Design of Stereolithography Trees for Use in the Investment Casting of Stereolithography Patterns

Christopher S. McDowell*, Mark C. Boomer
Johnson & Johnson Professional, Inc., 325 Paramount Dr., Raynham, MA 02767

Investment Casting Stereolithography Patterns

Stereolithography (SL) has become a useful tool in rapid prototyping of metal parts due to advances in resins and buildstyles for producing investment casting patterns. The production of the patterns, however, has been only one obstacle to the successful application of SL to investment casting. Difficulties in pattern removal from investment casting shells has been a major concern for foundries handling SL patterns, limiting even the most experienced foundries to 90% yields. In addition to shell cracking, improper and inadequate gating of SL patterns can lead to casting defects or failure to produce a satisfactory part. The costs of SL pattern generation, shell production, and raw metal stock, and the tight time requirements of rapid prototyping demand that higher foundry yields be achieved.

The investment casting process begins with the generation of a pattern. The pattern reflects the desired part geometry with an allowance for metal shrinkage. One or more patterns are attached to a structure which will provide a pathway for the molten metal to reach the patterns. This structure is a known as a tree and consists of feed tubes that carry molten metal to one or more gates. Gates connect the feed tubes to the patterns. Once the SL patterns are affixed to the tree, a ceramic shell is created around the tree and patterns. The shell is formed by repeatedly dipping the tree/pattern assembly into a slurry of ceramic and allowing each coat to dry before repeating the process. Sand is frequently poured over the ceramic before it dries to add strength to the shell. Once the shell is complete, the pattern and tree are removed from the shell by melting or burning. The shell may then be filled with molten metal, which solidifies in the cavities left behind by the patterns. Finally, the shell is broken away and the metal parts are cut from the tree.

3D-Systems' (Valencia, CA) development of the QuickCast^{TM} (QC) buildstyle has made the rapid generation of accurate investment casting patterns possible. The use of traditional wax trees in investment casting SL patterns, however, has limited the scope of SL in investment casting to pattern generation. This paper focuses on the use of SL to create trees for investment casting, and explores the possibility of using SL trees instead of wax trees. Casting SL patterns and trees may be effective in improving foundry yields, reducing the amount of metal required to create a casting, and even improving the quality of the resulting castings.

Applications of SL trees

Pattern geometry has a significant impact on the degree of difficulty in investment casting SL patterns. Thin and narrow features on SL patterns act as stress risers during pattern removal and may lead to shell failure. Thick sections and large geometries, while presenting less of a problem in terms of pattern removal, are difficult to adequately feed and may require strategic placement of feed tubes and gates. Development of SL trees for investment casting may address both of these aspects of investment casting SL patterns by making tree geometries flexible and by eliminating the use of autoclaving as part of the pattern removal process. Parametric Technology's Pro/Engineer® (Waltham, MA) solid modeling software was used in conjunction with 3D-Systems' SLA 250/40™ and Maestro™ software to create the trees used in this work.

Preventing Shell Cracking During Pattern Removal

Pattern removal represents the most significant problem arising from the use of QC patterns. Autoclaving is the traditional investment casting wax removal process. However, QC patterns exhibit extreme swelling upon exposure to steam during autoclaving, due primarily to the absorption of water. Part geometries such as thin walls, small holes, and sharp corners cannot readily collapse inward as this swelling occurs, resulting in shell cracking around the patterns. To avoid this problem, most foundries bypass the autoclaving step and subject shells containing SL patterns to direct burnout of the patterns in a flash-fire oven, typically the mold-preheat furnace.

While work continues on resins that are less sensitive to moisture, flash-firing remains the most promising route towards removal of patterns with difficult geometries. The use of the flash-fire technique, however, merely relocates the potential for shell failure when wax trees are used. Although the QC patterns generally have a greater coefficient of thermal expansion than the wax[1], their relatively open internal structure allows the pattern to fail and collapse inward during burnout, before sufficient stress is generated to crack the shell. The expansion of the solid wax tree, however, can build up tremendous pressure along the tree and lead to shell failure. It is important to note that some SL pattern geometries necessitate the use of a thick shell, in which case the use of a wax tree may not be precluded.

Changing shell composition to improve shell strength[2] may allow the processing of SL patterns without a substantial increase in shell thickness. However, for foundries whose processing of SL parts is only a small fraction of overall part production, or as in regulated industries where changes to shell composition require lengthy validation procedures, changing shell compositions to handle SL patterns is unrealistic. Increasing shell strength by increasing shell thickness is possible, but at significant cost due to several factors. First, an increase in shell thickness typically requires patterns to be spaced farther apart, decreasing the number of patterns that can be applied to the tree. Second, the additional process time required to augment the shell thickness adds to the total time required to produce the shell. As time is an essential element in RP processing, such an increase may be unacceptable. Finally, the increased usage of shell materials adds cost to the tree, as does the additional labor required for processing.

When pattern geometry requires avoiding autoclaving, it is possible to create an SL tree to which SL patterns may be attached prior to burnout and which provides better survivability of the shell. A properly designed SL tree can also improve the circulation of combustion gasses, a critical factor in the successful burnout of SL patterns[3].

Key to the successful use of the SL tree for reducing shell cracking is the incorporation of features designed to facilitate the collapse of the tree during the initial moments of burnout. The primary principle of SL tree design is the use of the ACES^{TM}, or solid, buildstyle, and the generation of a thin-walled, hollow geometry. This geometry can reproduce the desired shell volume while using less SL resin than an identical part made in the QC buildstyle. Additionally, the thin-walled part collapses at a lower stress during burnout and requires less oxygen to completely combust, freeing up oxygen for the combustion of the patterns. Since a good surface finish on the tree is not critical, the tree can be built 0.006" thick layers. QC patterns are typically built using 0.004" thick layers to improve surface finish. As a result of the larger layer thickness, the time to build an ACES tree is substantially less than the time it would take to build the same tree as a QC pattern.

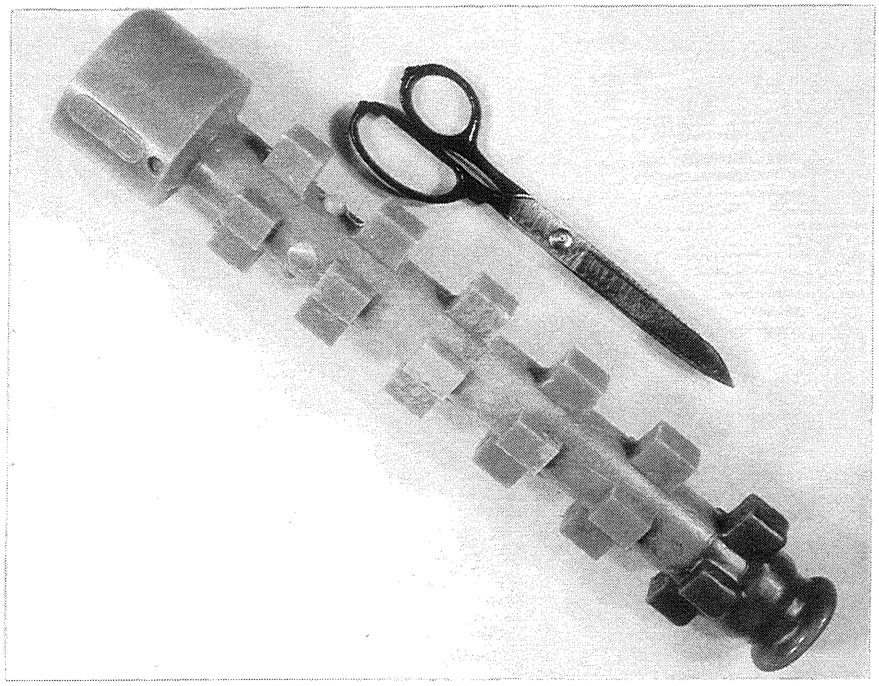

Figure 1 - Wax tree used for investment casting of production and prototype parts. Scissors are for scale.

Figure 1 shows a wax tree currently used to cast orthopedic implants in production. The tree is injection molded with a threaded insert in the mold that allows a threaded rod to be screwed into the tree for manipulation during dipping. This tree was used in conjunction with QC patterns to cast prototype parts in ASTM F-75, a Cobalt-Chromium-Molybdenum alloy. The components had thin sections and sharp edges, and it was difficult to drain excess resin from the patterns during processing. Autoclaving the mold to remove the SL patterns and wax tree proved disastrous; the ceramic mold was completely destroyed by the expansion of the SL patterns. Extensive shell cracking was also observed after flash-firing the mold to remove the patterns and wax.

Shell failure caused by flash-firing was observed along the length of the tree, and was attributed to stresses generated by the thermal expansion of the wax during the early stages of burnout. An attempt to remove the wax by slow heating (with the intent of subsequently burning out the SL patterns) in a convection oven also led to shell failure. To alleviate the cracking problem, an SL tree was created that mimicked the external geometry of the wax tree.

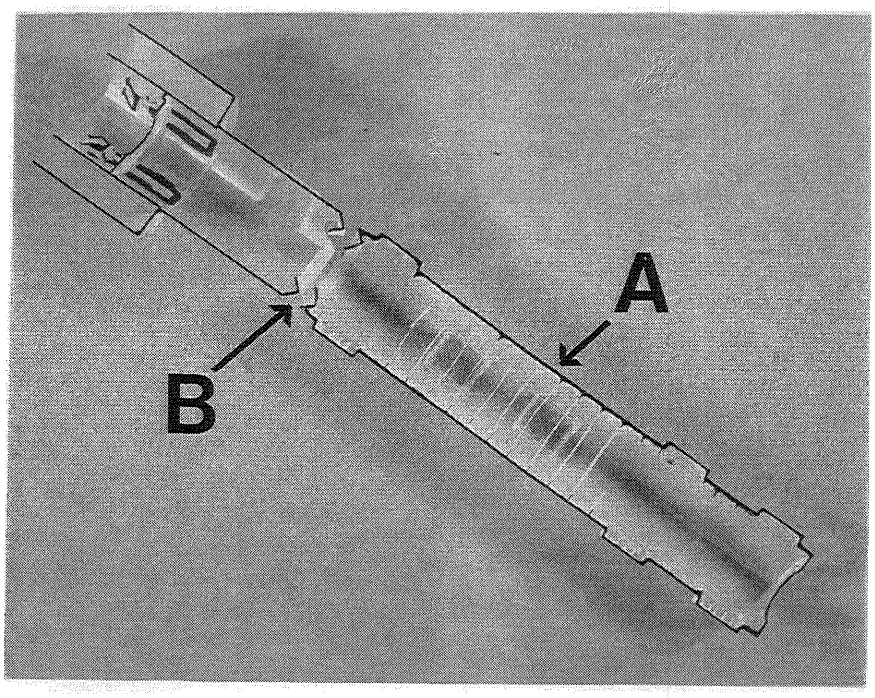

Figure 2 - Section through an SL tree. The SL tree reproduces the external geometry of the wax tree shown in Figure 1.

A cross section of the SL tree is shown in Figure 2, where several important features of the tree are revealed. Perhaps the most notable feature of the tree is its thin walls (A). At 0.025" thick, the walls of the tree were strong enough to hold QC patterns and survive general handling during shelling, but thin and weak enough to break readily as stresses developed during firing. All corners and edges were filleted and rounded to reduce stress concentrations in the ceramic shell.

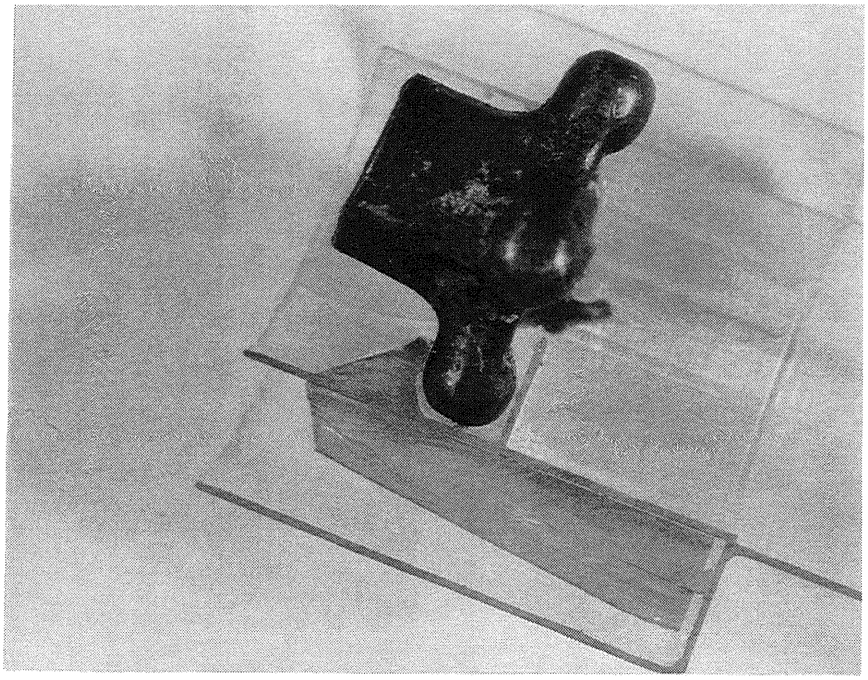

Figure 3 - Section of SLA tree showing support structure for threaded insert.

Another notable feature of the tree is the joint (B) connecting the two portions of the tree. The tree was too large to be built in a single piece on the SLA 250, so it was split in Pro/Engineer prior to building. The joint needed to be strong enough to hold the weight of the patterns on the lower half of the tree. The joint, a "bird's beak" type of connection, was sufficiently strong to hold the two parts together. The benefit of this type of joint is that it collapses into a narrowing "v" shape as circumferential stresses arise in the tree during firing. A simple flange-type of joint would be more structurally resistant to failure during burnout, transmitting stress to the shell and potentially leading to shell failure. Figure 3 shows a close-up of the top portion of the SL tree of Figure 2. A reinforcing structure was added to the tree to accommodate the threaded insert (shown in place) which was present in the original wax tree. The insert was placed into the tree and rotated 45 degrees to lock it into position under the reinforcement. The structure was made independent of the wall of the tree, and was strong enough to support the weight of the shelled tree. The strength of the insert reinforcement was not transmitted to the outer wall of the SL tree, preventing the transfer of additional stress to the ceramic shell during firing.

Figure 4 shows cross sections through two flash-fired ceramic molds made from the tree geometry shown in Figure 1. To create a ceramic shell strong enough to withstand flash firing of a wax tree required 11 slurry/sand layers. A section through the fired shell is shown in Figure 4a. The shell in Figure 4b was created over the SL tree shown in Figure 2. The shell over the SL tree survived firing even though only 6 slurry/sand layers were applied. Producing the ceramic mold by using an SL tree saved 2 days in the shell production area and reduced the weight of materials (slurry & sand) by 66%.

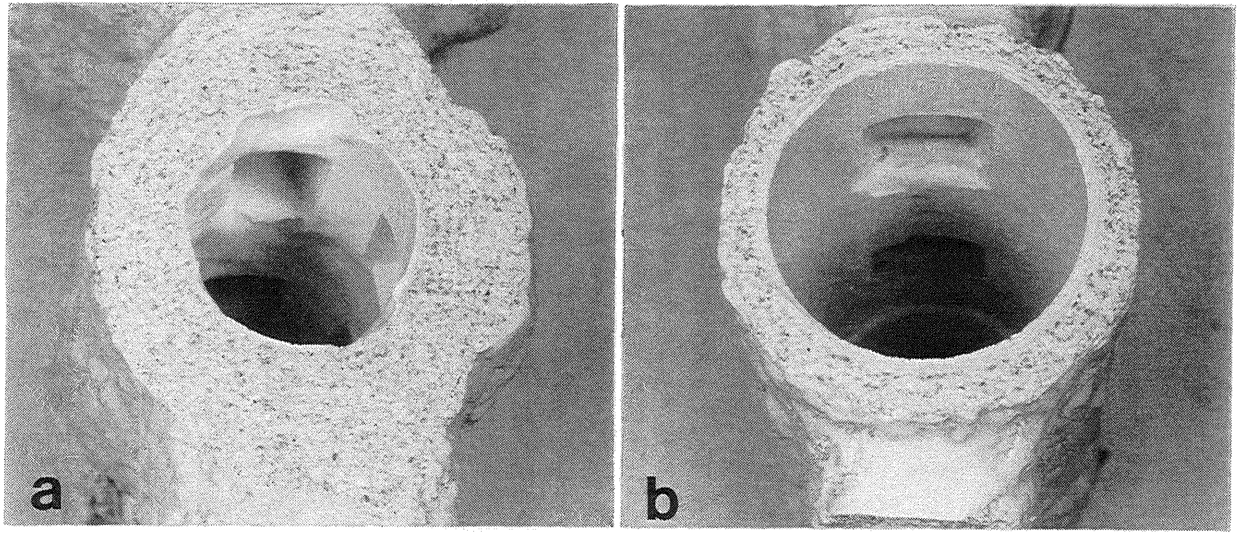

Figure 4 - a) Fired and sectioned investment casting shell showing thickness of ceramic mold created over a wax tree. b) Fired and sectioned shell showing thickness of ceramic mold created over a SL tree. The I.D. of the shells was the same.

Optimizing the Investment Casting of SL Patterns

Due to the large variety of pattern geometries encountered in prototype development, the gating and feeding of SL patterns remains, largely, an art. Foundries rely on experience for ensuring adequate fill of the mold as well as control over the actual filling and solidification of the metal. The usual strategy for feeding these parts is to apply excess gating, accepting less than optimal metal flow and extra finishing work on the castings. As an alternative, development of an investment casting tree might be performed in conjunction with the original solid model for the part. This would promote visualization of the entire casting process early on, perhaps eliciting design changes that improve the castability of the part.

When prototype parts need to be cast from expensive alloys, the elimination of metal waste becomes an important criterion for designing the tree. Using feed tubes and gates with circular cross sections minimizes heat loss in the shell while the metal is being poured, allowing the use of smaller diameter feed tubes and gates.

Since part complexity is not generally an issue in SL fabrication, complex features may be added to improve the metal flow characteristics of the mold. For instance, the outer surface of the tree might be grooved slightly to promote the laminarity of metal flow through the ceramic mold upon casting. Reducing turbulent metal flow through molds can reduce the chance that small ceramic fragments in the mold become trapped in the casting. Smooth gate-part transitions and bends in the tree can also help to promote laminarity.

When part geometries contain thick cross sections, metal shrinkage can cause voids to appear in the castings. To avoid shrinkage cavities, a reservoir of molten metal called a riser is created by forming a volume in the shell that solidifies after the part, allowing additional molten metal from the riser to fill the part cavity as solidification takes place. To keep the metal in risers molten, they must often be very large. Maximum heat retention is accomplished when the surface area of the mold is small in relation to the mass of metal in the riser. By using SL, hollow cylindrical or semi-spherical risers (geometries with low surface area/volume ratios) could be created and added to the tree to prevent shrinkage cavities.

Provisions must generally be made for handling the tree during the shelling process. In the example above, a special feature was made for allowing a threaded insert to be placed into the SL tree. This insert must be removed prior to burning out the shell. As an alternative to a separate, threaded insert, screw threads could be modeled directly into the SL tree.

Determining the Cost of SL Trees

As the production of SL parts can be expensive, minimizing the use of SL resources, including resin, build time, and post processing requirements is critical in making the use of SL trees feasible. Since surface finish and dimensional accuracy of SL trees is relatively unimportant, trees should generally be positioned to minimize build height. In the example described earlier, the lower, long portion of the SL tree was built lying on its side. Supports were generated inside the part, however, they did not contribute significantly to the strength of the part and were left in place (reducing the amount of post processing required). The total part height was reduced to about 2 inches, and though the tree was slightly out-of-round (the effect of cure depth and overcure characteristic of the SL process) there were no adverse effects on the performance of the tree. The tree consumed only 60g of resin (about $4 worth of resin).*

The small cross-sectional areas of these SL trees require minimal scan time. SL trees do not require any special build parameters, and can be placed into a build when there is extra room in the SL apparatus, to be built along with other ACES style parts. About 3 hours were required to model the SL tree from the above example in Pro/Engineer.

SL trees may also be used for proofing out tree geometries prior to producing production tooling for injecting wax trees. Optimization of tree geometry in the production of large numbers of castings can have tremendous impact on production costs. The flexibility offered by solid modelling and SL technology allows timely experimentation with a number of parameters of tree geometry that ultimately affect the raw metal requirements and quality of the castings.

SL trees clearly provide benefits over wax trees in reducing shell cracking when SL patterns with difficult geometries are to be cast. SL trees may also be employed to reduce shell material and process time, improve foundry yields, reduce raw metal stock requirements, and improve the quality of the casting, providing ample economic return on the investment of producing the SL tree.

Conclusions

The demanding pace of rapid prototyping and the high cost of SL patterns require higher foundry yields than are currently achieved. The use of SL trees in the investment casting of SL patterns has the potential to improve foundry yields significantly, through improved gating of parts and a reduction in shell failures during pattern removal. The SL ACES buildstyle in conjunction with solid modeling software packages can be used to create thin-walled tree geometries possessing an array of features that can significantly reduce shell stresses developed during flash-fire burnout and improve the flow of metal into the mold. The time savings associated with improved foundry yields and elimination of the autoclaving step can be one of the most significant advantages of the use of SL trees. While the initial cost of designing and producing an SL tree may be higher than that to produce a wax tree, the potential to ensure shell survival during pattern removal, conserve expensive alloys, and produce high quality castings may justify the added expense.

References

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* Due to the wide variation in pricing of SL parts between service bureaus and in-house facilities, no attempt will be made here to estimate an overall cost for producing the tree.