XB 5170 leaves little residual photopolymer on exterior surfaces after about 45 minutes. The part is then postcured in a standard PCA for 1 hour.

Next, the pattern is wrapped in bubble-pack, boxed and shipped to an appropriate foundry that is thoroughly familiar with QuickCast™. The foundry will then seal the vents and drains with a thin coating of investing casting wax, add their usual wax gating, etc., and apply pretested ceramic shell coatings that have proven to be fully compatible with the resin used to fabricate the QuickCast™ pattern. This is one of the reasons that prior testing and approval of the foundry is essential for success.

At this point the wax gating is removed in an autoclave. During the early testing of QuickCast™ this step was problematic. However, over the past six months we have learned that successful autoclaving (i.e. removing the wax gating without pattern expansion causing damage to the ceramic shell) depends upon:

- The type of resin used to build the pattern
- The spacing of the interior hatch vectors
- How well the resin has been drained from the pattern.

All three of these items affect the so-called void ratio, or R_v, defined by the relation

$$R_v = 1 - [M_q/M_s]$$

where M_q is the mass of the QuickCast™ pattern, and M_s is the mass of a solid STAR-WEAVE™ part of identical size. Obviously, when the parts have not been drained at all, and M_q=M_s, then R_v=0. Conversely, the smaller the value of M_q the higher the value of R_v. Observations from numerous foundry autoclaving tests have shown that the greater the value of R_v, the higher the probability of successful autoclaving. Recently, using XB 5170, void ratios as high as 0.67 have been achieved. As a result, successful autoclaving is now occurring for about 80 % of the patterns tested. Further improvements in this ratio are anticipated as experience with QuickCast™ increases.

Subsequent to autoclaving, the shell is cured and the QuickCast™ pattern is burned out all in one step. Here the shell is elevated from room temperature to roughly 1,000°C within about 2 hours in a fully aspirated furnace. The shell is then maintained at this temperature for another 1 - 2 hours and finally allowed to cool. Since the resin is almost entirely hydrocarbon based, if the burnout is done in a sufficiently oxygen rich environment, the vast majority of the pattern material will be converted to carbon dioxide and water vapor. Any residual ash should be removed with compressed air or fluid rinsing and drying.

Next, the appropriate metal is poured into the ceramic shell mold and allowed to cool. In the case of either titanium or magnesium this must be done under vacuum to avoid oxygen contamination and subsequent damage to the surface of the casting. For aluminum, ferrous metal and beryllium-copper alloys conventional methods apply.

Finally, the shell is broken away, the gates removed and the usual finishing steps taken such as grinding, sandblasting, milling, etc. The end result is then a precision shell investment cast ***metal part*** produced directly from a stereolithography generated pattern; bypassing the traditional requirements for expensive and time consuming hard tooling.

Results to Date

3D Systems formed QuickCast ™ teaming arrangements with three respected North American foundries in May-June 1992. These were the following:

- Solidiform, Inc. Fort Worth, Texas, USA
- Precision Castparts Corp., Portland, Oregon, USA
- Cercast Group, Montreal, Quebec, Canada.

QuickCast ™ patterns were generated in five different resins: three for the SLA-250 and two for the SLA-500. These patterns involved a variety of different hatch spacings, drainage intervals, and post processing methods.

Early in the testing phase it was found that the most critical step involved the removal of wax gating during the autoclave process. A resin that softens at elevated temperature is definitely beneficial. Further, a very high correlation was found between successful autoclaving and the extent to which the pattern had been drained of excess resin. In all cases those patterns with the highest void ratios, always produced the best results.

After some initial trial and error, all three foundries have now achieved successful results using QuickCast ™ patterns for shell investment casting. To date, a Boeing 737 cargo door bracket has been successfully cast in the following metals:

• A-356 Aluminum	Solidiform
• A-357 Aluminum	Cercast
• TI 6 Al-4V Titanium	PCC
• C-20 Beryllium-Copper	Cercast
• 304 L Stainless Steel	PCC

Figure 2 shows a QuickCast ™ pattern of the cargo door bracket, and examples of the final metal parts in stainless steel, beryllium-copper and aluminum.

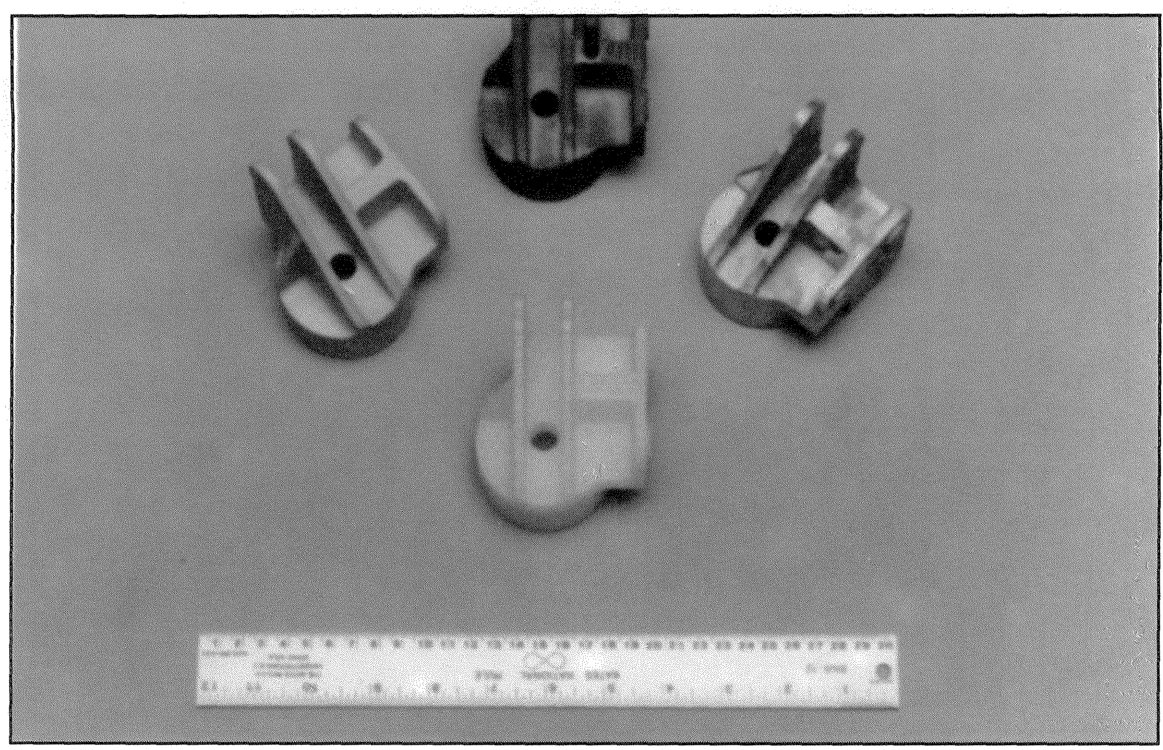

Figure 2. QuickCast™ pattern of the Boeing 737 cargo door bracket and final metal parts in stainless steel, beryllium-copper, and aluminum.

Also, a complex, six-bladed, centrifugal impeller has been successfully shell investment cast in A-357 aluminum directly from an SLA QuickCast ™ pattern, shown in Figure 3. The actual A-357 impeller casting is shown in Figure 4. Each of the three foundries is currently testing larger, more geometrically complex castings.

Figure 3. QuickCast™ SL pattern for the six-bladed centrifugal impeller.

Figure 4. The six-bladed centrifugal impeller cast in A-357 aluminum from the QuickCast™ SL pattern.

To date, the amount of residual ash has been measured in the range of about 10-30 micrograms per gram of initial pattern weight. The lower value corresponds to resin XB 5170. Three additional benefits of QuickCast ™ in XB 5170 are:

- *Substantial photopolymer savings.*
  With a hatch spacing of 3.8 mm, QuickCast ™ requires only 33% of the resin needed to build the same object with STAR-WEAVE ™.

- *A modest throughput increase.*
  Based on the test data from a representative range of parts, QuickCast ™ builds about 10-20% faster in XB 5170 than an equivalent part in XB 5149 using STAR-WEAVE ™. The mildly reduced photospeed of XB 5170 is more than offset by the substantial decrease in the required volume of material to be photocured. Additionally, reduced Z-wait intervals are possible as a result of the low viscosity of the new epoxy resin.

- *Thinner Layers.*
  With XB 5170, 0.1 mm layer thickness is optimum for both speed and surface quality.

Summary

In 1993, current and future stereolithography users can anticipate the following key advances:

- Further continued and significant improvements in part accuracy, to the point where 90% of all measurements of an SLA generated object will be within 120 microns of the intended CAD dimensions.

- The release of an epoxy resin for the SLA-500. With its greatly reduced curl, shrinkage, creep and slab distortion, this new photopolymer will result in a further quantum jump in overall stereolithography part quality.

- The ability to generate accurate patterns for rapid, low cost, small lot, shell investment casting applications using the new QuickCast ™ technique. This will enable customers to fabricate functional metal parts in prototype quantities much more economically than with traditional methods requiring hard tooling.

References

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[4] Schulthess, A., *"Eighth Report on Formulations for Investment Casting"*, Ciba-Geigy research Report No. 185,035, Marly, Switzerland, November, 1992.