3D Systems

Guide to Casting Using QuickCast™ Patterns

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Introduction

Investment casting, also known as lost wax casting, has been successful in creating near net shapes for thousands of years. 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.

In recent history, “Direct Cast Patterns,” produced with Rapid Prototyping (RP) technology, have afforded the investment casting industry a boost by allowing more designs to be cast without the initial expense and time to fabricate wax pattern tooling. Direct Cast Patterns may be defined as investment casting patterns created without the use of tooling to create the pattern shape.

Many RP technologies are capable of creating a direct cast pattern. However, only Stereolithography (SLA) provides the dimensional accuracy and 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. SLA produces a mostly hollow style pattern with an internal honeycomb structure called “QuickCast™” (a registered trademark of 3D Systems) that can be used in place of a wax pattern. This hollow build style is important, as it allows the pattern to collapse inward during the autoclave and shell burnout phases of the casting process and thus prevents expansion forces from cracking the shell. The mostly hollow build style also reduces the amount of material necessary to burnout.

The purpose of this guide is to assist foundries to successfully cast QuickCast patterns. While earlier guides from Express Pattern and 3D Systems provided general recommendations, recent improvements in both SLA technology and resins have made it possible to minimize the number of specialized processing steps required to successfully cast QuickCast patterns. This guide includes the most recent information on processing QuickCast patterns and will be updated frequently as new information becomes available. Please note that the recommendations put forth in this document are guidelines and may need to be modified by the individual foundry based on their processes and equipment.

This guide is organized into four main sections:

Part 1: Obtaining the pattern – The vast majority of investment foundries do not own SLA 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 a QuickCast 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 QuickCast 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 QuickCast 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 of differences from the methods used for wax patterns.

In addition, there are four appendices that provide additional useful information.

If you have any questions or suggestions for improvements to the guide, please contact the author.

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Part 1:

Sourcing the QuickCast Pattern

Fewer than one in forty investment foundries in North America have their own stereolithography (SLA) equipment. Consequently, the vast majority of foundries who wish to use QuickCast (QC) 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 blame the foundry if the casting does not meet their expectations, regardless of the condition of the pattern the customer supplied.

There are literally dozens of rapid prototyping service bureaus that can provide you with QuickCast patterns. Unfortunately, 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, but 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, as well as the quality control processes he uses.

Qualifying a Pattern Provider

Any company that owns a 3D Systems stereolithography (SLA) system has the software necessary to build QuickCast patterns. However, just as owning a milling machine does not make one a machinist, owning an SLA system does not make one a builder of quality patterns. Building high quality patterns requires knowledge, experience, skills, specialized equipment, and a detailed knowledge of how the patterns will be used.

If you have ordered patterns from a number of suppliers, you have likely found that the quality of the patterns varied greatly. Most likely, some were of such poor quality that you were not able to reliably convert the pattern to an acceptable casting. If you want to use QuickCast patterns in your business, it is important to be able to determine which providers will consistently provide high quality patterns.

The quality of your castings, and consequently your reputation with your customers, depends on the quality of the patterns you get from your supplier.
These questions will help you gauge the capability of a potential supplier.

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 will mark up the price so that he can make a profit), it also means that you have less visibility into the process, as your requirements must be translated through your provider. Furthermore, if there is a problem with the pattern, your supplier and his supplier may blame each other for the problem, making resolution difficult. It is very doubtful that a provider who does not build patterns in house could consistently provide high quality patterns.

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.

What materials do you use for building QuickCast patterns?

While any SLA resin can theoretically be used to build QuickCast patterns, the best patterns are built using resins specifically developed for investment casting. 3D Systems has spent years developing resins for investment casting applications and has the best resins available. Resins that are not developed specifically for investment casting applications may not autoclave properly or may have unacceptable levels of ash. If the provider cannot give you information about how his material performs as an investment casting pattern, he probably does not have much experience with QuickCast. Even worse, if he suggests that any resin will work for QuickCast patterns, you can be sure he has little experience with the process.

How do you drain the pattern?

The QuickCast build style is mostly hollow. In the build process, however, liquid resin is encapsulated in the hollow space. This 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 successful casting. After draining, the pattern is post-cured (flooded
with broad spectrum UV) to complete the solidification of the cured portions of the pattern. In this step, any uncured resin remaining in the pattern will be solidified, thus adding to the mass of the pattern.

Gravity draining often leaves far too much resin in the pattern. 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 can potentially 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, resulting in far less material that needs to be removed from the shell, much less ash remaining in the mold, and a greater chance of successfully casting the part. If the provider you are considering has not made the investment in a centrifuge, they likely are very inexperienced in building QuickCast patterns.

**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. Reputable providers will give you the option of leaving the test nipple attached so that you can recheck the pattern after receipt.

**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. As a result, 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.

**How do you handle multi-piece patterns?**

Some patterns are larger than the 30-inch platform 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.

**How do you ship patterns?**

QuickCast 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 is able to ensure that the chances of damage in shipping are minimized. Ask the provider what measures they use to lower the risk of damage.

**What data formats can you accept?**

Foundries get data in a wide variety of formats. It could be supplied in a number of native formats, IGES format, or one of a half dozen other formats. To build the QC pattern, the provider ultimately requires an 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 want to be sure that he can handle that function.

**Can you modify the data as needed?**

At the minimum, the data received from the customer must be scaled to compensate for shrinkage of the metal. It may also be necessary to add machine stock to certain surfaces, add stock over the entire surface for chemical milling, or add gate
stubs to the model. If the provider does not have the software and skills to make these modifications, they will likely have to outsource the job, adding time, cost, and chances or error.

**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 (ICI) or the American Foundry Society (AFS) and contribute knowledge to the industry. A service provider who is not actively involved in either organization most likely does not consider investment casting patterns to be a key part of his business.

Ask these questions of 3D Proparts. I think you will be pleasantly surprised at how we compare to competitors.

**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 strongly consider obtaining the software to do so. There currently exist very low cost and even free viewers available that will run on virtually any PC. (Ask us. We will send you one.) Having that ability will make it easier to communicate with your provider and allow you to view any adjustments he has made to the pattern design.

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. All but the least capable service providers will be able to apply a universal scale factor.

   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. Virtually any CAD system provides the ability to scale the entire model by a factor.

   Most CAD systems provide 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. Sometimes it is desirable to apply different scale factors to specific features of a part. The foundry may know from experience that a certain feature will shrink at a different rate than the rest of the casting and would like to apply a different shrink factor to that feature. Scaling in that situation, however, is much more complex. Edges that meet smoothly in the original model may no longer meet when different scale factors are applied, and the model must be smoothed before a valid STL file can be created. Such scaling is beyond the capabilities of most service providers.

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
Most foundries that reliably cast QuickCast 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 move the attachment point away from the surface of the casting. This will ensure that any damage incurred during pattern assembly will only affect an area that is eventually trimmed away.

An example is shown in the photo to the right.

4. Machine Stock
Most likely, the part file you received from your customer is of the finished part and not a casting model. 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 are QuickCast patterns 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 generally is the result of exposure to moisture. Some stereolithography resins 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 become distortions in 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 QuickCast 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 of mercury (250 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 was 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 SLA resins 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, QuickCast patterns must be incorporated into a system that includes the pouring cup, sprue, runners and gates. Creating an assembly with QuickCast patterns is similar to creating an assembly with wax patterns, but there are a few areas in which care must be taken. This section covers those areas.

Sprue and Runner Materials

The most common material used for gate/runner systems on QuickCast 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 QuickCast patterns for runners and sprues. The use of QuickCast 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 simply be glued together, eliminating any difficulty in using gate wax to join QuickCast components to wax components.

However, there are significant issues in using QuickCast sprues:

- It can be very expensive, typically doubling the cost of the QuickCast 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.
- QuickCast sprues will add to the buoyancy issues in dipping.

QuickCast sprues and runners typically make sense only for very small components where the entire assembly can be built in one piece. If QuickCast sprues and runners are used, and they are made in multiple pieces, it is important that a path for airflow is created between the components during assembly. For example, if a QuickCast pattern is to be glued to a QuickCast 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 QuickCast 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, QuickCast 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 QuickCast pattern may be somewhat similar 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.
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 QuickCast pattern in the assembly. Although it is possible to successfully cast QuickCast 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 internal support structure of the Quickcast pattern, turning to the consistency of gummy bears. As a result, the pattern can collapse inwardly as it was intended 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 ¼" spaghetti wax about 2" 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 QuickCast pattern. Building QuickCast 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.

One of the easiest ways to vent patterns is to use the vent kits available from 3D Proparts. The vent kits have unique features which simplify and speed not only the assembly process, but several other steps in the casting process. The following charts illustrate the vent and their use.
The vent kit consists of two parts; a molded wax vent and a ceramic plug that will plug the vent hole.

The vent has some unique features:
1. The vent is tapered at the same angle as the plug so that the plug will seal tightly.
2. A blind hole is molded into the vent that will serve as an airpassage later in the process.
3. A locking ring is molded onto the vent that will serve to lock in the patch.

The first step is to drill a 3/16”-1/4” hole into the pattern. This can be done with a drill, with a hand grinder with an appropriately sized bit, or even with a hot iron.

The vent is then attached over top of the hole, locating the vent so that the blind hole is directly over the drilled hole. The vent can be attached with sticky wax.
The pattern is then shelled normally with some care taken to avoid knocking off the vent.

After the shell is built, the end of the vent is cut off to expose the air passage. The cutoff is most easily done with hand held electric cutter, but can also be ground off. The pattern is now ready for autoclaving. The air passage will allow steam to enter the pattern quickly and soften the internal structure, enabling the pattern to collapse internally as intended.

After autoclaving, the vent will have melted out, leaving a larger air passage. This passage will serve as a chimney during burnout and will allow air to flow through the mold, bringing in fresh oxygen for combustion.

After burnout, the pattern will be reduced to a small amount of ash. The vent now will make rinsing the shell easier to remove any ash remaining in the shell.
After rinsing, the plug can be inserted into the vent passage. Because the angle of the plug is the same as was on the vent, it will seal tightly.

The last step is to lock the plug in place. This can be done easily with a little foundry mud. As the mud cures, that portion of the mud extending into the locking ring area will lock the mud into the shell, preventing the plug from backing out during the pour.

**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.

- To simplify the venting and patching process, use vent kits from 3D Proparts.
Part 3:

Shell Building

In general, existing shell building practices can be used successfully to shell QuickCast patterns. Most foundries use the same shelling method for QuickCast patterns as they do for their normal wax pattern assemblies. Over the years, however, a number of misconceptions about shelling QuickCast patterns have emerged. The author has done extensive testing in the shell building process with several investment casting resins. Results of that testing is incorporated into the recommendations here.

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 ½ inch 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 common misconception is that etching solutions can damage or even dissolve QuickCast patterns, and many foundries avoid etching assemblies with QC patterns. As a result, they sometimes have issues with shell adhesion on wax components of the assembly, especially molded wax sprues.
The author has tested patterns from a number of investment casting resins in both solvent based and citrus based etching solutions. Patterns were immersed for ten minutes, roughly twenty times the normal exposure. There was no effect visible on any of the patterns.

Based on these results, we see no reason that assemblies containing QuickCast patterns should not be etched in the same manner as wax assemblies.

**Pattern Dipping**

It is important to keep in mind that unlike wax patterns, QuickCast 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 QuickCast Patterns.

Fused Silica systems are designed to weaken after firing in the burnout oven. At temperatures above 1650°F 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 QuickCast 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 resins were prone to absorb moisture and sometimes expanded or softened to the point that their value as investment casting patterns was significantly reduced. However, resins 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 QuickCast 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.

Although it is increasingly rare, some foundries still use an alcohol-based slurry. QuickCast patterns will soften on prolonged exposure to alcohol. However, the exposure in dipping
is relatively short and the alcohol evaporates quickly. We would not anticipate significant issues if an alcohol based slurry is used.

Regardless of the shell type, or the base liquid of the slurry, QuickCast patterns can be and are regularly successfully shelled and casted. 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 QuickCast patterns. 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.

The author has tested patterns made from a variety of investment casting resins using a number of slurries. A variety of finishes on the patterns were tested including no finish, lightly sanded, and clear coated. Good slurry adhesion was obtained in all cases.

**Shell Coats**

In the past, foundries often used more coats on shells for QuickCast 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 QuickCast 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 QuickCast 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 QuickCast patterns because they believe that contact with the pre-wet solution may damage the pattern. While we have not done extensive testing, suppliers of pre-wet solutions have assured us that pre-wet solutions are much less aggressive than etching solutions and if etching solutions have no effect, pre-wet solutions certainly will not.
Shell Building Summary

- Inspect the assembly prior to dipping for cracks, leaks and solid sections
- There is no need to avoid the use of etching or pre-wet solutions
- 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 QuickCast 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 resins used to build QuickCast patterns are photo-cured materials, which, unlike thermoplastic materials, will not melt. Consequently, they cannot be simply melted out of the shell like wax patterns. They must instead be burned out of the shell which creates several problems in shell processing. Initial attempts to process QuickCast 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 re-heating 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 1500F.
   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.

**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 QuickCast 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 QuickCast patterns is high, and there is significant additional cost to process a QuickCast 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 QuickCast patterns would provide great benefit to the foundry.
Over the past few years, the author has worked with several foundries as well as resin and shell suppliers to develop procedures for evacuating the shell which increase casting yields and reduce the cost of casting. In that time, a number of key process improvements have been identified that greatly simplify the processing of QuickCast patterns. 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 QuickCast 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 QuickCast 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 QuickCast pattern.

Many foundries have had difficulty attempting to autoclave QuickCast patterns. Shells tend to crack during the autoclave cycle, often beyond repair. As a result, many 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.

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.

Some foundries have reported that the shell in the sprue area gets red hot before all the wax is melted out. In some cases, that area of the shell gets hot enough to go through cristobalite conversion and as a result, the strength of that area of the shell is seriously compromised when reheated prior to pouring. If the shell gives way during pouring, a very dangerous situation will then result.

The author ran tests in conjunction with two customer foundries to determine the cause of shell failure during the autoclave cycle and potential solutions. It was never previously clear whether it was thermal expansion of the pattern material or expansion of the air
inside the pattern that caused the cracking. We designed the following test to identify the cause:

In the first test, eight QuickCast patterns were built. 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 with 350ºF 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 QuickCast 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 275F would be approximately 8 psi. Considering that this internal pressure is resisted by an external steam pressure of more than 100 psi, 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.

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. Further testing will be done to learn more.

Another complication that is apparent is the presence of solid areas in the pattern. As a general rule, hollow QuickCast patterns cannot be built with a wall thickness of less than 0.020 inches, and most walls of 0.050 inches 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 in the pattern model and it will be built as part of the QuickCast 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 QuickCast 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.

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 QuickCast 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 QuickCast patterns are still in intact within the shell. The stereolithography resin 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 QuickCast 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.

The author worked 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. In one test, 36 patterns were burned out in an attempt to determine optimum temperatures and times for burnout. The QuickCast 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 QuickCast patterns. The 9-wall patterns contained 9 thin walls ranging from 0.020 inch to 0.100 inch. 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.

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

Two different furnace temperatures (1800F and 1500F) 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.** The photo shows part of the shell which was burned at 1500F for 30 minutes. 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 1500F and for any time longer than 30 minutes.**

Foundries have reported successfully burning out patterns at temperatures as low as 1100F.

**Oxygen Content:** Sufficient oxygen is necessary for proper combustion of the QuickCast 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 QuickCast 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 pre-heat furnace. Since most foundries use the pre-heat furnace to burn out QuickCast 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 QuickCast 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. Alternatively, the assembly can be placed on top of two bricks placed an inch or two apart. The space will allow air to flow between the bricks and up into 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 QuickCast 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 QuickCast 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 to the right.

**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 1650°F. 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 1500°F, although I have heard of some burning out as low as 1100°F.

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

We know of at least two foundries that burn out fused silica shells at 1800°F 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 an furnace with a temperature of 1500°F 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 DSM 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.
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.

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.

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. To simplify that process, 3D Proparts will provide small QuickCast patterns at no charge to allow you to test the process and develop the optimum procedures for your foundry. For more information, contact 3D Proparts.

**De-Wax Summary**

1. **Autoclaving the Assembly**
   a. Include a vent on every pattern.
   b. After the shell is built, cut off the shell at the end of the vent to expose the vent.
   c. Melt out the wax in the vent.
   d. Puncture the skin of the pattern.

2. **Burn out the Patterns**
   a. 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.
   b. Ensure that there is adequate oxygen in the furnace atmosphere.
   c. Burnout in a furnace set to 1500°F or higher.
   d. Burnout for a minimum of two hours for small patterns, three hours or longer for large patterns.

3. **Ash Removal**
   a. Cool the shell from the burnout process.
   b. Either:
      i. Leave the vents open, blow out the shell with compressed air and then cap the vents, or
      ii. Cap the vents and rinse the shell with water
Appendix A:
Why Use QuickCast Patterns?

Introduction

In spite of the fact that QuickCast patterns have been in use for 15 years and are the most popular means of creating direct patterns, the majority of foundries still don’t really understand all the ways that QuickCast patterns can be used to benefit both their customers and themselves. Most will admit that they use QuickCast patterns because their customers ask them to. A few have found that QuickCast patterns provide a competitive advantage.

The short answer is that by using QuickCast 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 QuickCast 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 QuickCast patterns. This was the first application to be exploited and is one that provides high value to the foundry customer.

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 QuickCast 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 QuickCast 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! QuickCast patterns could be used for every one of these tasks. Using QuickCast 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 build up of product, or for field tests, before they scale up to full production.

In such cases, those initial castings can be created with QuickCast patterns while the tool is being built. With QuickCast 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 QuickCast 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 QuickCast patterns, the economics of low volume casting change dramatically. There is no longer a tooling cost and even though the QuickCast 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.

In the example above, the cost of the QuickCast pattern is $600. Investment casting with QuickCast 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 QuickCast 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 QuickCast 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 QuickCast 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 substantially as well. The cost of the QuickCast 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.

As a result, investment casting using QuickCast 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 QuickCast 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 QuickCast 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 QuickCast 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:

A History of the QuickCast Build Style

Just about anyone involved in the investment casting industry over the last ten years is familiar with the term QuickCast. Not only is it the most widely used method of creating rapid prototyping patterns for investment casting, it is generally accepted as the most accurate way to make direct patterns for investment casting. However, the QuickCast patterns we use today are the result of a long and continuing process of development.

The term QuickCast is a trademark of 3D Systems, the manufacturer of stereolithography (SLA) systems. It simply refers to a build style for stereolithography that was developed specifically for investment casting patterns. The QuickCast build style essentially builds a hollow part. All outer surfaces of the part are built, but the interior of the pattern consists only of a system of ribs constructed to hold the walls in place. A QuickCast part has a small fraction of the mass of the same part built with a solid build style.

The introduction of rapid prototyping generated a great deal of interest in the investment casting community. It has traditionally been very difficult to prototype investment castings. Creating prototypes required either the creation of a wax pattern die to mold wax patterns, or machining wax patterns themselves. Both were time consuming and expensive. It was hoped that RP methods could be used to simplify the prototyping process so that initial castings for test purposes could be created without the cost and lead time associated with tooling. Other RP manufacturers had developed the means to build wax patterns directly, but had problems with accuracy, surface finish, and brittleness that significantly limited the usability of their parts.

Initial attempts to use solid stereolithography parts for investment casting patterns were met with very limited success. Foundries using a shell process had relatively poor results. SLA resins had a coefficient of expansion that was roughly an order of magnitude higher than that of the ceramic shell. Consequently, expansion of the pattern tended to crack the ceramic shell in the heat of the autoclave or furnace. Foundries using a solid ceramic casting process generally obtained better results. The greater thickness of the ceramic and the metal container were able to resist the expansion of the pattern. However, few foundries had solid mold capability. In general, the probability of successfully casting a solid SLA part was in the range of 10%.

The QuickCast build style was developed in 1992 by Dr. Paul Jacobs, then Director of R&D for 3D Systems, and patented by 3D Systems. Dr. Jacobs theorized that if the pattern...
were hollow, the pattern could collapse inwardly as it expanded, rather than cracking the shell. The R&D department then set out to develop a process to build hollow patterns. In the process, 3D Systems patented several other innovations related to building QuickCast patterns.

The team at 3D Systems came up with a build style that worked. They built the part as a very thin shell with internal ribbing to provide strength and dimensional stability. The internal ribbing was a lattice of equilateral triangles designed to provide a very strong structure with a minimum of material. The lattice was offset every 0.100 inch or so of vertical height. At each offset, the lattice was moved so that the vertices of the new triangles exactly lay over the centers of the triangles of the previous layers. The lattice was offset so that the pattern could drain completely. Due to the nature of the stereolithography build process, liquid resin is captured inside the pattern as it is built. The captured liquid resin must be drained from the pattern prior to use, or it would solidify upon exposure to ultraviolet light, and we would again have a solid pattern. To remove the resin, small holes are intentionally cut in the pattern to allow the resin to drain out.

3D Systems enlisted the help of three foundries to develop the process; Solidiform, a Dallas, Texas foundry specializing in aluminum, Precision Castparts Corporation, a Portland, Oregon foundry, and a Cercast foundry in Montreal, Canada. The foundries provided valuable feedback to 3D Systems to help them optimize shell thickness, rib spacing, etc. In addition, the foundries provided assistance in determining how to best burn out the patterns from ceramic shells.

In initial test versions of QuickCast, the sides of the equilateral triangles in the hatch pattern were set at 0.100 inch. This hatch spacing provided very good strength, but was almost too strong. It did not collapse easily as the resin expanded when heated and still tended to crack shells, although significantly less than for solid patterns. In addition, the openings in the hatch structure were small enough that surface tension of the resin hindered complete drainage. A number of different hatch spacings were tried up to 0.25 inch. The optimum spacing proved to be about 0.17 inch. That spacing yielded a void ratio (the percentage of air in the volume of the pattern) of about 66%.

Overall, the effort was successful. The QuickCast build style increased the probability that a stereolithography pattern would yield a satisfactory casting from about 10% to better than 50%. In addition, there was significantly less material to burn out than with a solid pattern. The first version of QuickCast software was released in June of 1993. For the first time, it was possible to quickly create reasonably accurate prototype patterns without the cost or lead time of creating wax pattern dies.

The first QuickCast patterns were far from perfect, however. It was far more difficult to cast a QuickCast pattern than it was to cast a wax pattern. Early users were plagued
with two persistent problems: leaking patterns, and incomplete pattern burnout. As we mentioned before, it is necessary to drain liquid resin from the pattern after it is built. To drain the resin, holes are cut into the bottom of the pattern, and into the top of the pattern to allow air to enter (later versions allow the user to specify the locations of vent and drain holes that will be built directly into the pattern). It is necessary to plug the holes again after the pattern is drained. If they aren't plugged completely, slurry can leak inside the pattern and result in an inclusion in the casting. Given that the pattern cost is significant, and that there is substantial cost and time invested in building the shell, the true cost of a leaking pattern can be several thousand dollars.

It is also important to take care that the pattern is free of even the smallest pinhole leaks. Initially, the drain and vent holes were plugged with gate wax. Results were inconsistent, however. The wax would sometimes melt sufficiently to open small passages into the pattern and leakage would occur. Today, the best results are typically obtained with resin cured in place to patch the holes. (Note: For additional assurance, Express Pattern completely tests each QuickCast pattern with both positive pressure and a partial vacuum to ensure that the pattern is free of any leaks.)

Burnout problems are a little more complex. The SLA resin is a cross-linked photo-polymer material, which means it will not melt like wax. Consequently, the pattern must be burned out of the shell. Fortunately, under the right conditions, the resin will burn cleanly and leave very little if any ash. The probability of a complete burnout is dependent on two factors: the amount of material in the pattern and the environmental conditions in the furnace. Environmental conditions are relatively straightforward. To achieve combustion, the pattern temperature must be elevated above a minimum combustion temperature for the resin, and there must be adequate oxygen in the atmosphere to support combustion. Less than optimum levels of oxygen increase the ash content. In general, increasing the level of oxygen in the furnace increases the probability of satisfactory burnout. Those foundries with specialized furnaces such as those produced by Pacific Kiln that allow control of the oxygen content in the furnace, have traditionally had a much easier time casting QuickCast patterns. However, several foundries have had good success without such furnaces.

The amount of material in the pattern can be a critical issue. The more material in the pattern, especially in thin sections, the longer the furnace cycle has to be, the more likely it is that shell cracking will occur, and the less likely a complete burnout will be achieved. Obviously the void ratio of the QuickCast style is a primary determinant. Early tests in foundries working with 3D Systems in developing the QuickCast build style showed that the yield (percentage of patterns successfully cast) increased significantly as void ratio increased. For example, increasing the void ratio from 50% to 66% increased the yield from 40% to about 80%. A further increase in void ratio to 83% increased yield to above 90%.

However, the void ratio assumes that all liquid resin has been removed from the pattern and in practice that can be difficult to achieve. Unfortunately, the viscosity and surface
tension of the resin tend to retard drainage. The problem is not unlike trying to get the last few drops of ketchup out of a bottle – no matter how long you hold the bottle upside down, there is always a little bit remaining inside. Now imagine the bottle had hundreds of wires forming a lattice through its interior. You can imagine the difficulty in getting complete drainage.

Any resin remaining in the pattern reduces the actual void ratio from the theoretical value possible in a perfectly drained part. Even worse, the resin remaining tends to be in the worst places – thin sections where drainage is most critical. Consequently, achieving complete drainage from QuickCast patterns is critically important in maximizing the probability of a successful casting.

A variety of means have been used to assist in the drainage. Early users would allow patterns to drain for days to maximize the amount of resin drained. However, long drainage times increased the time required to make the pattern and reduced its value. Attempts were made to use air pressure, and vacuum techniques with mixed results. Early on, some users employed centrifugal force to assist in removing material. An engineer at Ford put the pattern in a bucket with a short length of rope tied to the handle. He then swung the bucket by hand over his head to help drain the pattern. Although the process was very tiring and broken ropes resulted in somewhat spectacular failures, the idea had merit. It did increase the amount of resin that could be drained from the pattern. Another user improved on the idea by using the spin cycle on his wife’s washing machine. Although his wife was not pleased, it achieved better results than the bucket with much less effort and risk.

An early user found an even better idea. He had a relative who was a beekeeper and had watched while a centrifuge was used to remove honey (a fluid even more viscous than resin) from a honeycomb. He ordered a honey centrifuge and found that it worked very well to help remove liquid resin from the pattern. A honey extractor is now standard equipment among service bureaus to help drain patterns.

In the meantime, 3D Systems continued to improve the QuickCast build style. In 1995 they released version 1.1 of the QuickCast software. Version 1.1 used additional skin layers on down-facing and up-facing surfaces that significantly decreased the tendency of the skin of the pattern to break when supports were removed. In addition, version 1.1 used a square lattice structure rather than the original equilateral triangle lattice. The square structure had three advantages over the previous triangle structure. First, it is not as strong as the triangle structure and can collapse more easily as the pattern expands with heat. Second, the angles of connection of the ribs were less acute allowing less material to accumulate in corners due to surface tension. Finally, the use of a square hatch pattern allowed void ratios to increase to as much as 83%. It was during this period that the use of QuickCast patterns really became
established in the industry. Several foundries developed burnout procedures so that they could reliably cast QuickCast patterns.

In 1998, 3D introduced version 2.0 of the QuickCast software. Professor Phil Dickens and a doctoral student, Richard Hague, did much of the development at the University of Nottingham in England. The hatch pattern was changed again, this time to a hexagonal pattern. The manner in which it provides for drainage has changed significantly. Previous versions shifted the hatch pattern by one half of the basic cell so that resin could flow into adjacent cells. In version 2.0, only two of the six sides of the hexagonal cell are built on any layer. Two opposing sides of the hexagon are built for a several layers. Then another pair is built for several layers, and then the two remaining for several layers. In this manner, the part can easily drain in any orientation and there is still adequate strength for supporting the skin of the part. The hex pattern also increased the theoretical void ration to above 88%, further reducing the amount of material in the pattern. Foundries using Version 2.0 QuickCast patterns have reported yields as high as 98%. It is now possible for virtually any investment foundry to successfully, and reliably, cast QuickCast patterns.

The development of the QuickCast build style has certainly had an impact on the investment casting industry. Now there are fast and relatively low cost ways to provide prototype castings to customers so that they can prove out their designs prior to investing in tooling. As a result of this new availability, we will continue to see significant growth in demand for prototype castings. Although we will probably never see it used for high volume production runs, don’t be surprised if you begin to see it used for low volume runs to deliver production parts faster and without incurring the substantial time and cost of fabricating wax pattern tooling.
## Appendix C: Troubleshooting

<table>
<thead>
<tr>
<th>Problem Area</th>
<th>Symptom</th>
<th>Potential Problem</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern Issues</td>
<td>Softness in Patterns</td>
<td>Moisture Absorption</td>
<td>Dry pattern in a very low humidity environment.</td>
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<tr>
<td></td>
<td>Holes or Cracks in Pattern</td>
<td>Damage to Pattern</td>
<td>Return to Vendor for repair or replacement</td>
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<tr>
<td></td>
<td></td>
<td>Incomplete finishing</td>
<td>Return to Vendor for repair or replacement</td>
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<td></td>
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<td></td>
<td>Patch with wax</td>
</tr>
<tr>
<td>Leak Test Failure</td>
<td>Surface holes or Cracks</td>
<td>Find leaks and repair or return to vendor for repair or replacement</td>
<td></td>
</tr>
<tr>
<td>Discoloration</td>
<td>Overexposure to UV light</td>
<td>Most likely will not affect performance of the pattern.</td>
<td></td>
</tr>
<tr>
<td>Shelling Problems</td>
<td>Poor Shell Adhesion on QC Patterns</td>
<td>Contaminants on pattern</td>
<td>Wipe with etch solution or dip assembly in etch.</td>
</tr>
<tr>
<td></td>
<td>Poor Shell Adhesion on Runners, Gates or Sprues</td>
<td>Contaminants on runners and sprues</td>
<td>Wipe with etch solution or dip assembly in etch.</td>
</tr>
<tr>
<td>Problem Area</td>
<td>Symptom</td>
<td>Potential Problem</td>
<td>Solution</td>
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<tr>
<td>Autoclaving</td>
<td>Shell Cracks in Autoclave Cycle</td>
<td>Inadequate venting</td>
<td>Increase number and size of vents. There should be at least one vent per pattern.</td>
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<td></td>
<td></td>
<td>Vents not open to pattern interior.</td>
<td>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.</td>
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<tr>
<td></td>
<td></td>
<td>Solid areas in pattern</td>
<td>Do not autoclave. Melt sprues and runners out by hand or use flashfire furnace.</td>
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<tr>
<td>Burnout</td>
<td>Incomplete combustion (material other than ash in the shell after burnout)</td>
<td>Inadequate oven temperature</td>
<td>Increase furnace temperature to 1500F or higher</td>
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<td></td>
<td></td>
<td>Inadequate burnout time</td>
<td>Increase time in furnace to 2 hour for small patterns, 3 hours or longer for large patterns.</td>
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<tr>
<td></td>
<td></td>
<td>Inadequate oxygen to support combustion</td>
<td>Ensure that patterns are vented.</td>
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<td></td>
<td></td>
<td>Ensure that there is adequate oxygen in the furnace</td>
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<td>Ensure that air can get into the shell easily.</td>
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<td>Problem Area</td>
<td>Symptom</td>
<td>Potential Problem</td>
<td>Solution</td>
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<tr>
<td>Casting Problems</td>
<td>Inclusions</td>
<td>Leakage of slurry into pattern.</td>
<td>Ensure patterns are properly sealed.</td>
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<tr>
<td></td>
<td>Hex pattern on castings</td>
<td>Leakage of slurry into pattern</td>
<td>Ensure patterns are properly sealed.</td>
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<td>Surface Pitting</td>
<td>Incomplete combustion of pattern</td>
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<td>Increase airflow through pattern</td>
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<td>Increase oxygen in furnace</td>
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<td>Increase burnout temperature</td>
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<td>Increase burnout time</td>
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<td></td>
<td>Ash remaining in shells after</td>
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<td>Rinse shell prior to burnout</td>
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<tr>
<td></td>
<td>combustion</td>
<td></td>
<td>Blow out shell hot if unable to cool for rinse</td>
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