CHAPTER 9

Moving to Metal

It is possible to 3D print in metal starting with a powder that is fused (*sintered*) by a laser or glued with a binder. As of this writing, this remains a very expensive process, and these are not desktop consumer printers. However, there are ways to move from a 3D print in plastic to a cast metal object relatively cheaply. 3D printing can make traditional prototyping processes faster and more efficient.

This chapter goes through the highlights of two common techniques for casting metal parts: sand casting and lost-wax investment casting. The intent here is not to teach you how to do metal casting; you will need more than a book chapter for that. However, if you learn about the process and the issues that arise during casting, it will give you some ideas about how to create a print that will cast successfully. The end of the chapter goes over some techniques to create prints that are more likely to work well, and looks at the tradeoffs between direct metal printing versus printing in plastic and then using traditional casting.

The Sand-Cast Process

The sand-casting process is very old, and its origins are lost in antiquity. It is still used today in many applications, from one-off casts through mass manufacturing. In brief, one creates a *pattern* in some material such as wood, clay, or wax (and in this chapter, PLA). The pattern is a positive mold of what you want to cast in metal. Then sand infused with a binder is packed around the pattern. Channels for pouring molten metal are carved to the pattern, and the pattern is extracted. Molten metal is then poured into the empty space where the pattern was, and the final metal piece is extracted from the sand when it is cool enough.

In this section we will sand cast several pieces you have seen in previous chapters: the Leopoly bear, printed in halves without support (refer to Figures 4-8, 5-3 through 5-5, and 8-25 through 8-30); the simple heart pendant (Figure 4-2 and the first example in Chapter 8); and a model of a classic boat that you will hear a lot more about in Chapter 12's discussion about using 3D printing to teach history. The boat model (Figure 9-1) was created from plans of a classic boat from the Hart Nautical collection of the MIT Museum, and the design is used in this chapter courtesy of the MIT Museum. Diego Porqueras took the plans, recreated the boat in Solidworks, and then printed it in PLA.

Figure 9-1. *William Hand, Jr. historic half-hull boat (see text for credits for this and other uses of the boat in this chapter)*

Foundry artisan Peter Dippell cast all the sample pieces in this chapter. The author would like to thank him for teaching her about the process, casting the samples, and allowing her to photograph it all. The sand used here is a substance called Petrobond, which is more or less regular sand mixed with some oil. It is rather spectacularly messy but holds fairly fine detail well. The process here is at the artisanal level; sand casting is used as an industrial process in many industries. There's no reason, though, that 3D printing can't be used to make small-batch patterns for this type of casting, versus the one-at-a-time process shown here. At the end of the chapter we will discuss the possibilities.

■ **Caution** The material in this chapter is intended to give you an idea about how an experienced artisan can create a metal piece based on your 3D print. It should give you enough information to create a part that will cast well. It is not a do-it-yourself guide to casting, though. You need to know more about safety procedures and equipment, which you should learn directly from an experienced artisan.

Sand-Casting Terminology

Sand casting has its own terminology, which we will use in the rest of this section. Knowing their language may help you communicate with the foundry, so we will start with a glossary of sand-casting terms. There are a lot more terms out there and some usage inconsistencies among industries, but these will get you started:

- *Pattern*: The model (3D printed, in this case) of your final part.
- *Parting compound*: A substance used to keep sand from sticking to the pattern. With the materials used in this example, the parting compound is a powder that is the analog of dusting a pan with flour before baking.
- *Flask*: The metal frame that holds the sand in place around the pattern.
- *Riddle*: A strainer-like device to shake sand over the pattern without lumps.
- *Bench rammer*: A big mallet used to pound down the sand in the flask.
- *Strike-off bar*: A long bar used to smooth the sand across the top of the flask and wipe off any excess.
- *Drawscrew*: A screw threaded a short distance into the pattern, with most of it sticking out. It is used as a temporary handle to lift the pattern out of the sand when it is time to pour in the metal.
- *Basin, sprues, runners, and gates*: The sprues are channels that metal flows through to reach the mold, and also is what the excess metal that winds up solidifying in those channels is called. There is some inconsistency in different fields about how these words are used precisely, but generally the *basin* is the channel where the metal is poured in. Smaller channels that lead right into the mold cavity (where the pattern was) are called *runners.* The point where a runner enters the mold cavity is called a *gate.* Sometimes all of this plumbing is just referred to as the *sprues.* The metal parts that harden in the channels are typically called *sprues*, too.
- *Draft*: Introducing a slight taper on some surfaces to make a cast easier to pop out of the sand.

Patterns Made from PLA

Pieces to be cast are called *patterns*, and we will call them that for the rest of the chapter. The images that follow show the process of sand casting the patterns in Figure 9-2. These pieces were all printed in PLA without any special planning for this process, except for a little bit of gentle hand-sanding for some of the pieces.

Figure 9-2. *The PLA patterns used for the items in this chapter. Note the pins in the bear's lower half*

In Figure 9-3, the boat pattern is on a piece of wood at the bottom of the flask (the ring of metal that will contain the sand) and coated with parting compound. The coating ensures that the pattern will come out of the sand easily later on.

Figure 9-3. *The boat pattern in the flask*

Filling the Flask with Sand

Next the flask needs to be filled up with sand, as shown in Figure 9-4. It's important that the sand lays smoothly on the pattern, so rather than just pile it in, the sand is passed through the riddle. The riddle is essentially a giant, coarse strainer. The sand is mixed with oil in this example—a compound called Petrobond, which is rather expensive given that it is really just oily sand.

Figure 9-4. *Pushing sand (mixed with oil) through the riddle into the flask*

After the initial layer of sand is put in the flask through the riddle, we fill the rest of the flask with a small shovel. Then the sand is pounded down with the bench rammer (Figure 9-5) and the excess pushed off with the strike-off bar (Figure 9-6). Finally, a piece of wood is placed on top, and the whole thing is flipped upside-down (Figure 9-7 before the flip, Figure 9-8 after). The flask always rests on a piece of wood called a *backing board*, so that the sand does not fall out. The oil makes the sand slushy so that it will hold a shape better than you would think possible, unless you grew up making impressive sand castles.

Figure 9-5. *The bench rammer packs the sand around the pattern*

Figure 9-6. *The strike-off bar gets rid of the excess sand in the flask*

Figure 9-7. *Getting ready to flip the flask upside-down*

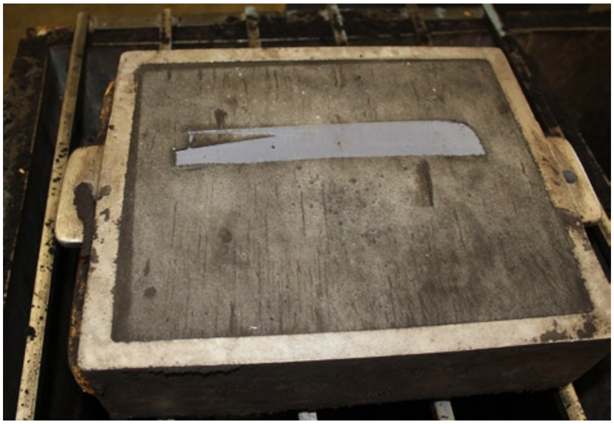

Figure 9-8. *The pattern in the flask after it has been flipped upside-down*

There are many different types of parting compound, depending on the "sand" and other aspects of the process. In this case, a light powder in a bag dusts what was the bottom of the pattern to prepare it for the next steps (Figure 9-9).

Figure 9-9. *Using parting compound on the "bottom" of the pattern*

The half-hull boat pattern we are working with is pretty flat on one side, but we still need to form what will be the bottom of the finished piece. To do that we will add the upper part of the flask and fill it with sand, too (Figure 9-10). The process here is similar to filling up the first part of the flask: running the initial layers through the riddle to make sure the sand touching the pattern is smooth and then filling in the rest with a small shovel and pounding it all down to make it smooth. (3D printer prints made on a consumer printer should almost always have an appropriate large, flat surface anyway to keep them attached to the build platform during the 3D printing part of the process.)

Figure 9-10. *Getting ready to fill in the rest of the flask*

Once the top half of the flask has been filled with sand and pounded down, it will have picked up an impression from what was the bottom of the pattern (Figure 9-11).

Figure 9-11. *The pattern and its impression on the top half of the mold*

Cutting Sprues and Runners

The next step is cutting the basin, sprues, runners, and gates—channels for the hot metal to run through from where the metal enters to the hollow mold cavity where the patterns used to be. In principle, we could have 3D printed the sprues, too, but we did not do that here. We talk about why not later in the chapter. To make the entry-point sprue (sometimes called a gate), we dug out a hole in the top half of the flask. We used a spoon to get things started (Figure 9-12) and then a tapered, hollow tube called a *sprue cutter* (Figure 9-13) to cut a clean, cylindrical hole.

Figure 9-12. *Getting the entry sprue started*

Figure 9-13. *Making a good, clean, circular hole*

Once a basin is set up, it's time to carefully lift off the top part of the flask again, and carve the channels that will take the liquid metal from this entry point into the mold cavity that will be left when we remove the pattern. Sometimes these final channels are called *runners*, or are just referred to as sprues, too. In Figure 9-14 we see the carved-out sprues, which were just created with fingers and spoons in this case. The runners should be positioned so that they are not inserted at a critical point of the pattern, because they will need to be cut off at that point later on.

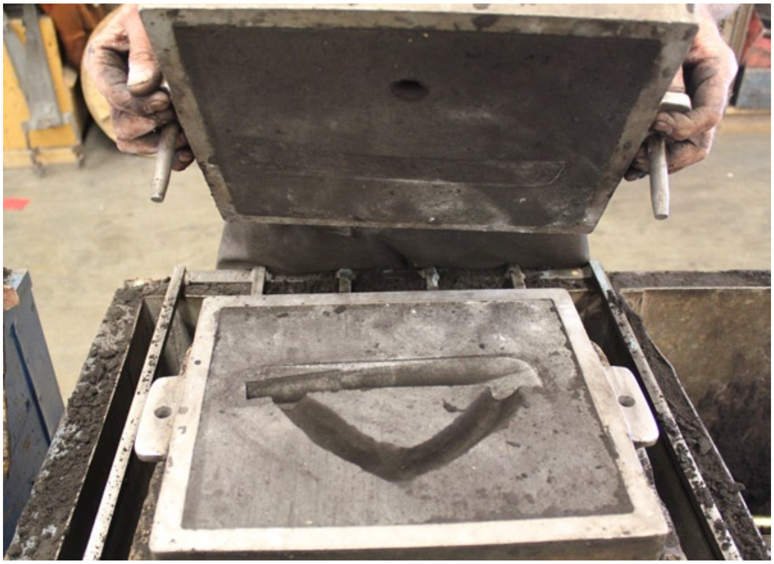

Figure 9-14. *Cutting the rest of the sprues*

This pattern is relatively simple because it has a flat base and no overhangs. (We will see that a lot of the characteristics like a flat bottom and no overhangs that make a 3D print simple translate into the moldmaking world as well.) A more complex print (like the bear) can be done as shown in Figure 9-15. Each half of this pattern has to be pulled out separately, but the initial alignment is done with some small pins on one side and holes on the other.

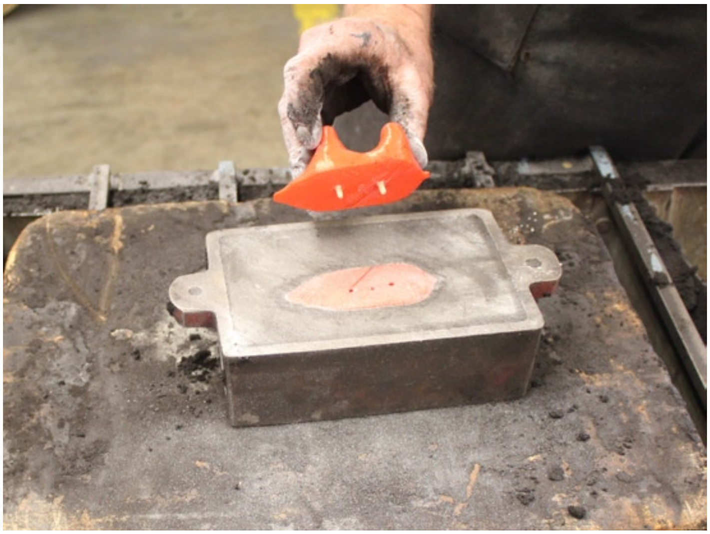

Figure 9-15. *Setting up a part to be cast from a two-piece pattern*

Once these channels are set up, the pattern is carefully removed with the drawscrew. The top of the flask is put back on, and the flask is ready for molten aluminum. The molten metal (here, aluminum) will enter the sand through the sprue we carved out in Figures 9-12 and 9-13 and then continue on through the runners and finally into the hollow created by the pattern (Figure 9-14).

Pouring in the Metal

Aluminum melts at 660 degrees C, so substantial equipment is required just to get it molten and to handle the metal safely. Good protective clothing is a must, too. Pouring in the metal results in a lot of smoke and some flame because some of the oil in the sand burns off in the extreme heat.

Heating up the metal and skimming off undesirable impurities is a process in and of itself. Figure 9-16 shows what this looks like right after the metal pour for two flasks put one on top of the other. (The bottom flask is on a piece of wood; the top one counts on the sand of the flask below it to keep in the sand.)

Figure 9-16. *Two flasks with molten aluminum cooling*

Finishing the Sand Casting

After a few minutes go by, the metal will have cooled enough to take out of the sand. When the flask is opened up again (Figure 9-17), we can see how our boat now has an additional piece—the sprues, which will we will have to cut off later.

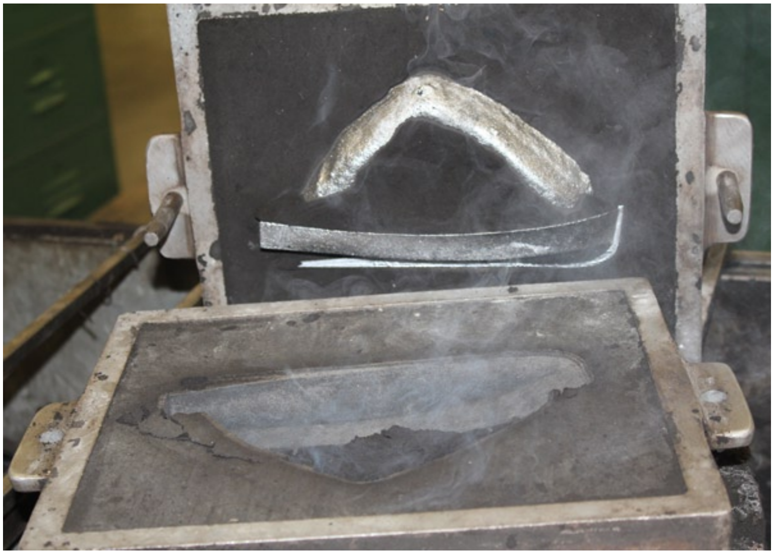

Figure 9-17. *Hot aluminum boat and sprues come out of the mold*

The next step is to pull the piece out of the sand with tongs, shake off the sand, and then wash it off and cool it down further with water. Figure 9-18 provides a better view of the boat and its sprues. In Figure 9-18, you can just see the sprue that went back toward the top of the flask (it's behind the triangular sprue in the foreground). The sprues will be cut off later on with a hacksaw or machine tools after the piece has cooled a little more. You can go back to Figure 9-1 to see what it looks like when the sprues have been cut off and the whole model cleaned up.

Figure 9-18. *The boat and its sprues*

Planning Ahead for Better Casting

The pieces that were cast in this chapter were taken directly from other examples in this book in the interest of end-to-end continuity. However, in practice, if you were printing with an eye to casting the output, you would want to optimize the end-to-end process to have the best possible output. This section looks at a few other pieces we have printed in other chapters of this book to see what the problems would be if we just cast them as-is.

We took the simple heart pendant (Figure 9-19) and Leopoly bear (Figure 9-20) as referenced at the beginning of this chapter and cast them, too. Both of these castings had some issues which could have been prevented with a little planning.

Figure 9-19. *Heart patterns and finished aluminum cast pieces*

Figure 9-20. *The bear, cut in half as in Figure 5-5, in PLA (two pieces) and aluminum (one piece)*

Adding Draft to Patterns

Good pattern-makers use a bit of *draft.* Instead of having vertical surfaces intersect horizontal ones at right angles, surfaces that would have been vertical instead are tapered a bit to facilitate removal from the sand. In this case, it would have helped to have a little bit of draft (just a few degrees) rather than the crisp verticals everywhere. Right angles can be printed by well-made 3D printers, but in sand casting the sand tends to get stuck in corners and edges and result in some imperfections. As you can see in Figure 9-19, the place where the vertical half-heart pokes upward is a little rough at its base because of the sharp edge there in the 3D-printed version.

■ **Tip** Engineering-style CAD programs (like Solidworks) have the ability to add draft to an object. It is difficult to do with beginner programs, however. If you are doing serious work that you want to be able to cast, you may need to step up to one of these more industrial-strength programs.

Avoiding Undercuts

An *undercut* in the mold-making world is the equivalent of an overhang in 3D printing. It is a part of the model that (in this case) would pull out sand when the pattern is pulled out. In Figure 9-20 we can see the bear that we printed in two halves in Chapter 5 (Figure 5-5) cast as one piece. As we saw earlier in Figures 9-2 and 9-15, each of the two halves went into half of the flask, with pins holding together the halves. In this case, there wasn't a lot of care taken during the cutting-in-half process to be sure that there were no overhangs right near the cut (there was—the bear's nose) and also that the pieces printed perfectly (the platform might not have been absolutely flat, or small imperfections could have been introduced in various ways). This resulted in the pieces having some undercuts and some gaps between the model halves at noticeable places, like the nose and tail.

Just as it is difficult for the printer to create an object that does not build up smoothly from the platform, it is hard to sand cast an object that cannot be pulled out of the mold smoothly. If a mold is made up of two pieces, those pieces also have to fit perfectly, with appropriate tolerances. As mentioned in the previous section, higher-end, engineering-oriented CAD programs have tools to separate parts for 3D printing and subsequent casting with the types of considerations noted here.

Layer Orientation

For the most part it will be natural to print an object in the same orientation that you would cast it because, as we saw in the bear example, many of the same considerations apply. However, objects tend to be strongest in the direction perpendicular to the layers, and so an object may pull out of a mold best and be strongest if it is printed at 90 degrees from the orientation in which it would be cast. (In the case of the bear, this would mean printing it on its tail, as we did in the discussion about support in Chapter 8.) This may require more support and thus more scarring of the original 3D print, though, which would require cleanup before or after the casting. This 90-degree layer orientation may also be preferable because the *x/y* resolution of a print is typically much higher than the layer resolution (smoother detail can be produced on side surfaces than on top surfaces), and because the rounding of the edges of the layers creates a very tiny undercut between each layer and the previous one.

Shrinkage and Clearances

Because metal contracts when it cools, your finished cast part will be smaller than your 3D printed part was. Be sure to account for this. You can look up the shrinkage for a particular material (usually stated as a percentage) for your material and plan your 3D printed part a little bigger, if your cast part needs to fit into something else precisely.

Think through *how* precisely parts need to fit together; don't make holes exactly the same size as the objects that need to fit into them. A little experimentation may be required to engineer your process end to end.

■ **Tip** There are some good manufacturing engineering textbooks that might be helpful to get a good structured overview if metal casting and working with metal is new to you. One of the classics of the genre is *DeGarmo's Materials and Processes in Manufacturing* (Wiley, 2011) by DeGarmo, Black, and Khoser, with new editions appearing regularly.

Printing Your Sprues?

Sand-cast patterns traditionally have been carved out of wood or another material that would survive the required number of uses. Because traditional patterns are used multiple times, being able to re-print them isn't as much of an advantage as it is in investment casting. There, the pattern is lost each time (more on that in the next section). However, the sprues and runners need to be re-created each time in sand casting.

With careful thought (to avoid lots of support and other additional work), it might be possible to print these sprues and runners as well. Depending on your comfort with your chosen CAD program and its capabilities, it might or might not be easier for you to figure out how to make an STL file with the appropriate plumbing in addition to your main model. Bear in mind, too, that whoever casts your model will need to extract what you build from the sand, which might get tricky if you also want to avoid support.

It is worth thinking through whether your geometry might lend itself to some process shortcuts such as printing your sprues and runners, and to confer with whoever will be casting your piece about whether some time might be saved by printing some or all of the sprues and runners.

Investment Casting

Sand casting is very versatile, but it is not good for capturing fine detail or for pieces that have complex geometries, such as a sculpture of a person. For that type of work, investment casting, sometimes called lost-wax casting, can be a good fit. With those advantages comes additional complexity. Investment casting has more steps and for high precision can take a lot longer than sand casting. Professional sculptors producing bronze statues typically use investment casting.

There are a lot of variations, but fundamentally the process goes like this:

- A piece is carved in wax. Typically, sprues are also carved in advance and attached to the piece so that there are strategic paths to flow in metal and to allow air to escape.
- This wax piece is then coated with several layers of ceramic or plaster, or alternatively a plaster cast is made around it.
- The plaster or ceramic is allowed to harden.
- The wax is "burned out" (melted away, hence the name, since the pattern is lost each time) leaving the plaster cast.
- The hollow mold is filled with metal.
- The ceramic mold is broken open, and the piece is removed and cleaned up.

One common variation (used for making a copy of an existing sculpture) is to make a mold of the existing sculpture. Then *that* mold is filled with wax, and the process continues as before, starting with creating the sprues.

Obviously lost-wax casting is very laborious, particularly if the wax piece has to be carved over and over. This is where 3D printing has a role.

Lost-PLA Process

Wax has been used for the investment casting process for centuries because it burns out at a relatively low temperature and leaves a clean mold. As it happens, PLA has similar properties. Although the term has not yet entirely caught on, some people in the 3D-printing community have referred to using PLA in place of wax in lost-wax as a "lost-PLA" process. You cannot carve PLA, but you can definitely print multiple molds to melt out. Some moderately priced resin printers use materials that are wax-like.

The sculpture in Figure 9-21 was created by Peter Dippell using a "lost-PLA" process. The story of the piece went like this:

- The subject was scanned with a 3D scanner (Chapter 4).
- This created an STL file (Chapter 5).
- The STL file was then converted into G-code (Chapter 6) and printed in PLA on a consumer-level printer.
- Sprues were added to the PLA piece.
- A plaster cast was poured around the sprued piece, taking care that there were no bubbles in the plaster that would cause imperfections.
- The cast hardened, and the PLA was burned out.
- Molten aluminum was poured into the mold.
- After a bit of cooling time, the cast and aluminum were thrown into a bucket of water.
- The mold was then broken off, and the statue extracted.

Figure 9-21. *An aluminum, investment-cast statue of Rich Cameron (this book's technical reviewer)*

In Figure 9-21 you can still see the 3D-printed layer lines. Whether this is a big problem or a charming reminder of where the piece was "born" is in the eye of the beholder. One can look at it as the "brush strokes" of a new medium! Alternatively the piece could be sanded lightly before casting, or the piece could be polished at this point. However, sanding or polishing risks losing some of the very detail that investment casting seeks to preserve.

Casting vs. Printing in Metal

So, why not just print in metal in the first place? As mentioned earlier, printing in metal is expensive, although some research work is underway to make it less so. The commonest technique is to have a fine powder of metal, sometimes with a binder, and to fuse it via one of several means. Typically the binder (if any) is then removed by heating the part. There is research work at the moment to characterize how strong these materials are, predict when they are likely to fail, and so on. But these techniques are new, and it will take time to understand them fully. Printing metal can also be dangerous. The fine metal particles used in these processes can be abrasive, extremely flammable, and explosive; traditional casting has its own issues, but they are perhaps more obvious.

The advantages of taking a 3D print from a desktop filament printer and casting it traditionally are, first, the cost, and second, that it is a smaller step from existing processes. The second point is also a minus—it *is* a smaller step, and less of a dramatic breakthrough than pure metal printing will be once the issues are worked out. But in the meantime, it is a potentially cost-saving parallel option. You also need to take into account the surface finish smoothness you require and what the minimum-cost method is to achieve that.

Finding Casting Services

If you want to cast a part in metal, search for "metal casting" or "investment casting" and your city name in your favorite search engine. You can also see whether your local community college or high school has a jewelry design program; if it does, the program likely knows of a small-batch casting service or may offer the service for a fee themselves. You can also talk to a shop teacher at your local high school or the people at a makerspace to find an artisan. Visiting a Maker Faire (`www.makerfaire.com`) is probably a good way to network, too.

Professional foundries may or may not be comfortable using PLA in their investment casting workflow because it is not a medium they have used before and they may have evolved proprietary formulations they do not want to change. They may want to do the intermediary step of taking a mold from the 3D print and then burning out their wax as usual.

■ **Tip** If you want to create an STL file and print in metal in the first place, there are service bureaus that will create metal-printed parts for you. You can find a service bureau for printing in metal by searching for "3d printing metal services." Service bureaus that can print metal usually publish *design rules* that explain what they can and cannot do (including material properties, feature size, maximum part size, and so on). Some service bureaus also let you publish your design and let others print it. There are many evolving business models in this space.

Summary

In this chapter you learned about options for taking a 3D-printed part and using it to create a metal one via traditional manufacturing processes. The chapter reviewed the process of sand casting and investment casting so that you know how to create a 3D-printed part to use as the front of the casting process. Finally, we explored how you might find casting services or a service bureau to let you print in metal directly.