TECHNICAL APPLICATION GUIDE

Investment Casting with FDM Patterns

Investment casting produces ferrous and non-ferrous metal parts with excellent surface finish and dimensional accuracy. This manufacturing process is ideal for applications that have relatively low production quantities or rapidly changing product designs.

Since investment casting uses expendable patterns and ceramic shells, it is excellent for complex and detailed part designs. It can produce intricate parts that are difficult, if not impossible, to machine, forge or mold. But this ability comes at a cost. Investment casting patterns are typically injection molded, and when designs are complex, the time and cost to produce tooling increases. The cost of injection molds for wax patterns usually ranges from $3,000 to $30,000. The typical lead-time is one to four weeks.

Substituting FDM patterns for the molded wax patterns eliminates the time and expense incurred with the injection molds while preserving the ability to produce complex metal castings.

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INVESTMENT CASTING WITH FDM PATTERNS

1. Overview

1.1. Application:

FDM may be used to replace any wax pattern for an investment casting application. This replacement eliminates tooling and molding for casting patterns (Figure 1).

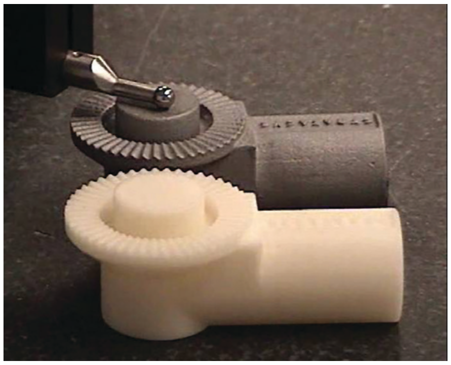

Figure 1: FDM pattern (front) with investment casting of gear set component.

1.2. FDM is a best fit when:

- Low-volume applications (quantity in inverse proportion to part size); typically less than 100 parts.
  - Prototype evaluation or process refinement.
  - Bridge-to-production or short-run production.
- Complex designs:
  - Feature-laden.
  - Internal ports, passages or channels.
  - Organic shapes.
  - Consolidated parts.
    - Multi-piece assemblies combined to create a single part.
- Size:
  - Minimum:
    - Approximately 0.035 in. (0.89 mm) thick when feature is < 0.5 in. (12.7 mm) long.
    - Approximately 0.125 in. (3.18 mm) thick when feature is > 0.5 in. (12.7 mm) long.
  - Maximum:
    - Limited only by foundry capacity; specifically the chamber of the flash furnace or the volume of the crucible.
- **Note**

  FDM is NOT recommended for small, fine-featured

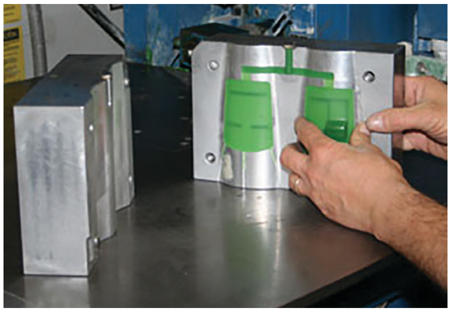

Figure 2: Injection molds create wax patterns for casting.

2. Traditional Process Overview

2.1. The steps in the traditional investment casting process are:

2.1.1. NC machine an injection mold.

2.1.2. Mold wax patterns. (Figure 2)

2.1.3. Build casting tree.

2.1.4. Make ceramic shell.

2.1.5. De-wax using autoclave.

2.1.6. Pour metal. (Figure 3)

Figure 3: Pouring molten metal into ceramic shell.

2.1.7. Break shell (knock out).

2.1.8. Remove gates.

2.1.9. Finish to specification. (Figure 4)

Figure 4: Finished castings.

2.2. FDM Adjustments

To incorporate FDM tooling into the investment casting process, adjustments, alterations and substitutions are made to the following steps:

2.2.1. Pattern-making.

FDM replaces wax patterns and eliminates injection mold.

2.2.2. Casting tree.

Add vents to promote airflow.

2.2.3. Ceramic shell.

Shell thickness increased.

2.2.4. Burnout.

High-temperature, long-duration furnace cycle followed by ashell wash is substituted for autoclave de-waxing.

3. File Preparation

3.1. Create CAD model.

Pattern designs for traditional processes may be used. Design modifications are unnecessary. As with traditional patterns, compensate for the investment casting process in the design.

3.1.1. Casting compensation.

3.1.1.1. Add machine stock.

Typically 0.020 in. to 0.030 in. (0.5 mm to 0.8 mm), the allowance is dictated by design and foundry specifications.

3.1.1.2. Apply shrinkage compensation.

Increase the size of the CAD model by the alloy-dependent compensation factor, which is typically between 0.007 in./in. and 0.020 in./in. (0.007 – 0.020 mm/mm).

Note that this compensation may also be applied to the STL file when processing it in Insight (see section 3.2).

3.1.2. Design modifications (optional).

3.1.2.1. Eliminate draft angles.

Since injection molding is eliminated, draft angles are unnecessary.

3.1.2.2. Add gates and vents.

FDM patterns may be constructed with integrated gates and vents. Doing so eliminates the process steps for making and attaching them before constructing the casting tree.

Modifications may be necessary. See discussion of gating and venting in section 6.1.1.

3.1.3. Export STL file.

After completing the pattern design, export the CAD model as an STL file. Ensure that settings, such as chord height, deviation and angle, will produce a fine mesh (small facets). This will minimize post processing efforts and preserve accuracy.

3.2. Prepare for FDM build.

Import the STL file into Insight and follow the standard workflow for job processing.

The key alteration when constructing FDM patterns is to use a sparse fill. This build style reduces the volume of material in the pattern, which prevents shell damage and minimizes residual ash in the burnout process. Ceramic shells have a very low coefficient of thermal expansion, so pattern expansion during burnout may cause the shell to crack. Also, FDM materials do not melt like wax, so they leave a small amount of ash (0.021%) in the shell cavity.

Equally important is the selection of part orientation and slice height. Both affect surface finish and feature resolution, which will be replicated in the metal casting.

3.2.1. Orient STL file. (Figure 5)

Orient the file for the best surface quality and feature definition.

3.2.2. Select Slice height. (Modeler setup > Configure modeler)

Use the smallest Slice height that is reasonable with respect to pattern size. Wherever possible, use a Slice height of 0.005 in. (0.13 mm).

Thinner slices produce smoother pattern surfaces. The tip used for thinner slices can also produce smaller toolpaths, which allows for the creation of thinner wall thicknesses (see Figures 6 and 7).

Next, slice the file and proceed to Toolpath > Setup.

3.2.3. Define toolpaths (sparse fill).

All FDM patterns must be constructed with a sparse fill interior style (Figure 8). From Modeler > Setup, select Sparse from the Part interior style menu. This style uses a uni-directional raster fill with wide air gaps surrounded by a perimeter contour.

3.2.3.1. Adjust sparse fill settings.

To promote burnout of the pattern while retaining strength, adjust:

- ***Part interior depth***: The minimum wall thickness for the bounding contours.
- ***Part sparse fill air gap***: The space between the internal rasters.
- ***Part sparse solid layers***: The number of solid layers above and below the layers containing sparse fill.

These settings are accessed through ***Modeler >Setup > Toolpath parameters***.

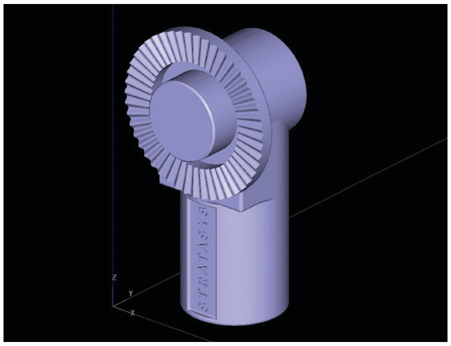

Figure 5: Open STL file in Insight and orient.

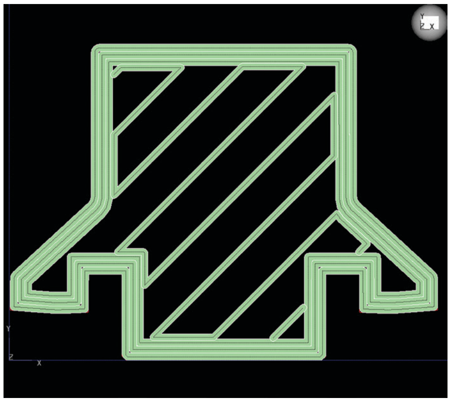

Figure 6: Larger slice heights increase the raster thickness-(0.013 in./0.33 mm) show.

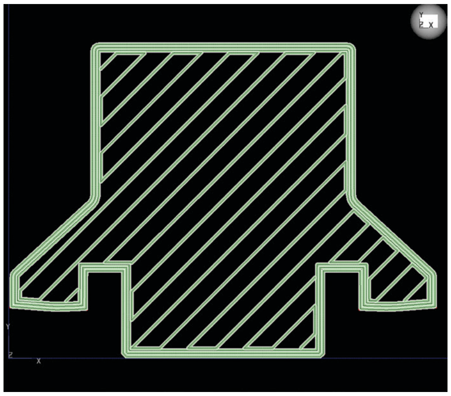

Figure 7: Thinner slices (0.005 in./0.13 mm shown) allow for smaller rasters for finer feature resolution.

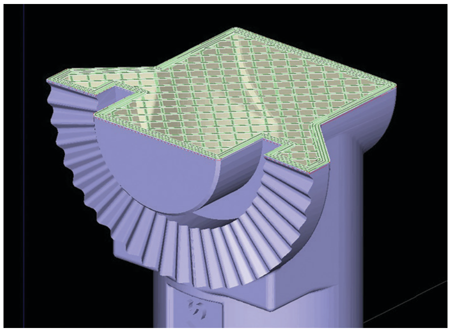

Figure 8: Cross-section showing the internal sparse fill used for FDM patterns.

Note that the settings are Slice height dependent. See Table 1 for specifications, and note that the settings are specified by tip size.

	Part interior depth	Part sparse fill air gap	Part sparse solid layers
T10	0.012 in. (0.30 mm)	0.060 in. (1.52 mm)	3
T12	0.014 in. (0.36 mm)	0.060 in. (1.52 mm)	3
T16	0.020 in. (0.51 mm)	0.10 in. (2.54 mm)	3
T20	0.026 in. (0.66 mm)	0.130 in. (3.30 mm)	3

Table 1: Sparse fill settings by tip size.

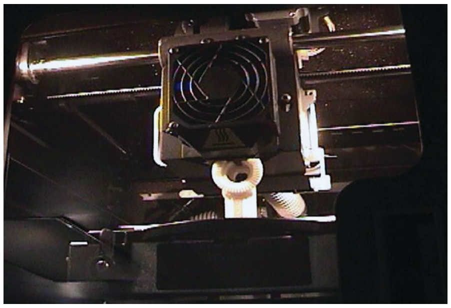

Figure 9: Pattern-making in a Fortus system.

4. Systems And Materials

4.1. FDM systems.

Investment casting patterns may be produced on the full line of FDM machines, including legacy systems and: (Figure 9)

- Fortus
  - 360mc
  - 400mc
  - 900mc
- Dimension
  - 1200
  - Elite
  - uPrint

A thorough review of the pattern surface is necessary. Depending on the geometry, the default sparse style may produce surface openings. Voids will allow the ceramic slurry to penetrate into the pattern. Note: this occurs more often on legacy and Dimension systems.

Review the pattern to ensure that the exterior is void-free, and if needed, adjust the sparse fill settings in Insight or fill any openings manually (see section 5.2.2).

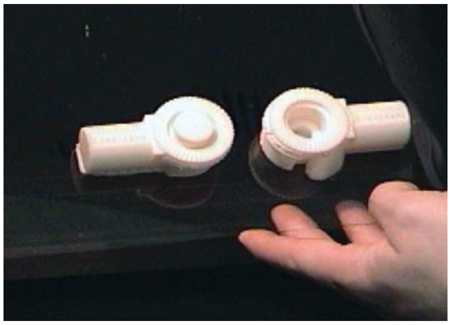

Figure 10: Gear set patterns constructed with ABS-M30 material.

4.2. Material options.

The investment casting process has been successful with the ABS family of FDM materials, including:

- ABS (legacy)
- ABS*plus*
- ABS-M30 (Figure 10)

These materials are recommended for investment casting patterns because they have shown good burnout characteristics. They are also easier to post process due to soluble supports and compatibility with solvent smoothing.

Other FDM materials may be candidates for FDM patterns, but no testing or evaluation has been conducted.

5. Pattern Preparationn

5.1. Remove supports.

Following the construction on an FDM machine, remove supports from the pattern. They may be removed manually or by dissolving in soluble support solution (where applicable). If dissolved, thoroughly wash pattern.

After washing patterns, thoroughly dry them. Moisture within the pattern is not acceptable because it will slow the pattern burn-out process, which increases the possibility of failure from shell cracking. To accelerate the drying process, expose the patterns to well-circulated, hot air. Maintain temperatures below those where the patterns will soften and distort. In the case of ABS-M30, use a maximum temperature of 158° F (70° C).

Figure 11: Finishing Touch Smoothing Station seals and smooths patterns in a few seconds.

5.2. Prepare surfaces.

The surface finish of a pattern will be replicated in the ceramic shell and transferred to the metal casting. So, it is important to smooth the surfaces of the patterns to the desired finish level.

Also, the surfaces must be sealed to prevent ceramic slurry from entering the pattern.

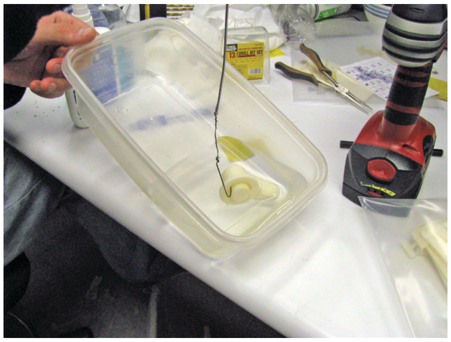

Figure 12: Solvent dipping is an alternative for sealing and smoothing.

5.2.1. Smooth surfaces to desired finish.

If available, use the Finishing Touch Smoothing Station (Figure 11) to prepare the patterns. This is a labor-free process that can be completed in less than five minutes. This process yields a smooth surface finish while preserving dimensional accuracy and protecting delicate features. Also, the pattern's surfaces will be sealed, so step 5.2.2 is not necessary.

Alternatively, apply a solvent to the pattern to smooth and seal the surfaces. These may be brushed onto the pattern, or the pattern can be dipped into them (Figure 12). Limit duration of exposure since the solvent will begin to degrade feature details and dimensional accuracy.

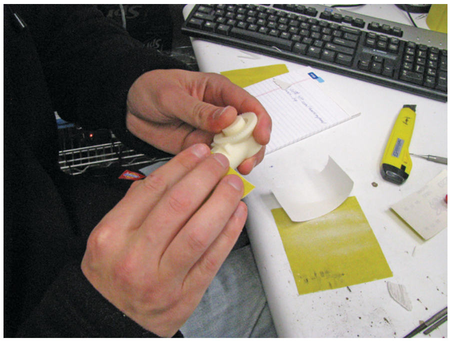

Figure 13: Patterns may be sanded to the desired surface finish and then sealed with filler or foundry wax.

Patterns may also be sanded to the desired finish (Figure 13). To avoid removing too much material, which will make the pattern undersized, sanding may be combined with surface fillers. However, before applying filler material, consult with the foundry to confirm that the material is compatible with the investment casting process.

5.2.2. Seal surface to prevent slurry from penetrating.

For patterns from a Fortus system, sealing is an optional but highly recommended step. Barely visible pin holes in the surface will result in casting defects. For Dimension-made patterns, as well as those from legacy systems, this step is almost mandatory.

As noted above, use of the Smoothing Station or solvents will seal a pattern's surfaces. Likewise, use of fillers should also adequately seal the pattern. If these options are not used, apply a paste wax to all accessible surfaces. As noted with fillers, confirm compatibility with the foundry process before applying.

5.3. Bonding sections.

If constructing a large pattern that exceeds the capacity of the FDM machine, construct it in sections. After building, bond the sections to create the final pattern.

5.3.1. Open mating faces.

Airflow through the pattern is critical for complete burnout without shell cracking. So, the outer face of the bonding surfaces must be opened to expose the underlying sparse fill. Drill several large diameter holes through these faces.

5.3.2. Assemble the sections.

The sections may be joined by solvent bonding (Figure 14) or hot air welding (Figure 15). Alternatives may be used, but consult with the foundry to confirm compatibility.

6. Create Casting Shell

6.1. Build casting tree.

The casting tree and its components (e.g., wax sprue and gates) require no modification. However, the configuration of the gates will change and vents may be added to promote airflow to the FDM pattern and expel gases during burnout.

The goal is to get oxygen to the FDM pattern early in the burnout cycle to promote burning of the pattern and vent gases. To do so, position gates, and size accordingly, to achieve maximum burn. Although not always required for success, the addition of vents is highly recommended. Vents will exhaust gases generated as the FDM pattern burns. They also provide a flow path for oxygen.

6.1.1. Attach wax gates and vents to FDM patterns.

If gates and vents have been incorporated in the FDM pattern, skip this step (6.1.1).

At the attachment point for the gate and vent, expose the underlying sparse fill by drilling through the outer shell (Figures 16 and 17). If the solid surface is left intact, the pattern may expand, which can crack the ceramic shell. Use a large diameter drill bit that is smaller than the profile of the gate or vent. Next, wax-weld the gates and vents to the FDM pattern (Figure 18).

6.1.2. Core packing (optional).

For complex internal cavities that may be difficult

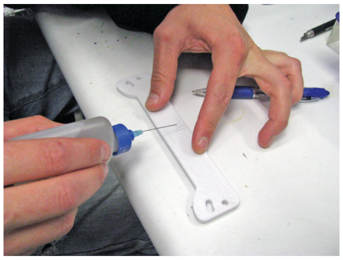

Figure 14: Solvent bonding is one option for joining pieces of a pattern.

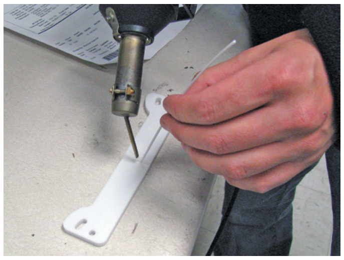

Figure 15: Hot air plastic welding may also be used to bond pieces.

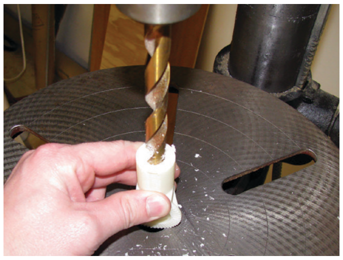

Figure 16: Drill through the outer shell of the pattern at the gate location.

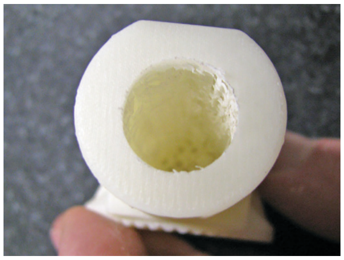

Figure 17: The hole, which will be covered by a wax gate, exposes the sparse fill to high temperatures early in the furnace cycle.

Figure 18: Wax-weld gates and vents to the FDM pattern.

to shell with ceramic, core packing material may be used. See section 8.2 for additional information.

6.1.3. Attach patterns to wax sprue.

Wax-weld FDM patterns to sprue (Figure 19).

Figure 19: Attach the patterns to the sprue to create the casting tree.

6.2. Build ceramic shell.

Using the standard processes of the foundry, build up the ceramic shell around the casting tree. However, make the shell slightly thicker than normal. Although dependent on part configuration and foundry practices, the general recommendation is to add three coats to the standard shell thickness.

6.3. Open vents.

After the ceramic shell has dried, expose the underlying vents. Gently break away (band saw or grinding wheel) the shell material to allow oxygen into the pattern's cavity and to create a path to exhaust gases during the burnout process.

6.4. Burnout casting tree.

To promote complete removal of the FDM patterns and decrease the potential for shell cracking, complete the burnout in two steps.

Figure 20: Begin the burnout process with a de-waxing step (autoclave shown).

6.4.1. Step 1: de-waxing.

So that heat and oxygen can access the sparse interior of the FDM pattern, removal of the tree's wax components is required.

6.4.1.1. Preferred method:

Use a torch to melt out the majority of the wax gates, vents and sprue.

6.4.1.2. Alternate method:

Place the ceramic shell in an autoclave for de-waxing (Figure 20). Use standard duration and temperature. When the cycle is complete, dry the shell completely before proceeding to step 2.

6.4.2. Step 2: FDM burnout

To burn out the FDM patterns, use of a furnace is required. Choose from the following two options. Note that these options represent suggested starting points for the foundry. Some adjustment may be required.

6.4.2.1. Method 1:

Pre-heat furnace to 1,600° F (870° C).

Place the shell in the pre-heated furnace for approximately four hours. Hold temperature constant.

6.4.2.2. Method 2:

Pre-heat furnace to 1,600° F (870° C).

Place shell in pre-heated furnace and slowly ramp the temperature up to 2,000° F (1,120° C). Hold at this temperature for two to three hours.

Following the furnace cycle, visually inspect for complete burnout. If any pattern material remains, return the shell to the furnace.

6.5. Wash shell.

Evacuate all residual ash from within the shell using a forceful stream of water. If allowed to remain in the shell, the investment castings will have inclusions.

Combine streaming water with agitation to remove ash (Figure 21). When the water runs clear, visually inspect shell to confirm that all residual material has been removed.

6.6. Plug vents.

The final step before casting is to plug the vent holes in the shell that were opened to aid the burnout process. Using shell patching material, seal these areas so that the shell will hold the molten alloy.

Figure 21: Thoroughly wash the shell to remove all residual ash.

Figure 22: Pre-heat ceramic shell prior to pouring metal.

7. Casting

Complete the balance of the investment casting process as usual. This includes:

- Pre-heating shell (Figure 22).
- Casting metal alloy (Figure 23).
- Removing (knock out) shell.
- Cutting off gates (Figure 24).
- Machining.
- Heat treating.

Figure 23: Cast metal into shell.

8. Tools & Supplies

8.1. Required items.

None. Beyond the tools and supplies for the standard process, nothing is required.

8.2. Optional items.

- Core packing material.
  - Ransom and Randolph, 50/50 core mix.
    - Available globally at: www.ransom-randolph.com.
- Sealing and bonding.
  - Solvents (MEK, Acetone, Micro-Mark's SAME STUFF, Weld-On

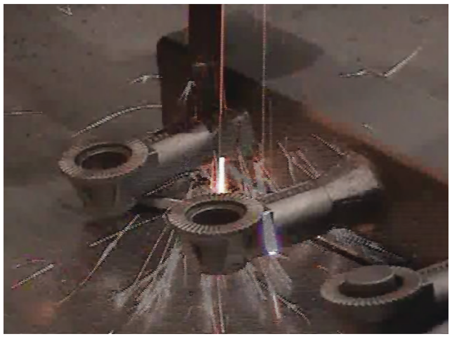

Figure 24: Cut off gates from cast parts.

#3 or similar). (Figure 25)
- Finishing Touch Smoothing Station. (Figure 26)
- Hot air welding tool.

• Sources:
- Hobby and industrial supply
- Stratasys resellers.

9. Recap - Critical Success Factors

9.1. Pattern:

• Sparse fill.

• Seal surfaces (no voids).

• Dry.

• Expose sparse interior.
- Open pattern where gates and vents attach

9.2. Ceramic shell:

• Generous venting.

• Thicker shell (additional coats).

• Core packing material.
- In complex internal structures.

9.3. Burnout:

• Controlled burnout cycle.

• Thorough shell washing.

Figure 25: Micro-Mark's SAME STUFF solvent.

Figure 26: Finishing Touch Smoothing Station.

Figure 27: Gear set castings produced from FDM patterns.

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