Somos®

Somos® Investment Casting Guide

HEALTH · NUTRITION · MATERIALS

DSM

BRIGHT SCIENCE. BRIGHTER LIVING.

Automotive part created with a TetraShell™ structure

Introduction

Investment casting, also known as lost wax casting, is one of the oldest metal casting processes and is still very much in use today. Investment casting produces near net shape castings in ferrous and non-ferrous metal and is known for providing a high quality surface finish compared to other casting techniques. Investment casting is an ideal process to cast metal parts when the final design of the part is still undergoing changes or when relatively low numbers of castings are needed.

While the process has significant advantages in its ability to create complex geometry with relatively tight tolerances, it requires that a tool be created to mold wax patterns. The substantial cost and time required to generate wax pattern tooling limits the range of applications for which investment casting is economically competitive.

Patterns

Direct Cast Patterns, which is substituting patterns produced with Rapid Prototyping (RP) technology in place of wax has allowed the investment casting industry the ability to cast more designs without the initial expense and time to fabricate wax pattern tooling. The tooling step is skipped and the result can be significant savings in both time and cost.

Many RP technologies are capable of creating direct cast pattern, however only Stereolithography (SL) provides the dimensional accuracy and smooth surface finish required for the majority of production investment castings. Consequently, direct casting patterns made with stereolithography are the most common and most widely accepted in the investment casting industry. SL can produce a mostly hollow pattern with an internal honeycomb or lattice structure that is ideal for the Investment Casting process.

TetraShell™ Structure

TetraShell™ is an SL build prep software that allows a user to hollow out and create a tetra-lattice structure within an stl file.

Methods

There are various methods, but for the purposes of this guide, the two most commonly used methods for producing the hollow patterns required for Investment Casting in SL will be discussed. Namely "TetraShell™", a trademark of DSM and "QuickCast™" (a trademark of 3D Systems). TetraShell™ is an SL build prep software that allows a user to hollow out and create a tetra-lattice structure within an stl file. The tetrahedryl structure was developed and licensed by the Milwaukee School of Engineering and DSM which owns the right to the TetraShell™ name and technology and has sole discretion in its distribution. The tetrahedryl structure created by the TetraShell™ software allows for strong patterns that can withstand the rigors of the investment (ceramic dipping) process, while also collapsing efficiently during the burnout process. Quickcast™ is a hollow build style, where the hollowing and honeycomb structure is created during the fabrication of the SL part.

For both methods, the objective is to create a hollow SL part with enough strength for the investment process, but hollow enough to ensure that the pattern will collapse inward during the shell burnout and prevent expansion forces from cracking the shell. The mostly hollow part also reduces the amount of material necessary to burnout, which reduces residual ash.

Contents

This guide is organized into four main sections:

Part 1: Obtaining the Pattern

The vast majority of investment foundries do not own SL equipment. Consequently, the foundry must either source the pattern from one of the many service providers, or allow the customer to supply the pattern. Most foundries prefer to source the pattern themselves since they will be held responsible for the quality of the casting and therefore want to control the quality of the pattern. This section provides information to help you obtain a quality pattern.

Part 2: Pattern Assembly

While assembling an SL pattern is very similar to working with wax patterns, there are some important differences. This section will provide a step by step guide to creating a successful tree.

Part 3: Shell Building

Building a shell using SL patterns is very similar to that for wax patterns, but again, there are a few important differences. This section helps you to avoid possible pitfalls.

Part 4: Pattern Removal

This section describes the steps necessary to remove patterns, sprues, gates and runners from the shell and prepare it for pouring. It is in this step that processing SL patterns differs most from processing wax patterns and where most failures occur. This section will help you to successfully de-wax shells with a minimum amount of differences from the methods used for wax patterns.

Part 1.

Obtaining the Pattern

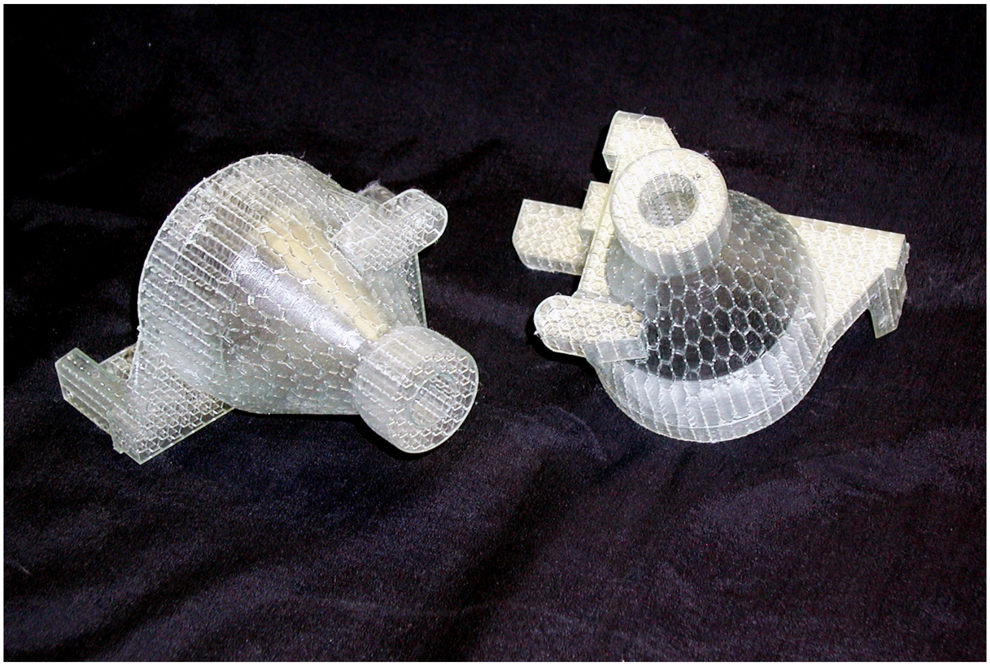
Fewer than one in twenty investment foundries in North America have their own stereolithography (SL) equipment. Consequently, the vast majority of foundries who wish to use SL patterns must obtain them from other sources, usually a rapid prototyping service provider who will build the pattern for a charge, or from the customer who is ordering the casting.

Most foundries prefer to have control over sourcing the pattern since they know that 1) the customer will most likely buy the least expensive pattern they can find without regard to quality, and 2) no matter what caveats the foundry puts into the casting quote, the customer will fault the foundry if the casting does not meet their expectations regardless of the condition of the pattern the customer supplied.

There are many rapid prototyping service bureaus that can provide you with SL patterns. However, obtaining a pattern that you can successfully and reliably convert to a metal casting that meets your customer's requirements involves more effort on your part than simply issuing a purchase order and supplying a data file to the pattern provider. To reliably obtain good patterns, you must not only select a capable provider, you must be involved in making adjustments to the pattern design, be aware of the materials used by the provider and be aware of how the provider processes, tests, finishes and ships his patterns and the quality control processes he uses.

Qualifying a Pattern Provider

Theoretically, any company that owns a stereolithography system can build hollow SL patterns. However, just as owning a milling machine does not make you a machinist, building high quality patterns requires much more than simply owning a stereolithography system. Those providers who reliably deliver high quality patterns have developed experience, knowledge, skills and an understanding of how the patterns will be used that allows them to consistently deliver high-quality patterns you can depend on.



The Top Ten Questions to ask a potential pattern provider:

1. Will my patterns be built in house?
Many stereolithography service providers are small and have limited capability in house. If they get an order for a part larger than they can build, or for types of parts they do not have experience building themselves, they may outsource the order to another provider. Not only does outsourcing usually mean increased prices (your provider marked up the price to give himself a profit), it means that you have less visibility into the process and your requirements must be translated through your provider. It is very doubtful that a provider who does not build patterns in house could consistently provide high quality patterns.

2. Can you provide references of specific foundries to which you provide patterns on a regular basis?
If the provider does not provide patterns on a regular basis to any foundry, it most likely means that foundry customers have not ordered patterns from them again after initial orders, suggesting that the patterns they provided were substandard.

3. What materials do you use for building SL Patterns?
While any SL material can theoretically be used to Build SL patterns, there are a very limited number that will perform successfully. There are wide variations in the amount of residual ash (ash remaining after the pattern is burned out) and variations in the accuracy of patterns built. If the provider cannot give you information about how his material performs as an investment casting pattern, they probably do not have much experience with producing patterns.

4. How do you drain the pattern?
SL patterns are mostly hollow. In the build process however, liquid resin is encapsulated in the hollow space. That liquid resin needs to be drained. Typically, drain holes and vents are modeled into the structure to allow resin to drain out of the pattern after the build. (The drain holes and vents must subsequently be patched and sealed as part of the finishing process). The more completely the pattern is drained, the less material there is to burn out of the shell, and the greater the chances of producing a successful casting. After draining, the pattern is post cured (flooded with broad spectrum UV light) to complete the solidification of the cured portions of the pattern. In this step, any uncured resin remaining in pattern will be solidified, adding to the mass of the pattern.

Gravity draining often leaves far too much resin in the pattern as resin viscosity and surface tension tend to resist complete drainage, especially in thin sections. In fact, for patterns with very thin sections, it may be impossible to completely drain the pattern using gravity alone. The resulting solid sections may make it very difficult to achieve complete pattern evacuation from the shell and may cause shell cracking through expansion.

A quality provider will have a centrifuge device to assist in draining the pattern. In our experience, using a centrifuge to assist in draining will cut the weight of the pattern by 50% or more compared to gravity draining alone, resulting in far less material that needs to be removed from the shell and a greater chance of successfully casting the part.

5. How are patterns checked for leaks?
One of the problems with a mostly hollow pattern is that any small holes in the shell can allow slurry to get inside the pattern, resulting in an inclusion in the casting. Small leaks may be nearly impossible to detect by the naked eye, particularly since they may only open up when subjected to the hydrostatic pressure encountered when the pattern is dipped in a slurry.

Quality providers use both pressure and vacuum testing to ensure that the pattern is completely sealed and watertight. In addition, they may use sophisticated leak detection equipment to ensure that even small leaks are located in the testing process. Finally, they will provide assurance that the pattern has indeed been leak tested in the form of a report or stamp on the pattern. Most providers will give you the option of leaving the test nipple attached so that you can recheck the pattern after receipt.

Centrifuge
Using a centrifuge to assist in draining will cut the weight of the pattern by 50% or more compared to gravity draining alone.

Pressure Check
Detect any small holes in the shell can allow slurry to get inside the pattern.

6. How do you know how accurate your patterns are?
The accuracy of the metal casting you send to your customer can be no better than the accuracy of the pattern you start with. In general, the pattern needs to be even more accurate than the casting to ensure that there is some tolerance remaining for casting variations. Some foundries allow the pattern 50% of the tolerance budget on the final casting.

However, most providers have only rudimentary measurement capability and cannot accurately measure the patterns they build. Consequently, they cannot ensure that the patterns are accurate. Better providers will have CMM capability and can provide you with inspection reports on the patterns they build.

7. How do you handle multi-piece patterns?
Some patterns may be larger than the standard platforms size of the largest stereolithography systems and must therefore be built in sections. The sections are then joined to create the pattern. It is important, however, that steps be taken to ensure that the sections are properly oriented and aligned when joined so that dimensional errors are not introduced. In addition, they must ensure that the joined surfaces are completely sealed and will not allow slurry to seep into the joined surface resulting in inclusions in the casting. The provider should be able to tell you how they handle such issues.

8. How do you ship patterns?
SL patterns are by nature fragile structures and great care must be taken in packaging to ensure that they will arrive intact and undamaged. With some patterns costing hundreds of dollars, it is important that the provider be able to ensure that the chances of damage in shipping are minimized. Ask the provider what measures they use to minimize the risk of damage.

9. What data formats can you accept?
In most cases, your customer provides you with a data file in some format. The pattern provider ultimately requires a STL file (the format required for stereolithography). Unless your customer can supply the STL file to you, or you can convert it to STL format, the provider will have to do the conversion. You will want to be sure that he can handle that function.

10. How involved are you with the investment casting industry?
Those providers that focus on serving the investment casting industry typically are involved with industry organizations such as the Investment Casting Institute or the American Foundry Society and contribute knowledge to the industry. A service provider that is not actively involved in either organization most likely does not consider investment casting patterns to be a key part of their business.

Communicating Pattern Requirements

The pattern provider needs more information from the foundry than just the data file to provide a quality pattern. You will need to supply additional information to communicate pattern requirements and to add features that will increase the likelihood of a successful casting.

If you do not have the ability to view STL files, you should seriously consider obtaining it. There are currently very low cost and even free viewers available that will run on virtually any PC. Having that ability will make it easier to communicate with your provider and allow you to view any adjustments they have made to the pattern design.

CMM
Better providers will have CMM capability and can provide you with inspection reports on the patterns they build.

Additional information needed includes:

1. Shrink Factors
Obviously the pattern must be scaled up to compensate for shrinkage of the metal upon solidification. The pattern can be scaled by any factor you desire. The CAD model you provide does not need to be scaled. That can be done using the software on the stereolithography (SL) system.

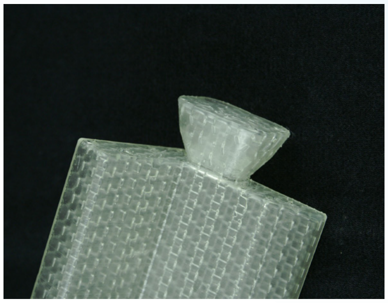
Most often a single shrink factor is supplied. For example, a shrink factor of 0.018 inches per inch might be specified for a steel casting. The SL system provides the capability to scale each of the three coordinate axes independently. For example you could scale the height of the pattern by a different factor than you would use for horizontal dimensions.

Simply indicate the scale factors you want to apply to the three coordinate directions when you order the part.

The SL software does not, however, provide the capability to apply different scale factors to different features of the part. Consequently, if there is an area of the casting that needs to be scaled differently than the rest of the casting, the scaling must be done directly in the CAD system that was used to design the part.

2. Tolerances
It is important to communicate any critical dimensions to the service provider. The STL file does not contain tolerance information.
The tolerance on the pattern must be less than that specified for the casting. Many foundries set the pattern tolerance at half the casting tolerance. Ask the provider if they will have a problem meeting the requested tolerance.

3. Gate Stubs
Many of the foundries that reliably cast SL patterns have stubs built at the gate locations. Gates need to be attached to the pattern at some point. If they are attached directly to the surface of the part, there is a chance that the surface may be damaged during assembly. Often it is worthwhile to build the gates on the pattern which moves the attachment point away from the surface of the casting. In that way, any damage incurred during pattern assembly will only affect an area that is eventually trimmed away.



Gate Stub

Many of the foundries that reliably cast SL patterns have stubs built at the gate locations.

4. Machine Stock
Most likely, the part file you received from your customer is of the finished part and not a casting drawing. You may want to add machine stock to some surfaces of the part. In many cases, the provider can add machine stock to the STL file without requiring the original CAD data. This is especially true if machine stock is added to a flat surface. If stock needs to be added to a contoured surface, however, it may be necessary to have that done in the original CAD system.

Receiving the Pattern

Not only can SL patterns be expensive compared to molded wax patterns, many more dollars will be invested in them before they are cast. It is well worth inspecting the pattern to make sure that it will perform as you expect before you begin processing it.

Visual Inspection: Upon arrival of your pattern, you should perform a visual inspection. Carefully look over the pattern for surface flaws or cracks that may have occurred during shipping. These will cause defects such as inclusions to the casting.

The pattern should have rigid or stiff surfaces. Softness in the pattern is generally a result from exposure to moisture. Some stereolithography materials are more susceptible to moisture absorption from the atmosphere than others. A soft pattern can deform under the external pressures exerted during the dipping process. Any distortion in the pattern shell will directly transfer to the casting.

Dimensional Inspection: In order to produce a dimensionally correct casting it is imperative to know the dimensions of the pattern. Measure and record critical dimensions. As a general rule, it is good practice to require that the pattern does not contribute more than 50% of the tolerance of the finished casting.

Remember, however, that the pattern will include allowances for metal shrink, therefore don't compare the pattern dimensions you measure to the desired dimensions on the final metal casting.

Leak Inspection: It is critical that the SL pattern be completely sealed and leak proof to prevent slurry from flowing into the internal structure causing an inclusion or other casting defect. After the primary shell coat is applied it is not possible to visually inspect the pattern for leaks. Therefore, it is important to verify that the pattern is sealed before you begin processing.

The pattern should have been vacuum tested by your supplier before shipment. However, the foundry will need to verify with a vacuum test to ensure that the pattern was not damaged in shipment.
If the pattern does not have a tube or port to attach a vacuum hose, you will need to add one. A tapered tube can be bonded to the pattern. Then using the tube center as a drill guide, pierce the skin of the pattern.

Using a hose attached to the port on the pattern and an automotive vacuum leak tester or other pump draw a vacuum on the pattern to 10 in/Hg – inches of mercury (250 mm/Hg – mm of mercury). Too much vacuum may damage the pattern, crushing it. If the vacuum holds and does not leak, the pattern is indeed properly sealed. A vacuum leak will indicate there is a hole somewhere in the pattern.

To find a hole, use a low pressure regulator to blow 1–10 psi (7–70 kPa) into the port on the pattern. Too much pressure will damage the pattern, blowing it apart. Find the hole by feeling or listening for escaping air. Additionally, the part may be submerged in liquid, escaping bubbles will identify the area with a leak. Alternatively, a solution of dishwashing soap and water can be brushed onto the part.

Seal any leaks with wax or if available the same material the pattern is made from. Repeat the vacuum test to verify the pattern is totally sealed.

Storing the Pattern: If the pattern will not be used immediately, store it in a cool, dry environment away from ultraviolet sources. Continued exposure to ultraviolet (sunlight and fluorescent lights both have high UV contents) will change material properties over time and may make the pattern unusable. In addition, most SL resins materials will absorb moisture over time which can affect both dimensional accuracy and stiffness. Storing the part in a sealed black plastic bag with desiccant is recommended.

Prolonged storage may require re-checking dimensions and leaks on the pattern.

Pattern Sourcing Summary

- Qualify the pattern provider to ensure that they have the knowledge, experience and capability to provide a pattern that will meet your requirements.
- Make sure that you provide adequate information about shrink, tolerances, gate location and machine stock to the provider to ensure that the pattern will result in an acceptable casting.
- Inspect the pattern you receive to ensure that it is leak tight and meets the dimensional requirements of the casting.

Part 2:
Pattern Assembly

As with wax patterns, SL patterns must be incorporated into a system including the pouring cup, sprue, runners and gates which create flow paths to deliver molten metal to the cavity created by the pattern after de-wax. The issues in creating the assembly are similar to those with wax patterns but there are a few areas in which care must be taken.

Sprue and Runner Materials

The most common material used for gate/runner systems on SL patterns is wax. The pattern assembly staff is already familiar with wax and is proficient with working with wax. In addition, wax is inexpensive.

Some foundries have used SL patterns for runners and sprues. The use of SL sprues simplifies some issues. Since there are no wax components in the assembly, there is no longer a need to eliminate them via autoclave or other means. In addition, the pattern, sprue and other components can be simply glued together, eliminating any difficulty in using gate wax to join SL components to wax components.

However, there are significant issues in using SL sprues:

- It can be very expensive, typically doubling the cost of the SL components required.
- It can be very difficult to join the assembly to a hook or some other device to allow the assembly to be hung after dips.
- SL sprues will add to the buoyancy issues in dipping. SL sprues and runners typically make sense only for very small components where the entire assembly can be built in one piece. If SL sprues and runners are used, and they are made in multiple pieces, it is important that a flow path is created between the components during assembly. For example, if an SL pattern is to be glued to a SL sprue, holes should be drilled in each of the mating surfaces and aligned so that when they are glued together, there is a path for airflow from one component to the other. That flow path is critical in the burnout phase of processing.

Gating

As with traditional investment casting the proper gating is crucial to ensure full metal feed to the casting. With high volume runs of wax patterns, the number and size of gates are optimized to minimize finishing and metal costs while maintaining casting quality. With SL patterns, however, we rarely have the luxury of optimizing the gating system. Because the patterns are expensive compared to wax patterns, foundries typically over-gate the pattern to ensure that will be filled completely. The additional cost of metal and finishing is usually far less than the cost of replacing the pattern and shell should it not fill properly.

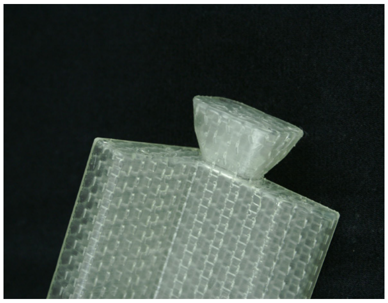
Over-gating also allows for better oxygen flow during the burnout process. As will be discussed in Part 4, SL patterns will not melt out like wax. Instead they must be burned out of the shell and getting oxygen to the cavity is essential for complete combustion of the pattern.

Finally, over-gating will strengthen the assembly. Because the pattern is mostly hollow and filled with air, its density is significantly less than that of slurry. Dipping a SL pattern may be somewhat akin to pushing a beach ball under the surface of a pool. The resulting buoyancy forces stress the attachment points and if the pattern is not attached securely, the pattern can break away from the sprue. Over-gating increases the ability of the assembly to withstand buoyancy forces. In extreme cases, it may be necessary to add additional strengthening features as well.

Attaching Gates

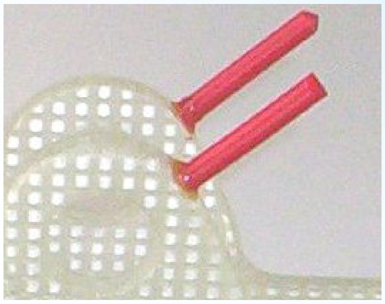
Wax gates can be attached directly to the pattern. In many cases, however, the pattern is designed with gate "stubs" as shown in the picture. The wax gate is then attached to the stub instead of directly to the pattern surface. There are several advantages using such stubs:

1. The use of stubs will minimize any distortion to the pattern from heat that is used when attaching wax gates.
2. Moving the point of attachment away from the surface of the casting will minimize the chances of damaging the surface of the pattern during assembly. When attaching gates it is advisable to drill small holes (1/8 inch or 3 mm) in the pattern before covering the area with a wax gate. When the wax is melted away, these holes will act as a pressure relief to keep air from expanding in the pattern during autoclave or burnout. These holes will also aid in air flow during the burnout of the pattern.



Gate Stub

The wax gate is attached to the stub instead of directly to the pattern surface.



Spaghetti Vent

Building SL vents will eliminate some of the manual labor needed during processing.

The pattern can be attached just as wax patterns with gate wax or "sticky wax," however, the surface to be gated may need some preparation to aid in a strong bond for the wax gate. This area can be cleaned by wiping the surface with Isopropyl Alcohol or it can be lightly sanded.

Vents

We recommend that at least one vent be attached to each SL pattern in the assembly. Although it is possible to successfully cast SL patterns that are not vented, vents reduce the risk of failure in two important ways.

1. Vents allow steam to enter the pattern during the autoclave cycle. The steam softens the pattern considerably and allows it to deform easily as it expands with heat to avoid cracking the shell. Much more detail is given in the autoclave section in part 4.
2. Vents significantly increase airflow to the pattern during the burnout process, increasing the amount of oxygen available for combustion. Vents can be created by adding wax plugs to the pattern which will be opened after the shelling operation. Many foundries use pieces of .25 inch (6 mm) diameter spaghetti wax about 2 inches (50 mm) long glued onto the surface of the pattern. Vents can also be added to the STL file so they are built in place on the SL pattern. Building SL vents will eliminate some of the manual labor needed during processing, but it does require careful consideration of where the vent will be after the pattern is assembled. After assembly, the vent should be on the outside of the assembly where it can be easily reached and opened, rather than on the interior of the assembly.

Use more vents fort larger patterns or those patterns with thin walled sections and/or complex geometry.

Pattern Assembly Summary

- Ensure that the pattern is adequately gated, which most likely means it would be over-gated compared to a wax pattern.
- Make sure that there is at least one vent per pattern. more vents should be used on larger patterns and those with thin walled sections and/or complex geometry.

Part 3:
Shell Building

In general, existing shell building practices can be used successfully to shell SL patterns. Most foundries use the same shelling method for SL patterns as they do for their normal wax pattern assemblies.

Side view of cut shell.

Pre-Shelling Checks

It is worthwhile to check a few items before beginning the shell building process:

1. Water-tight Patterns – It is imperative that the pattern assembly be completely sealed to avoid slurry leaking into the pattern during dipping. Slurry that seeps into the pattern will likely result in an inclusion in the casting. The pattern was most likely checked on receipt, but it is worth a quick visual inspection to see if the pattern may have been cracked in assembly or handling. If cracks are found, they can be repaired with wax. The resulting hump can be smoothed in finishing.

2. Vents – It is critical that the pattern include at least one vent to allow steam to enter the pattern during autoclave and to allow airflow during the burnout phase. If vents were not added in the assembly process, add them now.

3. Solid Sections – Inspect the pattern for any solid sections. If there are solid thin walls that are larger than 0.5 inch (.13 mm) square, it may be difficult to autoclave. Of course, it will not be possible to inspect for solid sections after the pattern is shelled so it is important to do it now.

Assembly Preparation

Wax assemblies are typically dipped in an etching solution to remove oil, mold release and any other materials on the surface of the pattern that might inhibit adhesion of the shell. A number of foundries believe that etching solutions will damage the SL pattern and therefore avoid etching any assemblies that contain them. As a result, they sometimes have issues with shell adhesion on wax components of the assembly, especially molded wax sprues.

Tests have been done in cooperation with Remet® Corporation, a supplier to the investment casting industry, and others with a customer foundry, to determine the sensitivity of Somos® ProtoCast 19120 AF material to various etching solutions. For the Remet® test, 6 SL sampletest bars were built in the Somos® ProtoCast 19120 AF material. The bars measured 6 inches by 1 inch by .25 inch. Two of the test bars were left as built, two were lightly sanded and finished with a light sandblast and the remaining two were lightly sanded and coated with a lacquer. One bar of each finish was dipped in a solvent based etch (Remet® Patternwash 2) for 60 seconds. The other bar of each finish was dipped in a citrus based etch (Remet® Citriwash) for 60 seconds. Each test bar was inspected to identify any damage to the pattern. None of the six bars showed any evidence of damage. There was no visual evidence of change such as color or change in reflectivity. Furthermore, there was not change to the touch. There was also no change in the stiffness of the patterns and the surfaces did not become tacky or change in any detectable way.

In the foundry test, the same type of test bar was dipped in an etch solution for ten minutes, twenty times the normal exposure for that foundry. Again, no SL pattern damage could be detected. Based on these results, it can be concluded that assemblies containing SL patterns can be etched in the same manner as wax assemblies.

Pattern Dipping

It is important to keep in mind that unlike wax patterns, SL patterns are mostly hollow and are lighter than the slurry solution in which they will be dipped. The buoyant force experienced during dipping places additional stresses on the assembly and can damage it. Use care in dipping the assembly. As mentioned in Part 2, additional gates or runners to the pattern will strengthen the assembly and make it better able to resist buoyancy forces.

Shell Types

While each foundry customizes their shell system to best perform for them, nearly all shell systems in use fall into one of two basic types: Fused Silica or Alumino silicate systems. Either shell system may be used successfully for SL patterns. Fused Silica systems are designed to weaken after firing in the burnout oven. At temperatures above 1650ºF (900ºC) the fused silica is crystallized into cristobalite. This crystallization weakens the shell and aids in the shell removal after metal is poured and cooled. The cristobalite conversion presents special challenges in the processing of SL patterns and is discussed in detail in Part 4. Alumino silicate shell systems are stronger and do not undergo a transformation at higher temperatures allowing them to be cooled to room temperature and reheated when the foundry is ready to pour metal. Most shell systems use water-based slurries. Early SL materials were prone to absorb moisture and sometimes expanded or softened to the point that their value as investment casting patterns was significantly reduced. However, SL materials developed in the last few years have very low water absorption. The primary coat is designed to dry quickly and the amount of moisture the SL pattern is exposed to is relatively minor. There is continued exposure with additional dips, but the amount of moisture that actually reaches the pattern is reduced with each additional coat.

Some foundries still use alcohol based slurries for particular applications. The Somos® ProtoCast 19120 AF material is chemically resistant to alcohol. Alcohol slurries will not degrade the SL pattern due to the limited exposure and quick evaporation of the alcohol.

Regardless of the shell type, or the base liquid of the slurry, SL patterns can be and are regularly successfully shelled and cast. To our knowledge, no combination of shell system and slurry type has a higher probability of failure than any other.

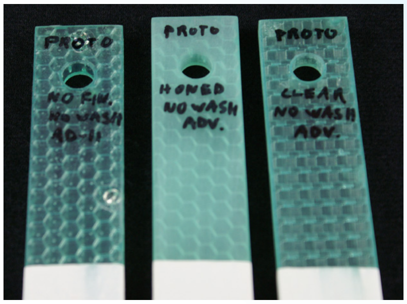
Shell Adhesion

Some foundries have observed poor shell adhesion to SLpatterns. A few even developed methods to improve shell adhesion such as coating the pattern with a spray adhesive. We suspect, however, that shell adhesion problems were the result of other deviations from standard shell procedures since there are a great many foundries that have not had problems with shell adhesion.

A study was performed to test shell adhesion on the Somos® ProtoCast 19120 AF material, with Remet®, a supplier of shell materials. Remet® uses a relatively simple procedure to test the adhesion of their slurries to wax patterns. The test uses a simple slab test bar, similar to the one we used in the etch sensitivity test described above. The test bar is dipped to half its length in the slurry solution, then hung vertically and allowed to dry. If shell adhesion is adequate, the top edge of the slurry coat on the bar will remain a straight line as it dries. If shell adhesion is not adequate, the slurry will slide down the surface of test bar, leaving a jagged top edge of the slurry coat.

Six QuickCast™ test bars of the Somos® ProtoCast 19120 AF material were supplied to Remet®. Two of the bars had no finishing, two were lightly sanded and finished with a light sandblast, and two were lightly sanded and finished with a coat of lacquer.

As can be seen in the photo, the slurry dried in a nice straight line on all six test bars, indicating that shell adhesion is adequate regardless of the finish used on the QuickCast™ patterns.



Shell Adhesion

The slurry dried in a nice straight line on all the test bars, indicating that shell adhesion is adequate regardless of the finish used.

Shell Coats

In the past, foundries often used more coats on shells for SL patterns than they did for wax patterns to provide greater strength to resist expansion of the shell during autoclave and burnout phases. Recent testing has shown, however, that cracking of the shell in the autoclave can be avoided relatively easily without the use of additional shell coats and is discussed in detail in Part 4. Consequently, it is generally not necessary to use more coats for a SL pattern than would be normally used for a wax pattern.

There are exceptions to this rule; if the geometry is particularly challenging, or contains thin walls that are solid rather than hollow, foundries may still elect to add additional coats. given the cost of SL patterns, adding extra coats is a relatively inexpensive way to increase the probability of a successful casting. Additional methods to add strength include; using wire mesh, adding chopped ceramic fibers or chopped stainless steel wool between coats.

Foundries often use a pre-wet solution to assist in shell building for certain shell situations. The assembly is dipped in the pre-wet solution to assist slurry to flow into tight areas and around complex features. A number of foundries avoid using pre-wet solutions with SL patterns because it is believed that contact with the pre-wet solution may damage the pattern. Testing with the etching solutions discussed earlier, which are much more aggressive, lead us to infer that the use of pre-wet will not have any detrimental effects on either the pattern or the strength of the shell.

Shell Building Summary

- Inspect the assembly prior to dipping for cracks, leaks and solid sections.
- Take care in dipping to avoid damage to the assembly from buoyancy forces.

Part 4:

Pattern Removal

This part of the process corresponds to the de-wax step in conventional investment casting, which whether done with an autoclave or a flash-fire furnace, eliminates all wax components including sprue, runners and patterns from the shell. De-wax would clearly be a misnomer since we are specifically discussing SL patterns, not wax patterns. However, the goal of the pattern removal portion of the process is the same; eliminating the sprues, runners and patterns from within the shell.

Background

The stereolithography materials used to build SL patterns are photo-cured materials, which, unlike thermoplastic materials, will not melt. Consequently, they cannot be simply melted out of the shell as can wax patterns. They must instead be burned out of the shell which creates several problems in shell processing. Initial attempts to process SL patterns using the same process used for wax yielded unsatisfactory results.

1. Shells were likely to crack in the autoclave, often beyond repair.
2. Patterns often did not burn completely, leaving a black tar or charcoal residue in the shell which was very difficult to remove.
3. If the pattern did burn completely, there was still a significant amount of ash left in the shell that needed to be removed from the shell prior to pouring in order to yield an acceptable casting. Consequently, it was usually necessary to cool down the shell after burnout and remove the ash from the shell prior to reheating and pouring metal.
4. If a fused silica shell system was used and the shell was burned out at conventional preheat temperatures, the cristobalite conversion had already taken place and the shell was now significantly weaker when it was cooled down to clean out the ash. The resulting weaker shell potentially presented a dangerous situation when it was reheated and metal was poured.

Over time, most foundries gravitated to the following general process:

1. Vents were added to patterns to provide for additional airflow during combustion. Vents were opened after shell building was complete.
2. Shells were not autoclaved to avoid the risk of cracking. Instead, the wax components of the assembly, sprue runners and gates, were melted out manually using a hand torch. (Foundries with flashfire furnaces were able to melt out the wax and burnout the pattern at the same time.)
3. For foundries with a fused silica shell system, burnout was accomplished using a process illustrated in the following figure. (Alumino-silicate shells can burn out at higher temperatures since there is no cristobalite conversion.)
    a. The shell was fired for approximately 2 hours at a temperature below the cristobalite conversion temperature, usually about 1500ºF (815ºC).
    b. The shell was cooled to room temperature and ash was cleaned out, usually with compressed air or by rinsing the shell with tap water.
4. Vents were patched and the shell was reheated to conventional pre-heat temperatures and poured.

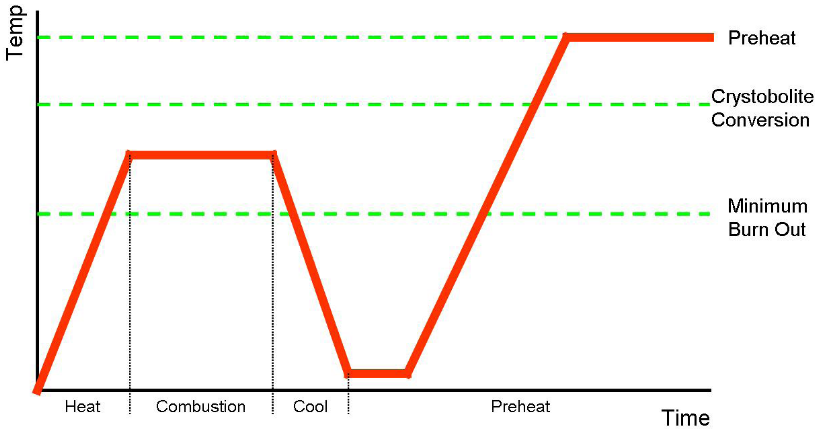


Chart representing the burnout process.

Process Issues

While this process yields good castings, several issues remain for the foundry:

1. It requires a great deal of manual effort for the foundry in what is often a highly automated process. Manual labor is required to add vents to the pattern, open the vents after the shell is built, melt out the sprue and runners, patch the vents, and clean the ash out of the shell. Melting the sprue by hand alone typically takes half an hour or more of labor. All the associated manual labor adds significantly to the cost of processing a SL pattern.

2. For foundries with only one furnace, lowering the temperature to below the cristobalite conversion temperature to burn out the pattern meant that normal production had to stop for that period, further increasing processing cost.

3. At several steps in the process, there are significant deviations from the normal process the foundry uses. Every such deviation is an opportunity for a mistake to be made, potentially resulting in a failed casting. Given that the cost of SL patterns is high, and there is significant additional cost to process a SL pattern, the cost of failure can be much higher than for a molded wax pattern. In addition, it may take a few days to obtain a replacement pattern and the resulting delay in delivering a casting to the customer may be longer than for the traditional wax method.

Clearly, a simpler process for casting with an SL pattern was needed. A leading SL Pattern shop has worked with a number of foundries, to test the Somos® ProtoCast 19120 AF stereolithography material. Recall that this resin is specifically designed to produce SL patterns with significantly reduced ash content. In the course of that testing, we have identified a number of key process improvements that greatly simplify the processing of SL patterns. The efforts were concentrated in the three areas that in the past have been most problematic for foundries 1) use of the autoclave to remove wax components of the assembly, 2) burnout of the SL pattern, and 3) ash removal.

Autoclaving the Assembly

For conventional investment casting, autoclaving is the most common way of de-waxing, or eliminating the wax patterns from the shell. The SL pattern, unlike wax, will not melt in the autoclave. However, there typically is still a great deal of wax in the shell in the sprue, runners, gates and vents that must be removed prior to pouring. It is very desirable to be able to autoclave the shell to remove this wax prior to going into the furnace to burn out the SL pattern.

Many foundries have had difficulty attempting to autoclave SL patterns. Shells tend to crack during the autoclave cycle, often beyond repair. As a result, most foundries skip the autoclave step altogether and melt the sprue out with a hand torch as shown in the photo. Any wax remaining in the shell is later burned out in the furnace. While this work-around avoids cracks in the shell, it typically requires 30 minutes or more of labor per shell to melt the sprue. Any residual wax generates a great deal of smoke in the furnace.

Autoclaving

For conventional investment casting, autoclaving is the most common way of de-waxing, or eliminating the wax patterns from the shell.

In addition, this manual step is a disruption to the normal process flow of the foundry and therefore increases the chances that a processing error will be made. It clearly would be preferable to directly autoclave the shells, avoiding labor, smoke, and any disruption to the regular foundry process.

Somos® and a leading pattern shop ran tests in conjunction with two customer foundries to determine the cause of shell failure during the autoclave cycle and potential solutions.

In the first test, eight SL patterns were built using Somos® resin material. Four trees were then created with two patterns per tree. A hole was drilled into the pattern on the surface of the gate that would be attached to the sprue and the pattern was attached to the sprue using sticky wax.

Shells were then built using a fused silica shell system. The four shells were then prepared as follows: Shell 1 had no additional processing. In Shell 2, the sprue was melted out with a torch, exposing the hole drilled on the gate surface. Shells 3 and 4 simply had holes drilled through the shell into the pattern, simulating a vent. The wax sprue was left in place.

All four shells were placed in the autoclave at once. The autoclave was pressurized to 106 psi (730 kPa) with 350ºF (177ºC) steam in 2.87 seconds. Shells were held under pressure for 20 minutes. All four shells were inspected after the autoclave cycle. Shell 1 had cracked. The remaining three shells had no damage.

From this test, it is clear that venting the interior of the pattern before autoclaving reduces the likelihood of shell cracking. The shell that cracked was the only one of the four assemblies that had a sealed pattern at the beginning of the cycle. All the patterns that were vented survived the autoclave cycle intact.

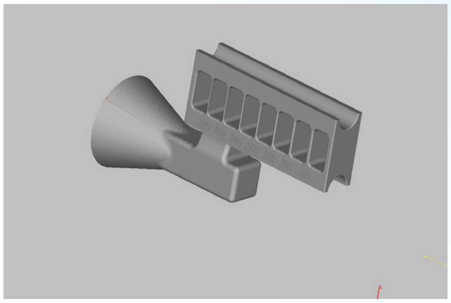
While venting clearly had a significant effect, the cause of cracking was not obvious. It had always been assumed that thermal expansion of the pattern material was responsible. In fact, the design of the hollow SL build style was an attempt to allow the pattern to collapse inward as it expanded rather than exert excess pressure on the shell. However, if the root of the problem was differential thermal expansion of the pattern material, all the shells would have cracked.

One theory was that internal pressure resulting from heating of the air inside the pattern caused the cracking. That would explain why the vented patterns did not crack. However, it was calculated that the pressure rise inside the pattern from a temperature rise of 275ºF (135ºC) would be approximately 8 psi (55 kPa). Considering that this internal pressure is resisted by an external steam pressure of more than 100 psi (690 kPa), it doesn't seem likely that the pressure would crack the shell.

A second theory was that the greater external pressure resulted in a compressive failure of the shell. With vented patterns, the internal pressure would be the same as the external pressure, eliminating any net forces on the shell. Sealed patterns would have a lower internal pressure and the resulting net external force on the shell could potentially result in shell failure. However, the cracks we observed were very clean breaks as would be expected in a shell tension failure. We did not see any crumbling of the edges of the crack, or multiple crack lines as would be expected in a shell compression failure.

The second test in another foundry confirmed that external pressure was not the culprit. In that test, four 9-wall patterns were shelled. Each pattern was vented in three places, yet all four patterns cracked in the autoclave. In each case, it was clear that the crack initiated at the 0.040” thick wall – the thickest wall that was built solid. This failure clearly points to thermal expansion of the pattern material.

In the first test, we broke apart the shell that cracked to inspect the pattern. We were somewhat surprised to find that the pattern was very rubbery and could easily be compressed. With this information, we theorized that upon exposure to the superheated steam, the resin softens quickly and even though it expands with heat, it can deform and collapse inward instead of exerting pressure on the shell. Venting allows the steam to reach the interior of the pattern, accelerating the softening of the honeycomb structure and skin of the pattern. Conversely, if the pattern is sealed, heat must be transferred through the skin of the pattern before reaching the internal hexagonal honeycomb structure, significantly slowing the softening process.



Nine Wall

A sample of a nine wall pattern for testing.

The mechanism of softening, however, is not entirely clear. Is it heat alone that softens the material? Or is it primarily absorption of humidity with the rate of absorption is accelerated by the heat? It may be a combination. Somos^t has plans to test this phenomenon and updates to this guide will be forthcoming.

Another complication that is apparent is the presence of solid areas in the pattern. As a general rule, hollow SL patterns cannot be built with a wall thickness of less than 0.020 inches (.5 mm) and most walls of 0.040 inches (.1 mm) and under will be solid due to the difficulty of draining high surface tension resin from very thin sections.

As a result of these tests and our current understanding of the process, we recommend the following procedure for avoiding shell failure during the autoclave process.

1. Include at least one vent on every pattern on the tree! A simple piece of spaghetti wax will suffice. A hole can be drilled under the vent so that as soon as the wax vent is melted out, there will be a path for pressure release from the pattern. However, it may be prudent not to drill the hole. If the vent is dislodged during a dip, the hole would allow slurry to enter the pattern, ruining the casting. If the hole were not yet drilled, the pattern could still be salvaged. More than one vent will provide a path for steam to flow through the pattern, accelerating the softening. An alternative to using a wax vent is to include the vent built in the pattern model and it will be built as part of the SL pattern. This approach will minimize downstream labor.

2. After the shell is built, cut off the portion of the shell at the end of the vent to expose the vent. The end of the vent can simply be ground or cut off.

3. Melt out the wax in the vent. This can be done with a lance heated in a flame as shown in the photo. If a built in vent is used, there is no need to melt out the vent. It may be worthwhile, however, to poke through some of the honeycomb structure to increase the area available to flow of steam into the pattern.

Open Vents

Melt out the wax in the vent which can be done with a lance heated in a flame as shown above.

4. Puncture the skin of the pattern. To be really safe, you can use a thin drill bit, but the hot lance used to melt the wax will work fine. If a built-in vent is used, this step will not be necessary.

5. If there are solid areas on the pattern, melt out the sprue by hand. There is little that can be done to ensure that the substantial solid areas of the pattern will soften quickly enough to avoid cracking the shell from thermal expansion. Extra coats on the shell will strengthen the shell, but it is hard to predict how much it can resist the thermal expansion. With the above steps, most shells can be successfully autoclaved.

Burnout Process

After autoclaving, most if not all of the wax has been eliminated from the shell. However, the SL patterns are still in intact within the shell. The stereolithography material used to build the pattern will not melt and must instead be burned out of the shell. The burnout process must not only result in the complete combustion of the pattern, it must also not compromise the integrity of the shell. The shell must still be able to create an acceptable casting.

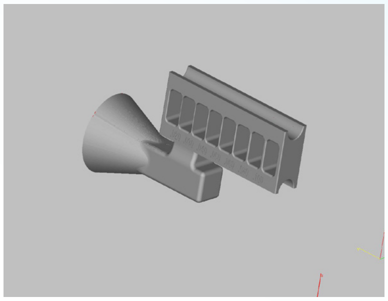
Fortunately, given the right conditions, the material will burn completely and leave only a small amount of ash that can be removed from the shell with relative ease. Once done, the shell is every bit the equal of one built using molded wax patterns.

Burnout under the wrong conditions, however, can result in incomplete combustion, leaving a tarry substance in the shell that can be very difficult to remove. Several variables affect the burnout process.

They include:
1. Furnace Temperature
2. Time in the furnace
3. Oxygen Content of the furnace
4. Shell composition

Foundries who developed the ability to cast using SL patterns generally experimented with the above variables until they found a process that worked for them. In addition, they generally held that process close to the vest, reluctant to give competitors any information about it. Over the years, we picked up bits and pieces of information about what worked and what didn't work, but never were able to provide a complete recipe to foundries.

During the development of the Somos® ProtoCast 19120 material, work was done with a number of foundries to more completely understand how each of the above variables affects the burnout process and to be able to provide specific process recommendations to the foundry. Testing was conducted in which 36 patterns were burned out in an attempt to determine optimum temperatures and times for burnout. The SL pattern used in the test was the 9-wall part, a test part that has been used for 15 years in developing the ability to successfully cast SL patterns. The 9-wall patterns contained 9 thin walls ranging from 0.020 inch (.5 mm) to 0.100 inch (2.5 mm). At least two of the thinnest walls would be extremely difficult to build hollow so there would be two or more solid thin walls in the pattern. Consequently, to eliminate the possibility that the wax gates and sprue could affect the results, the pattern was built with a gate and sprue attached as shown in the photo. The patterns were not vented.



Nine Wall

A test part that has been used for 15 years in developing the ability to successfully cast SL patterns

36 such patterns were shelled using a fused silica shell system.

Two different furnace temperatures (1800ºF/980ºC and 1500ºF/816ºC) and 6 different times (30, 60, 90, 120, 150 and 180 minutes) were chosen for 18 distinct temperature/time combinations. Two patterns were burned at each combination. The furnaces used did have plant compressed air added during firing to add oxygen. The air was not directed into the shells.

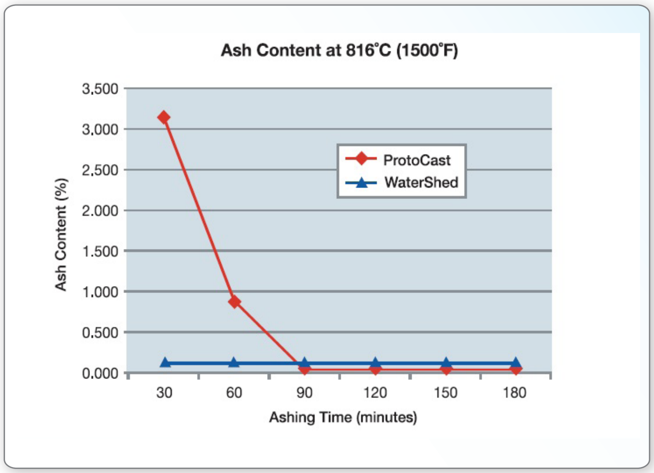
18 shells were placed in each furnace. The pattern material burst into flame almost immediately and burned quickly, as shown in the photo. The flame went out within a few minutes, so the material apparently burned out rather quickly.

At each half hour increment, the furnace was opened and two shells were removed. Over the period of three hours, all 36 shells were removed from the furnace. After the shells had cooled, one of each pair was cut open and inspected for signs of incomplete combustion.

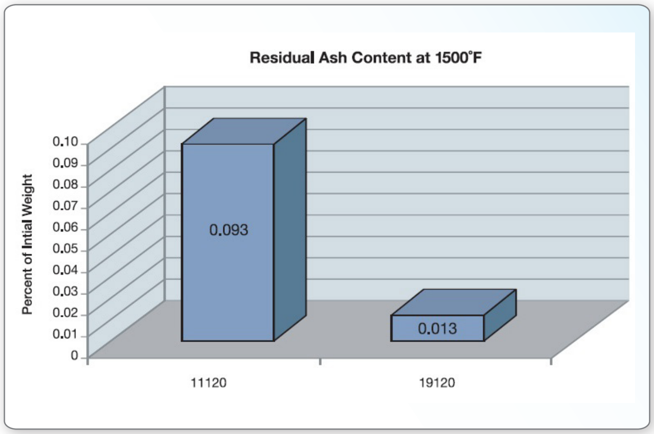
We expected to find incomplete combustion at the lower furnace temperature and shorter burn times. However, we found no sign of incomplete combustion in any of the shells Even the 0.020 inch wall section (where the pattern was solid) burned out cleanly. We could then conclude that, for the set of conditions used in the test, and assuming that there is adequate oxygen available to support resin combustion, patterns will burn out adequately at any temperature above 1500ºF (816ºC) and for any time longer than 30 minutes.

Further testing by Somos® on residual ash levels showed that there is benefit to longer burn times. The conditions of the above test were repeated in the laboratory to determine the amount of ash remaining after combustion. Resin samples were burned at 1500ºF (816ºC) and 1800ºF (982ºC) and at oven times of 30, 60, 90, 120, 150 and 180 minutes for both Somos® WaterShed 11120 and Somos® ProtoCast 19120 materials.

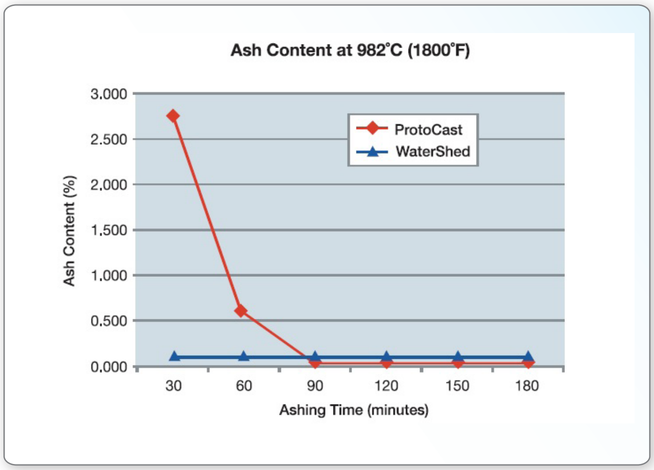
The following chart shows the residual ash levels for burnout at 1500ºF (816ºC).



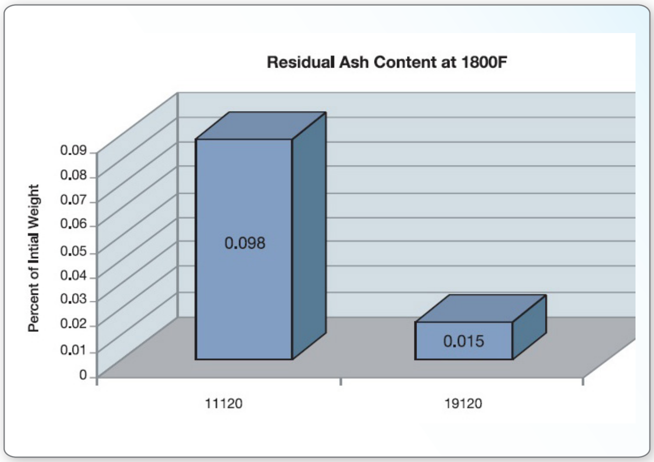
The Somos® WaterShed 11120 material very quickly reduces to a small amount of residual ash. The Somos® ProtoCast 19120 material, on the other hand, takes longer to reduce, but ultimately reduces to a much lower ash level — approximately 1/6 the amount of ash that the Somos® WaterShed 11120 exhibits as shown in the following chart:



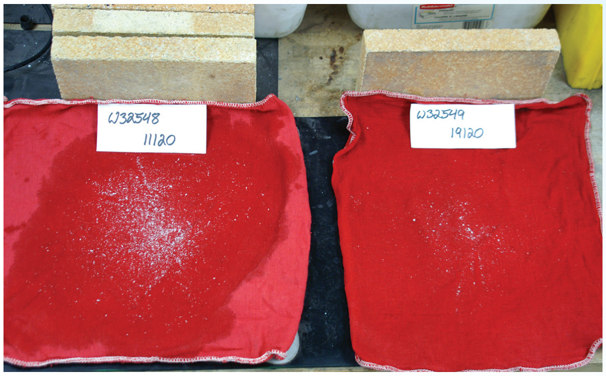
The following chart shows results for burnout at 1800ºF (982ºC).



As in burnout at 1500ºF (816ºC), the ultimate level of residual ash for Somos® ProtoCast 19120 is significantly lower than for Somos® WaterShed 11120 as shown in the following chart.



Overall, Somos® ProtoCast 19120 exhibits about 1/6th the residual ash levels of Somos® WaterShed 11120. In testing at a foundry, two shells were built, one using Somos® Watershed 11120 patterns and one using Somos® ProtoCast 19120 patterns. They were burned out at the same time in the same furnace and for the same temperature. The shells were allowed to cool prior to ash clean out. For clean out, the shells were partially filled with water and the water was agitated around to ensure all ash was obtained. The water was then poured out through a sieve in which a new shop towel was used to catch the ash.



Ash Comparison

The ash collected from the Somos® WaterShed 11120 (left) and Somos® ProtoCast 19120 (right) patterns.

The effect is rather dramatic.

It is clear, however, that the low levels of residual ash associated with Somos® ProtoCast 19120 will not be achieved in short burn cycles. Consequently, we recommend that Somos® ProtoCast 19120 patterns be burned out for a minimum of 2 hours and longer for larger patterns or patterns with thin walls.

Oxygen Content: Sufficient oxygen is necessary for proper combustion of the SL pattern. If there is not enough oxygen, ash content increases significantly and will look like small pieces of charcoal rather than the white feathery ash normally associated with SL patterns. In extreme cases, a tarry residue will be left in the shell.

Oxygen is not necessary for preheat. Consequently, most preheat furnaces do not have the capability to increase the oxygen level in the furnace and much of the oxygen that was originally in the furnace is depleted in the process of heating the furnace. Without somehow adding oxygen to the furnace atmosphere, it is difficult to achieve complete combustion in a conventional preheat furnace. Since most foundries use the pre-heat furnace to burn out SL patterns, this is a significant issue.

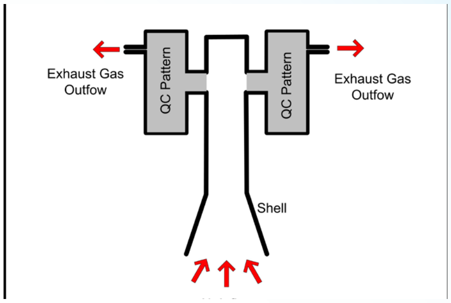
To complicate the issue further, oxygen is of no use unless it is present in the far reaches of the shell cavity where pattern combustion needs to take place. The shell used for conventional investment casting makes it very difficult for oxygen to reach the pattern and for combustion gases to escape. While the pouring cup is fairly open, the passage to the SL pattern narrows considerably at the gate. Since the cavity is a closed vessel, there is minimal airflow into the cavity, increasing the difficulty of getting oxygen directly to the combustion site and of getting combustion gases out.

Fortunately, there are relatively simple solutions to this problem. The vents that were added to help get the shell through the autoclave safely will also be of tremendous value getting oxygen to the pattern and allowing combustion gases to escape.

Some foundries simply make a long nozzle for an air gun (stainless tubing works well) and use it to blow air directly into a vent, forcing plant air into the shell. Oxygen is supplied by the plant air and consequently it is not necessary to adjust the oxygen level of the furnace atmosphere. There are some potential downsides to this method, however. First, the plant air could cool the inside surface of the shell and introduce thermal stresses that could cause some local cracking. This effect will be at least partially offset by the heat generated by combustion. Second, air must be blown into each cavity, which can be time consuming for an assembly with multiple patterns. It might also be difficult to get to all the patterns if they are spaced around the assembly.

A better process may be to allow the vents to act as "natural chimneys" for the gases of combustion to escape as illustrated in the figure. As combustion gases escape through the vents, air will be drawn naturally through the pouring cup. This configuration will provide good burning provided that:

1. Air can get in through the pouring cup. Clearly, it will not work if the pouring cup is set on a flat floor of the furnace, effectively closing off the flow of air. Most foundries will set the assembly on a grate above the floor of the furnace.



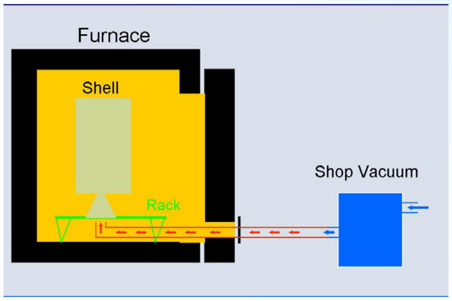
Creating "Natural Chimneys"

As combustion gases escape through the vents, air will be drawn naturally through the pouring cup.

2. The furnace atmosphere has sufficient oxygen. If the furnace has no provision for adding oxygen to the atmosphere, there will probably not be sufficient oxygen in the furnace. Some foundries run a line with plant compressed air into the furnace and turn it on when they are burning out SL patterns.

One foundry came up with a novel solution. They drilled a hole through the door of their furnace and covered it with a simple swinging plate. They use the same steel rack for all SL shells and the shell is always located on the same spot on the rack. They have locating pegs in the furnace so that when the rack is inserted, the pouring cup will be positioned in exactly the same spot each time.

They also have a locating bracket on the floor of the furnace directly below the pouring cup. To deliver the air, they simply attach a long pipe with a 90 degree elbow on the end to the exhaust of a simple shop vacuum cleaner. During the burnout process, they insert the pipe through the hole they cut in the door and push it in until it reaches the bracket. It is then located directly below the pouring cup with the elbow pointing right into the pouring cup. When they turn on the shop vacuum, the furnace is provided with a steady source of low pressure, oxygen rich plant air to support combustion. The setup is illustrated in the figure below.



Simple System to Add Oxygen

When the shop vacuum is turned on, the furnace is provided with a steady source of low pressure, oxygen rich plant air to support combustion.

Shell Type: Alumino-silicate shell systems are stronger and do not have a transformation at higher temperatures allowing them to be cooled to room temperature and reheated when ready to pour metal.

Fused silica shells, however, are a little more complicated to work with. Fused silica undergoes a conversion to cristobalite at temperatures above about 1650ºF. In general, foundries prefer to avoid the cristobalite conversion because shell strength decreases dramatically when the shell is cooled to remove burnout residue. The shell may not have sufficient strength upon reheating to safely allow pouring. To avoid the conversion to cristobalite, many foundries burn out the shell at a lower temperature, generally around 1500ºF (816ºC) although I have heard of some burning out as low as 1100ºF (593ºC).

Many foundries, however, only have a single preheat furnace which complicates processing SL patterns. If the temperature is lowered to burn out a SL pattern, the furnace can't be used to preheat regular production shells. Consequently, production stops to burnout SL patterns. Of course, it is possible to schedule SL burnout around regular pouring schedules, but it increases scheduling complexity and may increase the time required to process SL patterns.

We know of at least two foundries that burn out fused silica shells at 1800ºF (982ºC) routinely and have not had significant issues with shell strength. However, we suspect that the strength of the shell after cristobalite conversion may vary significantly with the particular formulation of the shell system. Burnout at temperatures above the conversion temperature may work well with some shell systems and not at all with others. In addition, the fluid pressure on the shell will vary with the size (primarily height) of the casting. The weakened shell may be able to withstand the pressure of small castings, but not larger ones.

To summarize the burnout process:
1. Ensure that vents are opened and there is a path for airflow through the shell to bring fresh air to support pattern combustion. If you opened the vents to get them through the autoclave, that should be sufficient.
2. Ensure that there is adequate oxygen in the furnace atmosphere. There are several ways to do this as explained in the text.
3. Burnout in a furnace with a temperature of 1500ºF (816ºC) or higher. Lower temperatures will probably work, but we have not done any testing at lower temperatures. Higher temperatures may speed combustion but will not likely result in more complete combustion.
4. Burnout for a minimum of two hours for small patterns, three hours or longer for larger patterns. These times are conservative. Residual ash testing by Somos® showed that low ash levels take a minimum of 90 minutes to achieve.

Ash Removal

Once the combustion is complete, there will be a small amount of ash in the shell.

With the introduction of Somos® ProtoCast 19120, the amount of residual ash has been reduced dramatically! Compared to the Somos® WaterShed 11120 material, residual ash has been reduced by more than 80%. The reduction is even higher compared to other stereolithography material In addition, ash from the Somos® ProtoCast 19120 material contains no antimony. With other typical SL resins, 50–80% of the residual ash is antimony or antimony salts.

Is it necessary to remove the ash?

Ash removal is a significant disruption to the process, typically requiring the shell to be cooled before ash removal. If the ash removal step could be skipped, then the vents could simply be patched (although carefully since the shell is hot) and the casting poured. Not only would it save time and effort, it would eliminate the concern of cristobalite conversion and weak shells.

Surface Pitting

What happens if your pattern isn't cleaned out well.

If the casting is poured without removing the ash, it typically will float to the top of the melt and result in some pitting on the surface of the casting, as shown in the photo. For some applications, the resulting minor surface imperfections are acceptable. Even if the resulting surface is not acceptable, it may be possible to repair the surface with minor welding.

For the majority of applications, however, it will be necessary to remove the ash to minimize imperfections in the casting. There are differing opinions on how best to remove the ash.

One foundry claims that it is best to remove the ash by blowing out the shell with compressed air while it is still hot. They claim that the ash is fine and feathery while hot, but as the shell cools, it is more likely to stick to the walls of the shell and be much harder to remove. To be sure they have removed as much ash as possible, however, they still allow the shell to cool and rinse it afterwards.

Most of the foundries either blow the shell out with compressed air, or rinse the shell with water. With either method, the shell is first cooled to a temperature at which it can be easily handled, usually near room temperature.

If compressed air is to be used, it is best to remove the ash before the vents are capped. That way, air blown into the sprue passage will blow ash out the vents and vice versa. The vents allow for flow through the cavity. If the vents are capped first, it will be much more difficult to remove the ash.

If water is to be used, it is probably best to cap the vents first so that water doesn't leak out of the shell in several places. Once the vents are capped, the water can be poured into the shell, swished around to pick up any ash that is there, and simply poured out. Foundries often pour the water out through a sieve fitted with a filter cloth to see how much ash was in the shell.

To be thorough, one might use both methods; blow out the shell with compressed air, cap the vents, and finally rinse with water.

We have heard of foundries who use boiling water to rinse the shell or even citrus solutions, but we have not seen any evidence that it does any better a job of cleaning the shell.

De-Wax Summary

A. Autoclaving the Assembly

1. Include a vent on every pattern.
2. After the shell is built, cut off the shell at the end of the vent to expose the vent.
3. Melt out the wax in the vent.
4. Puncture the skin of the pattern.

B. Burn out the Patterns

5. Ensure that vents are open and there is a path for airflow through the shell to bring fresh air to support pattern combustion and allow combustion gases to escape.
6. Ensure that there is adequate oxygen in the furnace atmosphere.
7. Burnout in an furnace set to 1500ºF (816ºC) or higher.
8. Burnout for a minimum of two hours for small patterns three hours or longer for large patterns.

C. Ash Removal

9. Cool the shell from the burnout process.
10. Either:
    a. Leave the vents open, blow out the shell with compressed air and then cap the vents; or
    b. Cap the vents and rinse the shell with water.

Shell Rinse

To be sure as much ash as possible has been removed, the shell is cooled and rinse it afterwards.

To summarize the ash removal steps:

1. Cool the shell from the burnout process.
2. Either:
   a. Leave the vents open, blow out the shell, and then cap the vents, or
   b. Cap the vents and rinse the shell with water Process Development

Ultimately, each foundry has to develop a process that works for them. Hopefully the guidelines presented here will help to reach that point quickly.

Appendix A.
Why Use SL Patterns?

In spite of the fact that SL patterns have been in use for more than 20 years and are the most popular means of creating direct patterns, the majority of foundries still don't really understand all the ways that SL patterns can be used to benefit both their customers and themselves. Most will admit that they use SL patterns because their customers ask them to. A few have found that SL patterns provide a competitive advantage.

The short answer is that by using SL patterns, foundries can increase the value of the services that they provide to their customers in addition to providing benefits to themselves.

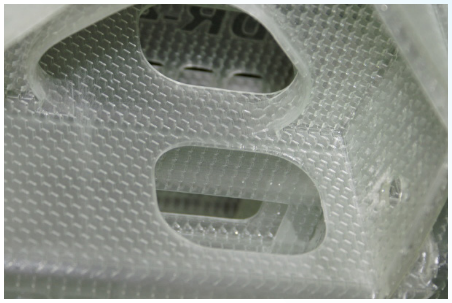
There are four primary ways in which SL patterns can be used to increase the value provided to your customer:

1. Prototype Castings
2. Process Development
3. Initial Production Castings
4. Low Volume Production

Each of these applications will be discussed in detail.

Prototype Castings

Prototype Castings are what most people think of when they think of SL patterns. This was the first application to be exploited and is one that provides high value to the foundry customer.



A pattern with TetraShell™

Conventional investment casting requires customers to build (and pay for) wax pattern tooling before the first casting can ever be made. This presents several disadvantages to the customer:

1. There is a significant upfront investment, in both money and time, before any castings are available to test the viability of the product. If the product is not viable, all that investment is lost.

2. If testing identifies any design issues, the tool will require rework to correct those issues.

3. Because of both the time and cost involved in creating the tooling and in making tooling changes, the number of design alternatives that can be evaluated is limited.

4. Because the tool must be modified for each design alternative, it is not possible to simultaneously test multiple design alternatives without creating multiple tools.

5. If design issues are identified, customers will be reluctant to consider any design changes that cannot be incorporated into the existing tool. Consequently, they will likely accept a sub-optimal design revision. If instead SL patterns are used to create the prototype castings, all those disadvantages go away. The upfront investment is very much smaller – just the cost of the pattern rather than the cost of the wax pattern tool. If design issues are identified, no tool rework is required! Many more design iterations can be evaluated, and they can also be evaluated simultaneously if desired. Finally, there are no restrictions on the design alternatives that can be considered because there is no existing tool to be salvaged.

Clearly the use of SL patterns for prototype castings offers several advantages for the customer. However, many foundries do not realize that there are several advantages for them as well.

- Providing prototype castings significantly increases the chance that they will get the production order.
- Casting prototypes allows the foundry to get experience with the geometry before they need to supply a quote for the production work, thereby minimizing their risk in quoting.
- Casting prototypes allows the foundry to be involved earlier in the product development process. Consequently, the foundry will have greater input on design features that affect the difficulty of manufacture.
- The interactive process generates good will and helps build a continuing relationship with the customer.

Process Development

There are a number of tasks in the development of the investment casting process that simply cannot be completed until patterns are available. Such tasks include:

- Final Gate Locations – While an experienced foundry engineer can usually predict where gates should be located for a particular casting, especially with the help of casting software, the actual results are sometimes different than predicted and gating changes must be made.
- Assembly Optimization – In general, foundries attempt to place as many patterns on an assembly as can be reliably cast in order to minimize cost. Experience and casting software can assist in determining both the optimum number of patterns in the assembly and the optimum orientation of the patterns. However, sometimes the first assemblies cast show less than optimal results and changes to the assembly must be made.
- Final Shrink Determination – Reference books publish volumetric shrinkage factors for metals that define how much the metal will shrink upon solidification under ideal conditions. However, every foundry engineer knows that actual shrinkage values will vary over a part, depending on wall thickness, nearby features, etc. Actual part-specific metal shrinkage is very difficult to predict and usually can only be determined after the first castings are inspected.
- Dip Programming – A number of foundries use robots in the shell room. The particular motions used in dipping to ensure that all parts of the pattern are evenly coated are very geometry dependent and difficult to predict. Most programming takes place after patterns are available.
- Straightening Fixtures – Many castings deform in the solidification process and need to be subsequently straightened. While experience and software can help predict casting deformation, castings often deform in ways that weren’t anticipated. Consequently, straightening fixtures often can’t be created until after the first castings are available. Note that all of these steps are done after a tool is available and patterns can be molded. The delivery of production castings is then further delayed by the time required to complete these tasks.

In the case of gate locations and final shrink determination, if the initial estimates were off, modifications to the tool might be required, further delaying the delivery of castings to the customer.

However, none of these tasks actually require the use of molded wax patterns! SL patterns could be used for every one of these tasks. Using SL patterns in process development provides two key advantages:

1. All these tasks can be completed while the tooling is in process so that production can start as soon as the tooling is delivered.

2. If there are changes required due to gate locations or shrink, they likely can be incorporated into the original tool rather than incurring the cost and time associated with tooling rework.

The benefit for the foundry is that by doing these tasks before tooling is delivered, casting delivery times can be shortened. In addition, they minimize the risk that tooling changes required by variations in shrink or gate location changes will seriously delay deliveries.

Initial Production Castings

Every customer wants their castings as soon as possible. In general, the foundry is at the mercy of the tooling supplier. Castings cannot be made until wax pattern tooling is available. Consequently, initial castings are typically delayed several weeks or even months after the order was placed.

In many cases, however, the customer does not need full production deliveries at the start of the program. They may want a few castings to do initial buildup of product, or for field tests, before they scale up to full production.

In such cases, those initial castings can be created with SL patterns while the tool is being built. With SL patterns, initial castings can usually be delivered in four weeks or less.

This strategy provides several benefits for the customer:

- Limited quantities of castings are available much sooner than would have been possible using only molded wax patterns.
- If the use of the initial castings made from SL pattern brings to light design issues, they can likely be corrected in the tooling before it is delivered, avoiding down time and further delay of product.

Low Volume Production Castings

The cost of wax pattern tooling effectively eliminated investment casting as a manufacturing option for very low volumes of metal components. While the cost of machining a part is generally higher than the cost of casting without tooling, the amortized cost of tooling over low volumes made investment casting the more expensive process. Consequently, investment casting is rarely even considered when very low volumes of parts are required. For example, assume that customer needs ten pieces of a reasonably complex metal component. For that component, conventional investment castings cost $450 each and the cost of tooling is $15,000. The component can instead be machined at a cost of $1500 each. The total cost of the ten pieces using conventional investment casting is $19,500 compared to $15,000 for the machined components. Even though the per piece cost can be significantly less for castings, the cost of tooling prevents investment casting from being a cost effective solution for most low volume requirements.

With SL patterns, the economics of low volume casting change dramatically. There is no longer a tooling cost and even though the SL pattern is much more expensive than a wax pattern, the cost of the casting can be significantly less than the cost of machining the same part.

For example, the cost of the SL pattern is $600. Investment casting with SL patterns results in a total cost of $10,500, significantly less than the $15,000 total cost for machining. In fact, the foundry could charge $1300 per casting, still undercutting the machined cost by $200 per part while increasing their profit by $150 per casting. The numbers in this example are valid for that one geometry and the casting cost, tooling cost, machining cost and SL pattern cost will vary with the size and complexity of the part to be created. However, the ability to avoid the tooling cost by using SL patterns instead of molded wax patterns will often make investment casting very competitive if not significantly less expensive than machining.

The relative cost of machining and investment casting, both with molded wax patterns and with SL patterns is largely dependent on the geometric complexity of the part to be produced. Geometric complexity can be defined as the presence of features that increase the difficulty of manufacture. Such features include tight tolerances, thin walls, undercut features, complex curvature, etc.

As the geometric complexity increases, the cost of machining goes up dramatically. In addition, the cost of tooling to mold wax patterns increases dramatically. The cost of the SL pattern, however, is largely independent of geometric complexity. A simple geometry and a very complex geometry having the same overall dimensions and volume are likely to cost very nearly the same amount. Similarly, the cost of investment casting (without the cost of tooling) is much less dependent on geometric complexity.

Consequently, investment casting using SL patterns will have the greatest cost advantages over machining for those components with higher geometric complexity. For simple geometries, investment casting is not likely to provide much if any cost advantage.

Such low volume applications offer several advantages for foundries including:

1. New Markets – Because of the cost of tooling, investment casting has not been a cost effective method of manufacture for low volume applications. The lower cost structure provided by using SL patterns now makes investment casting very competitive and opens up new markets that have never been available before.

2. Better Margins – The prices customers are accustomed to paying for low volume orders are based on the cost of machining. Consequently, with their lower cost structure provided by using SL patterns, foundries can charge more than they normally would for castings and still be less expensive than machining, allowing them to make better margins than they ever did on the higher volume orders they typically run.

3. Less Vulnerable to Foreign Competition – Because of the lower dollar volumes involved and because of the need for fast turnaround, this is business that is unlikely to go offshore.

Summary

There are a number of good reasons for foundries to use SL patterns in their business, both to benefit their customers and themselves. This guide is intended to help foundries develop that capability quickly and with a minimum of effort.

Appendix B: Troubleshooting Guide

Problem Area	Symptom	Potential Problem	Solution
Pattern Issues	Softness in patterns	Moisture absorption	Dry pattern in a very low humidity environment.
			Return to vendor for replacement.
	Holes or cracks in pattern	Damage to pattern	Return to vendor for repair or replacement.
			Patch with wax.
		Incomplete finishing	Return to vendor for repair or replacement.
	Leak test failure	Surface holes or cracks	Find leaks and repair or return to vendor for repair or replacement.
	Discoloration	Overexposure to UV light	Most likely will not affect performance of the pattern.
Shelling Problems	Poor shell adhesion on QC patterns	Contaminants on pattern	Wipe with etch solution or dip assembly in etch.
	Poor shel adhesion on runners, gates or sprues	Contaminants on runners and sprues	Wipe with etch solution or dip assembly in etch.
Autoclaving Problems	Shell cracks in autoclave cycle	Inadequate venting	Increase number and size of vents. There should be at least one vent per pattern.
		Vents not open to pattern interior	Make sure that wax in pattern is removed prior to autoclaving and that the skin of the pattern is punctured prior to placing the shell in the autoclave.
		Solid areas in pattern	Do not autoclave. Melt sprues and runners out by hand or use flashfire furnace.
Burnout Problems	Incomplete combustion autoclave cycle (material other than ash in the shell after burnout)	Inadequate oven temperature	Increase furnace temperature to 1500°F or higher.
		Inadequate burnout time	Increase time in furnace to 2 hours for small patterns, 3 hours or longer for large patterns.
		Inadequte oxygen to support combustion	Ensure that patterns are vented.
			Ensure that there is adequate oxygen in the furnace.
			Ensure that air can get into the shell easily.
Casting Problems	Inclusions	Leakage of slurry into pattern	Ensure patterns are properly sealed.
	Hex pattern on castings	Leakage of slurry into pattern	Ensure patterns are properly sealed.
	Surface pitting	Incomplete combustion of pattern	Increase airflow through pattern.
			Increase oxygen in furnace.
			Increase burnout temperature.
			Increase burnout time.
		Ash remaining in shells after combustion	Rinse shell prior to burnout.
			Blow out shell hot if unable to cool for rinse.

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