



FORMLABS WHITE PAPER:

Fabricating Metal Parts With 3D Printing

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Introduction

While plastics compose a huge percentage of the parts in products we interact with every day, many applications still demand the strength and long-term durability of metals.

Stamping, milling, turning, and extrusion are all mature metal part manufacturing processes, but are more costly and less nimble than the product development options available for plastic parts.

Direct 3D printing of metal has been promoted as a way to quickly create near net shape parts in durable materials like titanium, but high equipment costs, the need for specially trained technicians, and a limited selection of alloys has meant limited use of the technology for all but the most exotic, high-value applications.

Engineers and designers can leverage the speed and flexibility of 3D printing without the expense of direct metal printers by using metal casting workflows. For applications where parts require fine features or complex geometries, casting remains a cost-effective and highly capable manufacturing process, producing critical components for aerospace, automotive, and medical applications.

While stereolithography (SLA) 3D printers are thought of primarily as tools for creating plastic parts, their high precision and broad material library is well-suited for casting workflows that produce metal parts at a lower cost, with greater design freedom, in less time than traditional methods.

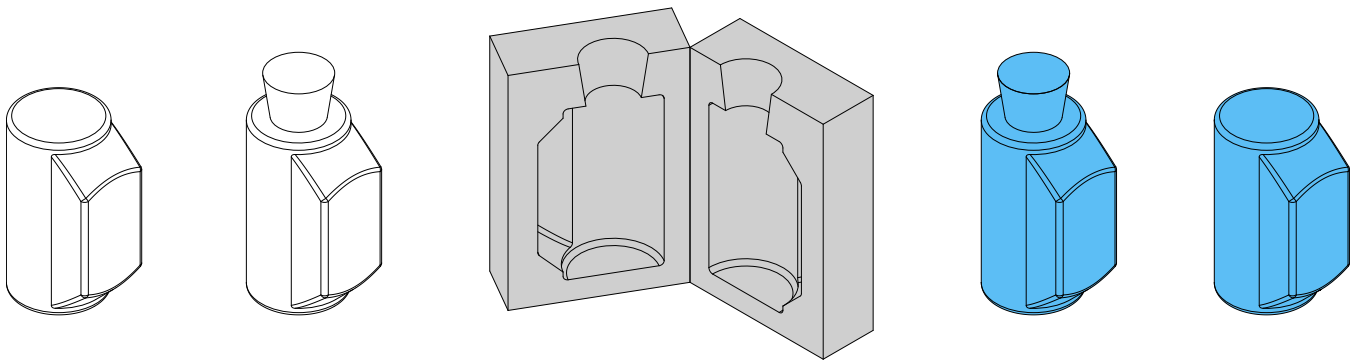
This white paper outlines how to fabricate metal parts through sand casting and investment casting processes with Formlabs 3D printers and resins.

Casting Basics

Metal casting dates back to at least 3200 B.C., progressing through many cycles of innovation to become the reliable, modernized process it is now. Today, industrial metal casting processes are used to make everything from knee implants to tractor parts.

The basic process to create cast metal parts with has a few common steps across different techniques:

1. A manufacturer creates a pattern that represents the part, either as a removable element to make an impression in a material like sand, or left inside of the mold material and subsequently burned or melted out.
2. In either case, a cavity in the shape of the pattern is left behind, and molten metal is poured in.
3. The molten metal cools, and the mold is either opened up or broken apart to retrieve the casting.
4. Cast parts have vestiges of the process where vents, gates, and feeders that direct gases and molten metal during casting. To finish the cast parts, a foundry worker trims away excess material and files, grinds, machines, or sandblasts parts to achieve final geometry and surface requirements. In some cases, the cast parts are also heat treated.



Original design

Pattern

Mold

Casting

Finished casting

In any casting process, two basic forms must be fabricated: the pattern and a mold of some kind. The pattern is essentially a slightly modified version of the part to be produced.

The design for the pattern differs from the final part geometry in a few ways:

- Patterns are scaled up to compensate for shrinkage that occurs in casting.
- Patterns often contain elements relevant for the casting process that will not be present in the final part (e.g., gates for metal to flow through at a controlled rate, vents for gases to escape through, etc.)
- Patterns may have certain features oversized or filled in to accommodate secondary operations used to produce very tight tolerance features (boring, tapping, etc.)

Patterns are typically made from wood, foam, plastic, or wax. Sometimes the pattern design will incorporate elements related to the casting process, like gates for molten metal to flow through.

A mold includes the negative of the pattern along with sprues, gates, vents, risers, and other features to control the flow of metal and gases during casting.

Molds are made from a variety of materials (e.g., ceramic, graphite, plaster, sand) and must be able to withstand the high temperatures and mechanical stresses of the casting process.

Direct Investment Casting

The direct investment casting process moves straight from creating a pattern to surrounding that pattern with investment material. Since the wax injection method of creating a pattern requires multiple steps, it is considered indirect.

Direct Investment casting is best for short runs of parts or initial testing of a part concept, as each printed part will require some finishing steps. Direct investment casting is also a good choice for large parts or parts with thick cross sections that may be more difficult to mold successfully in wax due to warping and shrinkage.

Direct investment casting is valuable for producing parts with geometries that are too complex to be molded or for parts with extensive undercuts and fine surface texture details, where molding is possible but carries high tooling costs.

Traditionally, patterns for direct investment casting are carved by hand or machined if the part is a one-off or expected to be only a handful of units.

With the advent of 3D printing, engineers started experimenting with directly printing patterns in order to achieve shorter lead times and geometric freedom that exceeds the design for manufacturability constraints of molding processes.

Cast parts from SLA patterns printed on a Form 2 in Clear Resin.



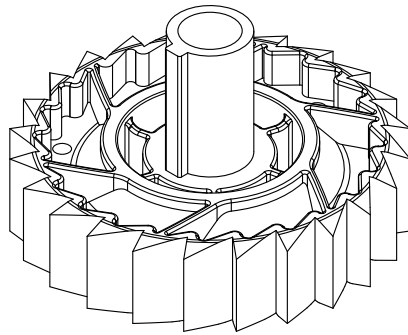
Creating Patterns With the Form 2

There are two typical methods for printing direct investment casting patterns with Formlabs resins. Determining which method is right for your application depends on part size, complexity, and geometry.

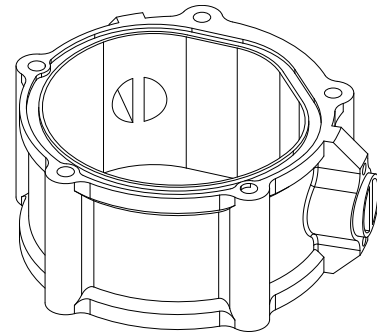
Smaller, thin-walled parts work best when printed as a solid part in Castable Wax, using a flask-style investment mold. essentially following the same process guidelines that are used for [jewelry casting](#).

Larger parts with significant cross sections should be designed to print as lightly supported, thin-walled shells, and use a ceramic shell investment process.

The thermal expansion of larger, solid SLA resin printed patterns can cause cracking of ceramic shell investment material. To successfully cast large printed patterns, we recommend shelling the model to a 0.5-0.8 mm outer wall thickness. In general, thinner walls work better, but you may need to increase the thickness to have adequate stiffness, especially for large parts.



*small ratchet gear
(5.4 cubic cm part volume)*



*4" diameter pump housing
(84.2 cubic cm part volume)*

A hollowed-out part will generally need internal support to successfully print and retain dimensional accuracy. Those internal support structures should be designed to be as minimal as possible, so that they easily break during burnout and do not trap uncured resin.



Printed SLA patterns from a Form 2 in Clear Resin with internal supports.

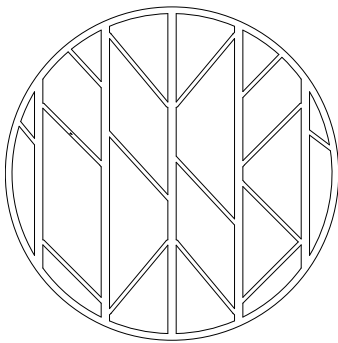
Thoroughly wash the printed pattern with isopropyl alcohol according to material requirements and allow it to fully dry before performing a final post-cure if required, by [the material specifications](#). Uncured resin can cause issues during casting, so pay special attention during cleaning to ensure there are no small pockets of uncured material. Formlabs Clear Resin is often preferred for this application due to the ability to see into the printed pattern and verify that internal geometry is completely clean, with no uncured resin remaining.

Designing Internal Supports for Successful Printing and Burnout

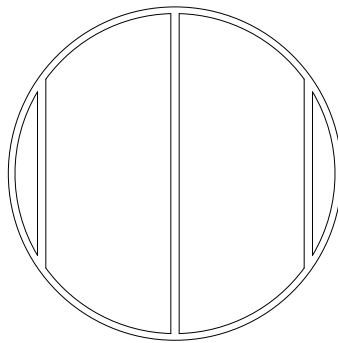
The location and orientation of a 3D print's support structures are important design considerations for successful burnout and casting from printed patterns.

Pattern models need internal supports **(A)** both to print successfully, and to provide enough stiffness and strength to resist the weight of the investment material as the shell is built up.

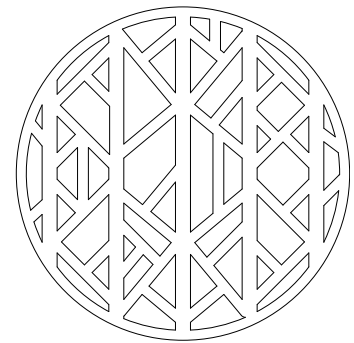
With too little support **(B)**, a pattern will distort and break before the ceramic shell has reached full strength, with too much support **(C)**, the pattern will not collapse as readily, potentially cracking the ceramic shell during dewaxing/burnout.



(A)



(B)

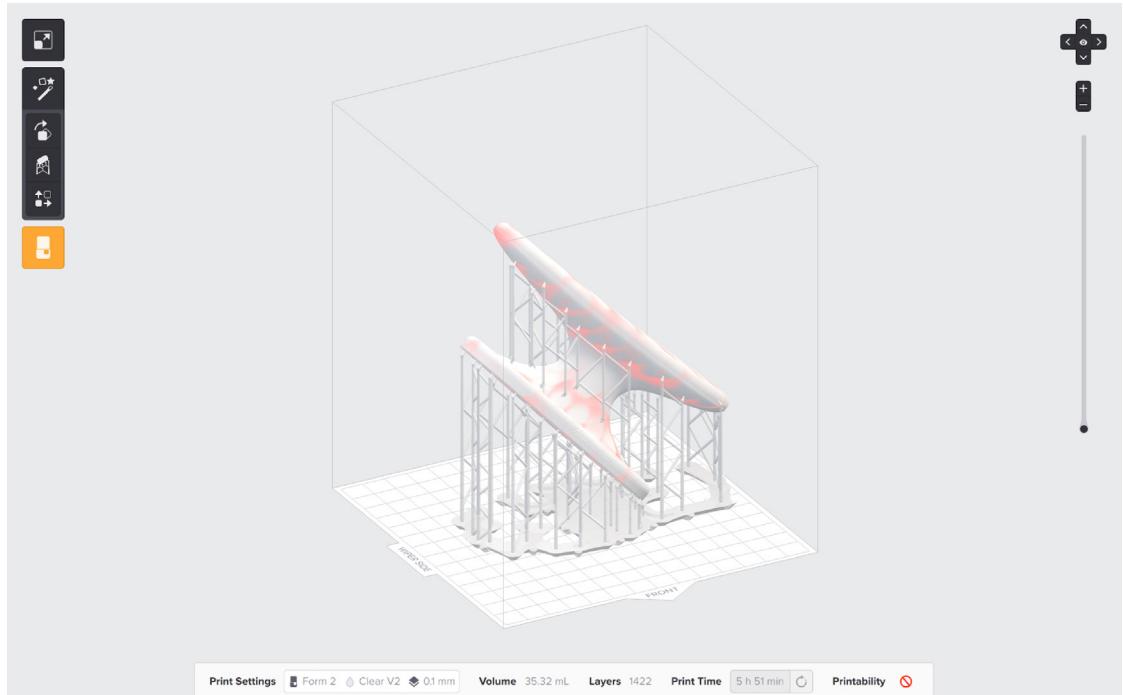


(C)

Formlabs print preparation software, PreForm, generates simple internal support structures. For more complex lattice structures, common software includes nTopology, MeshMixer, and Materialise TetraShell.

Include a small drain hole through the outer shell of the model for draining any uncured liquid resin that may remain in the part after printing.

Preparing to Print Your Pattern



Setting up a shell-style pattern for printing with PreForm. The cross-section view below shows the thin exterior walls of the part geometry, with sparse internal support structures generated by PreForm.

Internal Supports generated from another program:

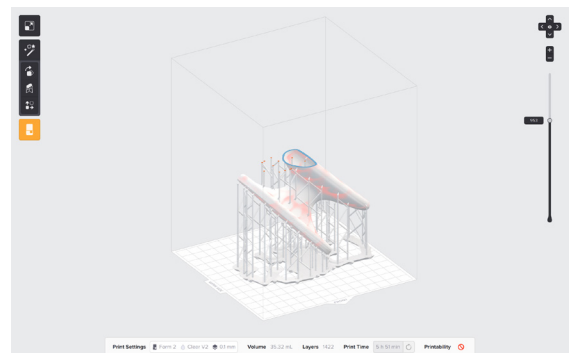
Once the model has been shelled and internal support structures generated, save the file as an STL or OBJ format, which can be read by PreForm. Open the file in PreForm and use the orientation and layout tools to place the parts before adding supports.

Generating internal supports within PreForm:

To use internal support structures generated by PreForm, start with an STL or OBJ of your model that has already been shelled out to the desired outer wall thickness.

Orient the part, considering how any generated supports will impact pattern breakdown during dewaxing/burn out.

From there, you can choose to manually or automatically generate support structures for your model. Even if you use PreForm's automatic support feature, generated supports are modifiable, and individual supports can be added or removed as needed.



Preparing the Printed Pattern for Investment

File or sand prints to remove any remnants of external supports and create smooth, even surfaces. The surface quality of the final part is dictated in large part by the surface of the pattern. In some cases, you can apply a coating, such as a thin wax, to printed patterns to improve the adhesion of the investment slurry.

Sprueing and Venting a Direct Printed Pattern

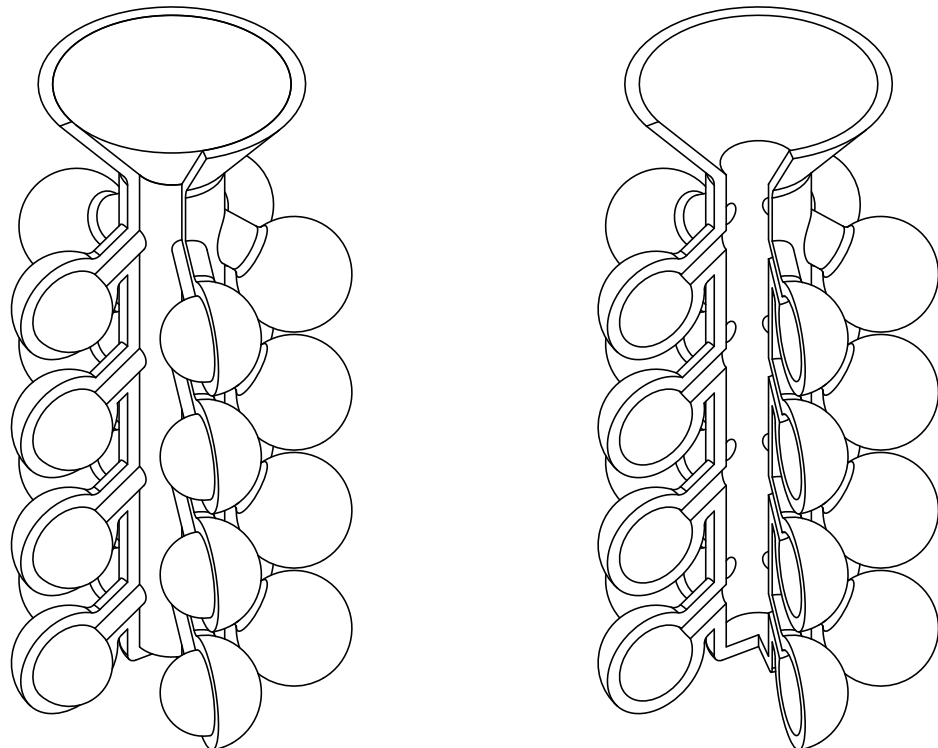
Printed patterns are usually connected with wax to the rest of the tree, an array of parts joined to a central column, typically made of wax.

During dewaxing or burnout, the central column melts out along with any other wax present, and acts as the primary delivery channel for molten metal during casting.

Depending on your casting process and pattern design, you may need allowances for residue from degraded patterns to exit the mold. Running compressed air or water through the empty mold helps to clear out any ash from the burnout or dewaxing process.

At this stage it's important to consider how pattern orientation relates to material flow. Molten metal should be able to flow easily, with minimal turbulence while it fills the mold cavity.

Orient patterns so that metal flows from thick sections of the parts to thin sections and add venting to any areas where air may be trapped during casting. Venting requirements will vary based on metals, specific mold materials, and the casting process used.



Left: A tree of parts with a cutaway of the shell shows pattern geometry;

Right: A cutaway with the ceramic shell only, representing after pattern material has been burned out.

Creating the Ceramic Shell



Ceramic shell after burnout of printed SLA patterns in Clear Resin.

Once the patterns, vents, feeders, and gates are attached to the tree, dip the tree in a slurry and coat them with a refractory material to build up the full thickness. Using a slightly thicker shell for printed SLA patterns than you would with traditional wax patterns will reduce the chance of cracking during burnout/dewaxing.

After the pattern is coated with investment material to build up an adequate thickness, the pattern and any wax elements, like sprues or feeders, need to be burned out.

Vent hollow SLA patterns through the ceramic shell to ensure complete collapse and burnout of the patterns.

Mark vent locations, grind down those surfaces to reach the pattern, and puncture the walls of the patterns with a heated metal tool or wire. Alternatively, drill through the patterns to create ventilation holes.

If the skin of the pattern is not punctured, gases within the pattern may expand excessively and crack the ceramic shell.

After the pattern is successfully burned out, the holes created to vent during burnout need to be patched. Typically, the process is to seal the ceramic shell first with a small amount of wax, and then use a patching compound on top of the wax, which reinforces the ceramic shell. This order of operations prevents any of the patching material from entering the mold cavity where it could cause inclusions or other flaws in the cast parts.

Example Burnout Schedule

The optimal burnout schedule for medium and large direct printed patterns that use a ceramic shell process will vary depending on your equipment, shell material, and other outside variables.

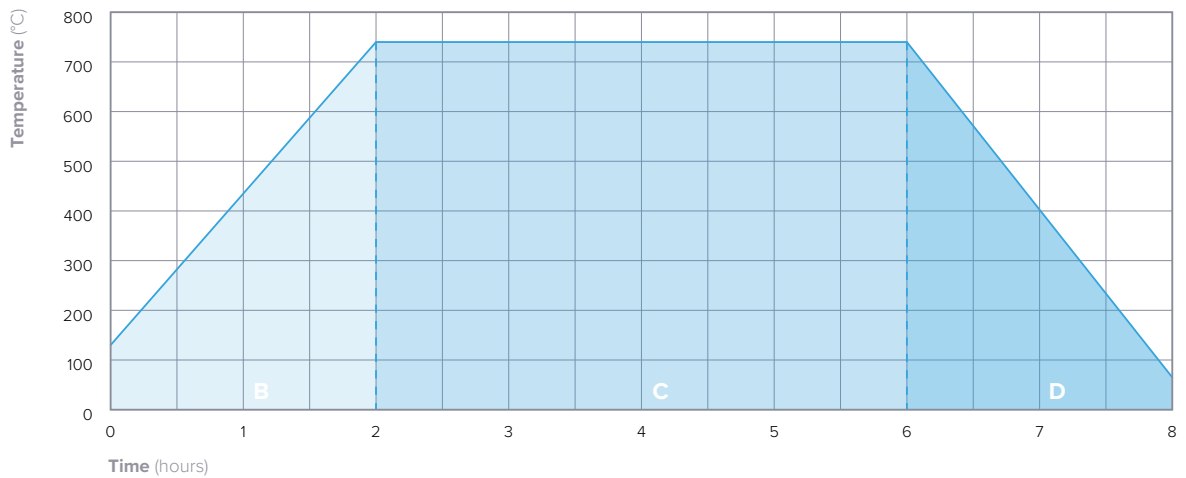
Here's an example of a dewaxing/burnout schedule used by Formlabs customer, Artcast, to produce the boat cleat and door knob handle parts shown in this white paper:

Steam Dewax

PHASE	TIME	PSI
Steam	30 min	80–90

Burnout following dewax

	PHASE	TIME	TEMPERATURE °C	TEMPERATURE °F
A	Start	0 h	130 °C	266 °F
B	Ramp	2 h	to 740 °C	1364 °F
C	Hold	4 h	740 °C	1364 °F
D	Cool		65 °C	149 °F



Indirect Investment Casting

The process of making patterns from molds or tooling is referred to as indirect investment casting because it requires creating molds for producing the patterns in addition to final investment molds.

Rigid molds for wax (often referred to as tools) are commonly fabricated by machining aluminum or steel. Machined metal molds cost thousands of dollars to produce and take weeks of machining and polishing work before first shots can be run and pattern parts evaluated within a casting process. **By directly printing tooling, engineers and designers can reduce the time between concept and first tests from weeks to a matter of days.**

Molds for producing wax patterns can be printed with High Temp Resin. For optimal surface finish of molded parts, treat the interior surfaces of the mold by sanding and polishing for a smooth look, or beadblasting if a uniform matte look is desired.

To ensure the final cast parts are dimensionally accurate, compensate for shrinkage by scaling up the printed mold. The exact shrinkage of the wax and the casting process can be obtained from supplier specifications.

While molded pieces must follow design rules for moldability (e.g., no undercuts, draft is beneficial, etc.), you can achieve increased pattern complexity by using assembly jigs to combine multiple components into a single structure.



Printed mold in Clear Resin for wax injection.

3D Printed Tooling and Assembly Jigs for Casting Workflows

Formlabs High Temp Resin has the ability to withstand elevated temperatures, making it well-suited for investment casting tooling. You can use High Temp Resin to produce molds for injecting waxes, assembly fixtures, and custom-built wax-working tools.

If the molds are rapidly cycling, freshly molded wax parts may still be soft and prone to distortion. You can transfer parts from the 'hot' mold being actively used for injection to a cool mold, which acts as a jig for fully supporting parts as they cool.

High Temp Resin is also useful in the production of wax models to create jigs for rework and assembly of components that are easy to produce and stand up to sustained heat of tools without the high fabrication cost of metals. The insulating nature of High Temp Resin also helps to protect the rest of the workpiece from excess heat.

Sand Casting

In the sand casting process, a foundry worker fills containers known as mold boxes or flasks with a mixture of sand and binder, then packs sand around the pattern. The pattern is removed to leave a negative impression of the pattern behind, and molten metal is poured into the cavity.

An open-faced mold may be used for parts with features on a single side. Parts with features on multiple surfaces require closed cavity molds, with upper and lower moldboxes, referred to as cope and drag.



Grey Resin printed pattern and finished aluminum casting from an open-faced sand mold.

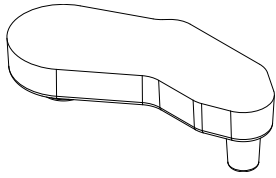
In a closed mold, metal travels through a gating system before reaching the part cavity. This gating system is carefully designed to minimize structural and aesthetic imperfections resulting from improper metal flow.

Closed cavity sand molds sometimes make use of suspended cores to create internal cavities in the finished castings, as in the case of engine blocks or pump housings.

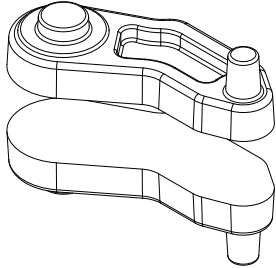
There are a handful basic sand casting pattern styles, including open, split, cope-and-drag, match plate types.

Comparing Pattern Creation and Casting Methods

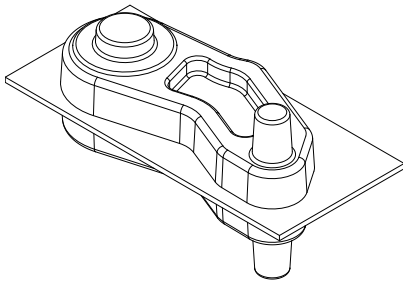
	SMALL PARTS	LARGE PARTS	SMALL FEATURES/ SMOOTH SURFACE FINISH ON CAST PART	GEOMETRIC FREEDOM
Investment Casting: Direct Printed Pattern in Castable Wax	Yes	No	Yes	High
Investment Casting: Direct Printed Pattern in Clear Resin	No	Yes	Yes	High
Investment Casting: Indirect Pattern (Printed Mold)	Yes	Yes	Yes	Medium
Sandcasting: Direct Printed Pattern in any hard resin	Yes	Yes	No	Low



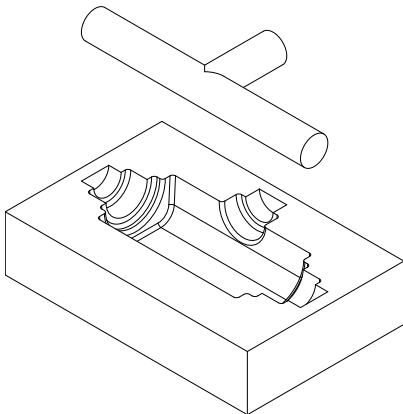
Open refers to an open-face mold style, where metal is poured into a single cavity left by the impressing and removal of a pattern.



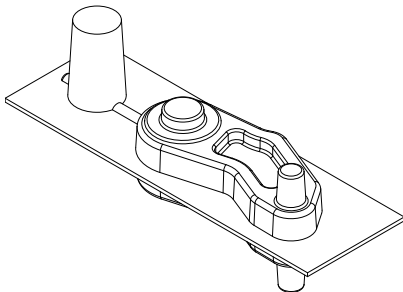
A **split pattern** takes the full geometry of the part and splits that geometry along a parting line, with each one half of the pattern being used on the cope side, and the other on the drag side of the mold box.



Match plate patterns take a similar approach to the split pattern, but include a plate feature as well. The plate is usually made from metal or wood, but in the case of a printed pattern, the plate can be integrated with the model geometry.



Core Boxes are used to mold sand parts that make up the interior cavities of parts (e.g., the empty space in a plumbing fixture) that cannot be made using a sandcasting pattern alone. These cores are suspending within the mold cavity created by the pattern elements, molten metal is poured around them, and when the metal cools, the core portion is broken apart and removed from the cast part.



Cope-and-drag style patterns are a further extension of the match plate concept. In addition to the alignment plate, a cope-and-drag style pattern incorporates risers, gates, and other casting process features. This reduces the manual work associated with prepping the packed sand mold box for casting, and limits variations in the cast parts that might be introduced by moving from one operator to another.



Conclusion

Desktop SLA printers provide a range of meaningful solutions for foundries for pattern production and rapid tooling at a low cost, with the accuracy and precision that modern cast part designs demand. By adding 3D printing to the traditional foundry workflows, manufacturers can be more responsive to customer demands, delay investments in hard tooling, and validate designs cost effectively. Additionally, the growing use of topology optimization in engineering and product development means an increased demand for geometries that can be achieved through direct printing of patterns.

[Learn More About 3D Printing in Manufacturing](#)

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