TECHNICAL APPLICATION GUIDE:

FDM SACRIFICIAL CORES AND MANDRELS FOR COMPOSITE LAYUPS

Stratasys® 3D Printers and Production Systems

Hollow composite parts present a unique manufacturing challenge. Straight-pull tube shapes and straight-walled cavities are easily addressed, but configurations that trap a mandrel need an alternative solution.

Possible options include extractable cores, soluble cores, two-piece layups, layups within a closed clamshell mold, and clamshell molds combined with extractable cores. However, these choices are not often ideal.

Sacrificial cores made of eutectic salt, ceramic, urethane or memory bladders require additional tooling, which increases time and cost. Puzzle-like extractable cores are reusable and do not require tooling, but severely limit geometry. Two-piece layups are followed by a bonding step that leaves a seam, which may weaken the part. The best alternative is to press the composite material into the cavity of a closed clamshell mold, but this option is only available if there is easy access to the cavity.

FDM® sacrificial, soluble cores are a more efficient and cost-effective approach for accurate, seamless parts and high-quality, internal surface finishes. Simply wrap composite materials on a soluble core and dissolve the core after the resin has cured. This approach makes one-day delivery possible and design revisions practical. Wrapping composite around a core, versus pressing it into a cavity, makes the process simpler and less labor intensive, while eliminating the need for tooling.

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Figure 1: Composite brake duct manufactured from soluble FDM core.

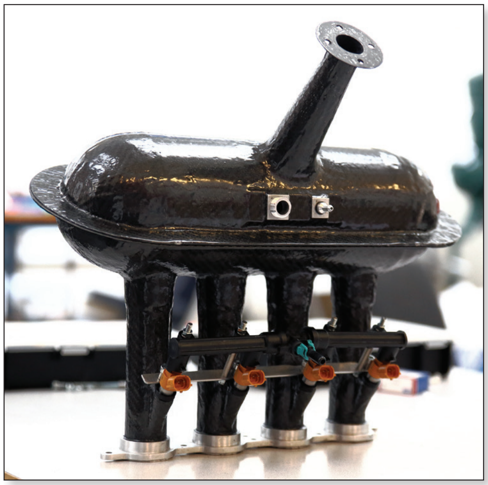


Figure 2: Soluble core eliminated all tooling for this manifold.

Application compatibility:

(0 – N/A, 1 – Low, 5 – High)

FDM: Idea (NA), Design (NA), Production (5)

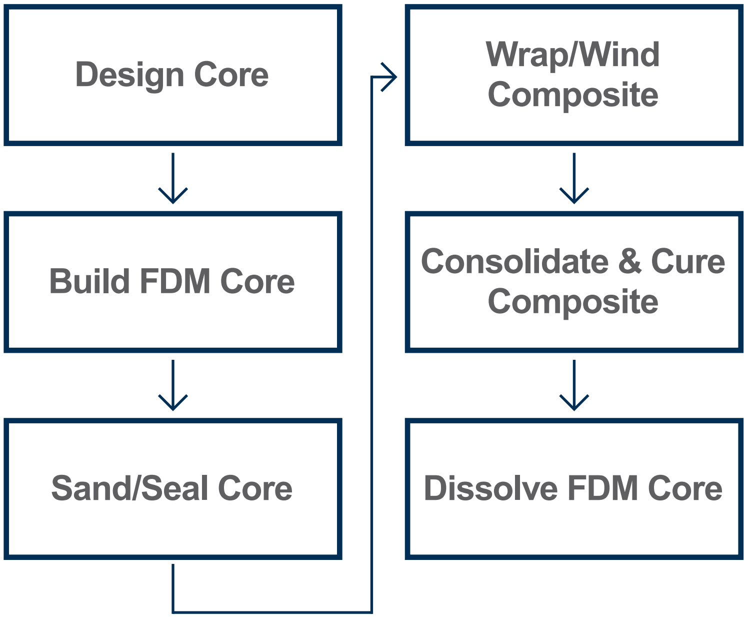
PolyJet™: Design (NA), Production (0)

Companion and reference materials:

- Technical application guide
  - Document
- Application brief
  - Document
- Videos
  - Commercial
  - Success story
  - How it's used
- Case study
  - Champion Motorsport
- Referenced processes
  - Best Practice: CAD to STL
  - Best Practice: Removing Soluble Supports
  - Best Practice: Orienting for Strength, Speed, or Surface Finish
  - Best Practice: Sectioning an Oversized Part
  - Best Practice: Bonding
  - Best Practice: Media Blasting
  - Best Practice: Solvent Smoothing

1. PROCESS OVERVIEW

Unlike the traditional process of manufacturing hollow composite components, FDM soluble cores require no tooling. Composite material is simply wrapped around the core and the core is dissolved after the composite is cured.



When control over both internal and external part surfaces is needed, the FDM soluble core may be used in conjunction with a clamshell mold, to improve the quality of the part's exterior.

2. MATERIAL COMPATIBILITY

2.1. Composites.

2.1.1. Resin systems.

FDM soluble cores are compatible with most epoxy resin systems. However, the solution that dissolves the core can also attack and weaken certain polyester resins. Consult the resin manufacturer's specifications for compatibility with base solutions, specifically sodium hydroxide.

Figure 3: Envelope bagging is one of the consolidation methods compatible with FDM soluble cores.

2.1.2. Consolidation methods.

FDM soluble cores are compatible with the following consolidation methods:

- Vacuum/autoclave

  This method has been tested up to 105 ˚C (221 ˚F) and 550 kPa (80 psi). Note that these results are geometry and layup dependent.

  – Envelope bagging (Figure 3)

    This is the simplest method for vacuum/autoclave consolidation, but external surface finish and accuracy are not well controlled.

  – Through-bagging with clamshell mold

    The bag passes through a thin-walled core that is then placed in a clamshell mold. This option produces the best interior and exterior surface finishes and uses the least amount of material to produce the core.

- Inflatable bladder with clamshell mold

  Inflatable bladders may be used instead of a pass-through bag. As with the bagging method, the bladder presses the core and composite layup against the walls of a clamshell mold to control external finishes. Unlike pass-through bagging, vacuum and autoclave are not used.

- Shrink tubing

  The simplest of all methods, shrink tubing produces a good finish on external surfaces. It is a low-pressure consolidation method that does not require a vacuum or autoclave.

  For parts with concave surfaces and tight bends, consider alternatives to shrink tubing since it does not conform well to these features. Additionally, shrink tubing requires that all areas of the part fall within the minimum and maximum perimeter allowances. For example, a 50 mm (2 in) diameter shrink tube with a shrink ratio of 2:1 may be used only on composite layups with perimeters that range from 25 to 50 mm (1 to 2 in).

- Shrink tape

  Like shrink tubing, shrink tape is a low-pressure consolidation method that does not require a vacuum or autoclave. Although it offers a better exterior surface finish than vacuum bagging, the composite part will have a spiral pattern.

  An advantage of shrink tape over shrink tubing is that it conforms better in areas with concave surfaces and tight bends. Shrink tape can also conform to geometries with large changes in circumference.

2.1.3. Curing processes:

FDM soluble cores are compatible with the following curing processes:

- Room-temperature cure

  This low-temperature option preserves core strength and minimizes thermal expansion.

- Elevated-temperature cure

  To prevent damage to the soluble core, the maximum curing temperatures are 121 °C (250 °F) for FDM SR-100™ and 93 °C (200 °F) for FDM SR-30™ material.

3. CORE DESIGN

To begin the process, a CAD model of the core is needed. This CAD model represents the hollow area of the composite part.

3.1. Create the core.

Design the core as a solid body if the Insight™ software program will be used to create a sparse interior fill style (Figures 4 and 5).

Alternatively, the core design may be optimized in CAD for strength, build time and material consumption. When using this option, the CAD model should be a hollow structure with internal strengthening members.

3.2. Add attachment features (optional).

For winding processes, the soluble mandrel requires an attachment feature. Add this feature to the mandrel's CAD model.

If the soluble support material lacks the strength needed for mandrel attachment, create the feature as a separate body in the CAD file. In the Insight software program, the attachment feature is added to a custom group that uses the ABS model material while the balance of the mandrel is made with soluble support material (Figure 6).

3.3. Extend core and add trim line.

For open-ended parts, extend the core beyond the part's perimeter to provide extra room for layup and winding. The excess composite material will be trimmed after curing.

Optionally, add a ridge line at the part's perimeter. The ridge serves as a trim line in the cured composite.

3.4. Add permanent features.

For composite parts that will have embedded items, such as internal flow veins, structural components or hard points, the soluble core may include them or have pockets designed to hold them (Figure 7).

If ABS material is suitable for these features, the core may be built with a soluble support body and rigid plastic features. Add the permanent features to the CAD model as separate bodies. In the Insight software, they will be included in a custom group that allows them to be made with ABS material.

For all other permanent features, add pockets to the CAD model that will allow them to be inserted into the soluble core after it has been built. If pockets are not suitable, design the core so that it can be assembled around the permanent features. Note: Aluminum features must not be used since aluminum is not compatible with WaterWorks™ solution, which is used to dissolve the core.

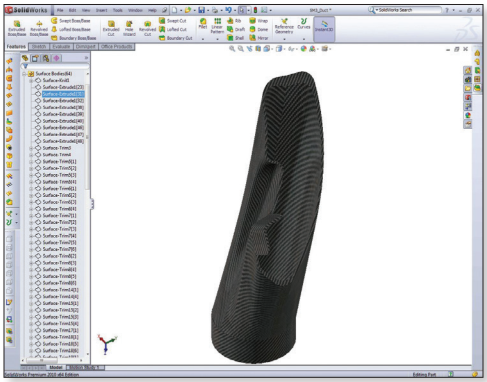


Figure 4: CAD model of the final product (brake duct shown).

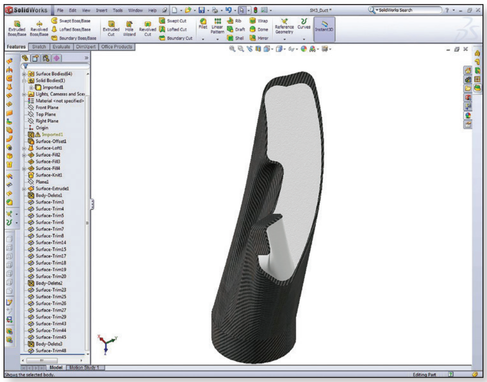


Figure 5: CAD model of brake duct and the soluble core (white).

Figure 6: An ABS feature is integrated into the core for attachment of the mandrel (ABS-M30™ black, and SR-30 white).

Figure 7: Pockets are left for permanent features to be embedded into the core (ABS-M30 black, and SR-30 white).

3.5. Export STL file.

Adjust settings, such as chord height, for the STL file so that small facets are produced. This will create smooth surfaces that require less post-processing of the soluble core. See the *Best Practice: CAD to STL*.

4. FILE PREPARATION

4.1. Orient the STL.

Import the STL file into the Insight software program and orient. There are three considerations when orienting a part: accuracy, surface finish and fluid flow.

If a high level of accuracy or good surface finish is required, the core should be oriented so that critical surfaces are vertical. For example, a cylinder should be oriented so that its centerline is vertical. In many cases, a compromise must be made to have as much of the geometry as possible in the vertical position. For instance, a tube with a 90° bend should be oriented like the letter “V”. The elbow joint itself will suffer from stair-stepping but the majority of the geometry will be at a 45° angle. In addition to providing accuracy, this orientation will also provide the highest strength to handle consolidation pressures.

If dissolving time is most important, the core should be aligned in a way that promotes the best fluid flow through the core.

To do this, align the ends of the core along the Z axis (Figure 8). This orientation promotes fluid flow along the channels formed by the sparse interior fill created in Section 4.4.1. The creation of these pathways accelerates the dissolving process to remove the core from the part (Section 7.4.2). Note: For most core geometries, orienting a part for accuracy also presents a good scenario for fluid flow. See the *Best Practice: Orienting for Strength, Speed, or Surface Finish.*

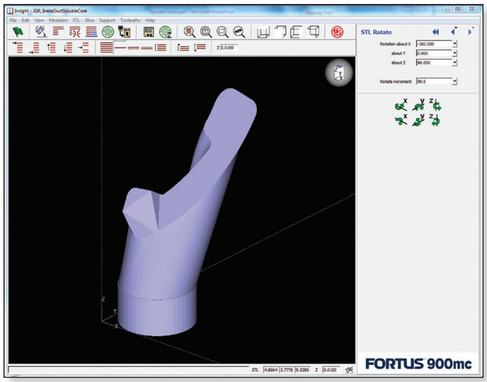


Figure 8: Align the core with its length along the Z axis to promote flow through its sparse fill.

4.2. Slice part.

For most soluble cores, the recommended ***Slice height*** is 0.25 mm (0.010 in) (T16 tip).

Alternatively, a 0.33 mm (0.013 in) ***Slice height*** (T20 tip) may be used. Consider this option when build time is critical and the core has side walls that are perpendicular to the build platen. For example, a thicker slice will have little effect on the surface finish of a straight cylinder, but it will noticeably affect the surface quality of a tube with a 90° bend.

When using a 0.33 mm (0.013 in) slice height, a T20 tip must be inserted into the system’s head (support side) instead of the standard support tip.

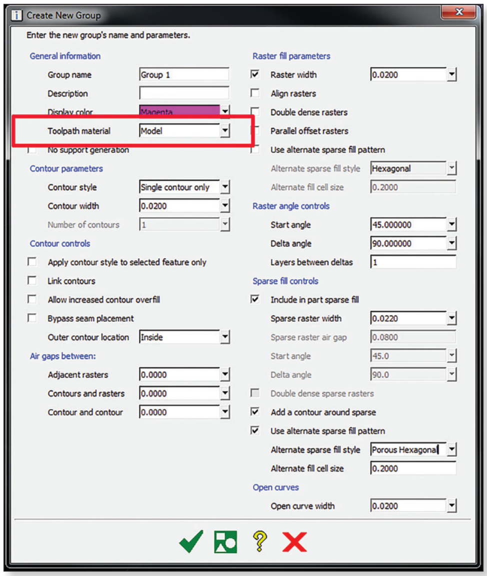


Figure 9: Create a custom group and set Toolpath material to Model for attachment points.

4.3. Create custom groups (optional).

If the soluble core or mandrel will have attachment points or permanent features built with ABS material, custom groups are required. By adding these features to a custom group, the core or mandrel will have both soluble support and ABS elements.

Create a new custom group and select ***Model*** in the ***Toolpath material*** drop down box (Figure 9). Next, add the desired features to the group.

4.4. Define toolpaths.

The goal for toolpath setup is to decrease the amount of material in the core so that it dissolves faster. At the same time, the core must maintain structural integrity while exposed to heat and pressure during composite layup and curing.

To achieve this, the core is constructed with a modified ***Sparse - double dense Part interior style*** (Modeler > Setup… > Part interior style > Sparse - double dense) (Figure 10).

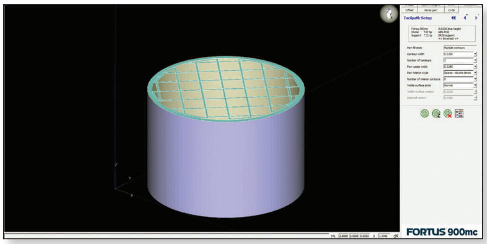


Figure 10: The toolpath uses Sparse – double dense with two or three contours around the perimeter.

4.4.1. Modify toolpath settings.

- Open ***Advance parameters*** (Toolpath > Setup… > Toolpath Parameters).
- Set ***Number of contours*** to 2 or 3 depending on required strength and enable ***Linked contours***.
- Set ***Part sparse fill air gap*** to 6.35 mm (0.25 in) as a general maximum. For most cores, leave the air gap at the default.

  If the air gap is too large, shallow-angle or horizontal surfaces may exhibit “waffling”. If waffling occurs, either decrease the air gap globally or create a custom group for the layers below the surface and decrease the air gap locally. The latter option creates a transition zone between the wide air gap region and the solid layers.
- Set ***Part sparse solid layers*** so that the top and bottom surfaces (“capping layers”) have approximately the same thickness as the side walls.
- If rasters on horizontal surfaces are separating, the ***Raster to raster air gap*** may be decreased to as little as -0.08 mm (-0.003 in).

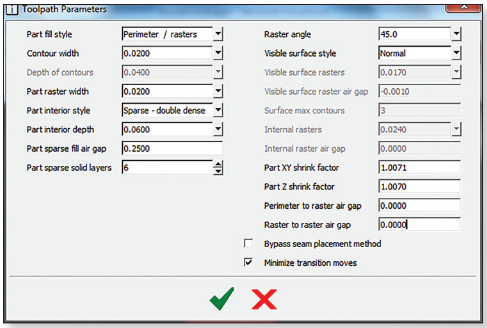


Figure 11: Part sparse fill air gap, Contour width, Number of contours and Part raster can be varied.

4.4.2. Optimize settings.

For the vast majority of composite parts, the toolpath settings in Section 4.4.1 will provide satisfactory results. If desired, these may be adjusted to decrease build time and material consumption or improve strength. In either case, adjustments are made to ***Part sparse fill air gap***, ***Contour width***, ***Number of interior contours*** and ***Part raster width*** (Figure 11).

For faster builds and lower material consumption:

- Increase air gap, decrease contour width or number of contours, and/or decrease raster width.

Caution: Consider the process temperatures and pressures. If adjustments are excessive, the core surface may dip between rasters or the core may collapse.

For greater strength:

- Decrease air gap, increase contour width or number of contours, and/or increase raster width.

  Caution: These adjustments will increase the volume of support material, which will increase the time needed to dissolve the core.

4.4.3. Remove top & bottom surfaces (optional).

Mandrels for tube-type geometries with inlet and outlet faces that are not tooling surfaces should have the capping layers removed to promote fluid flow. Manually remove them after building or eliminate them in the Insight software program prior to building if these surfaces are roughly parallel to the build platform (Figure 12).

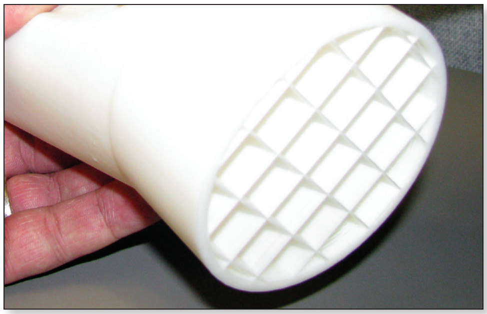


Figure 12: Bottom surface of a soluble mandrel with the cap layers removed (SR-30 white).

To eliminate capping layers, use custom groups.

- Generate all toolpaths.
- Create a custom group for the solid capping layers (Toolpath > Custom groups…).
  - ***Number of contours***: 2 or 3, enable ***Linked contours***.
  - ***Raster to raster air gap***: Set to match current ***Part sparse fill air gap***.
  - Check ***Align rasters***. Check ***Double dense rasters*** box if ***Sparse - double dense*** was used.
  - Ensure that ***Toolpath material*** is set to ***Support***.
    - Note that inverting materials will not invert custom groups. A custom group set to use model material will designate model material regardless if ***Invert build materials*** is enabled.
- Add all capping layers to this custom group.
- Generate toolpaths for this group only. When regenerating all toolpaths it is possible that additional cap layers may be inserted under the custom group that was just created.
- Alternatively, if the geometry does not have any walls with angles greater than 22.5° from vertical, the entire geometry may be added to a custom group with raster air gaps rather than generating sparse fill.

4.4.4. Apply *Alternate sparse fill style* (optional).

For geometries with poor fluid flow through the core that cannot be resolved by orientation, ***Porous Hexagonal*** sparse fill style can be used. This style allows fluid to flow in all directions. Note: This option will increase build time.

- Create a custom group for the sparse fill curves.
  - Check ***Include in part sparse fill***.
  - Check ***Use alternate sparse fill pattern***.
  - Select ***Porous hexagonal*** from the drop down menu.

4.5. Switch model and support materials.

The core is the "model" in FDM terms but it needs to be built with the soluble support material. The following toolpath option causes the model to be built with support material and the support to be built with model material.

- Check ***Invert build materials*** box (Modeler > Setup… > Configure Modeler) (Figure 13).

For a hybrid core in which certain features are to remain model material, a custom group must be used to designate model material for them. In the custom group, change ***Toolpath material*** to ***Model***.

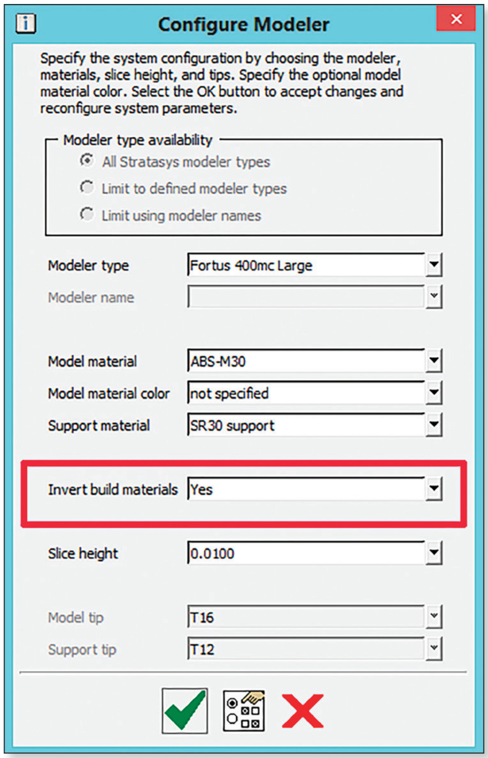


Figure 13: Check the Invert build materials box to make the core from soluble support material.

5. MATERIALS

5.1. Soluble support materials:

SR-30 is recommended for soluble core applications.

- SR-30

  For lower temperature curing below 93 °C (200 °F), SR-30 is capable of producing nearly any geometry and should be used unless higher temperatures are necessary.

- SR-100

  For higher curing temperatures above 121 °C (250 °F), SR-100 may be an option. However, part geometry is limited and guidelines for acceptable part designs are currently not available.

- SR-20™

  This soluble support material offers no advantages and has not been tested, so it is not recommended.

5.2. High temperature alternative

Note: This is not a soluble core method.

For applications that exceed the temperature and strength characteristics of SR materials, cores constructed from ULTEM 9085 resin support offer an alternative.

Rather than dissolving, the core is extracted mechanically after the application of acetone, which makes the material brittle and easy to remove. This option is recommended for resin cure temperatures of 176 °C (350 °F). The use of ULTEM 9085 resin support as a core material requires good access for manual removal of the core after the composite is cured, so this option is geometry-dependent.

Also consider using cores made from ULTEM 9085 resin support material if the composite part includes aluminum inserts. Unlike the dissolving solution for SR materials, acetone will not corrode aluminum.

6. POST-PROCESSING

After building the FDM soluble core, prepare it for the composite layup process.

6.1. Detach support structure.

Because the model material is stronger than the support material used for the core, be especially careful when removing support material in areas where there is a large interface between support and model material.

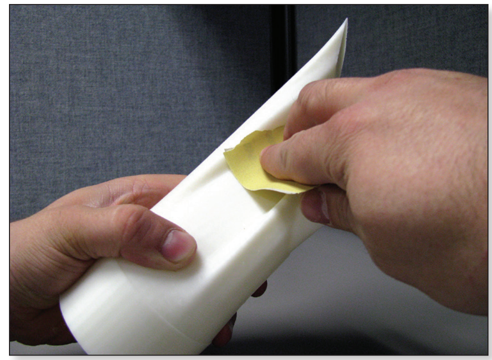


Figure 14: Sand the soluble core to the desired smoothness level.

6.2. Smooth surfaces (optional).

If surface roughness on the interior walls of the part is undesirable, smooth the surfaces of the soluble core. The core may be hand-sanded with 120- to 600-grit sandpaper (Figure 14). Optionally, a grit/soda blaster may be used, loaded with walnut shells or baking soda. See the *Best Practice: Media Blasting*. Alternatively, SR-30 support material may be chemically smoothed in a Finishing Touch® Smoothing Station. See the *Best Practice: Solvent Smoothing*.

6.3. Attach permanent features (optional).

If the core includes features built separately or with non-FDM features, such as mandrel attachment points or embedded hardware, apply cyanoacrylate adhesive in the receiving pocket. Then insert the feature into the soluble core. See the *Best Practice: Bonding*.

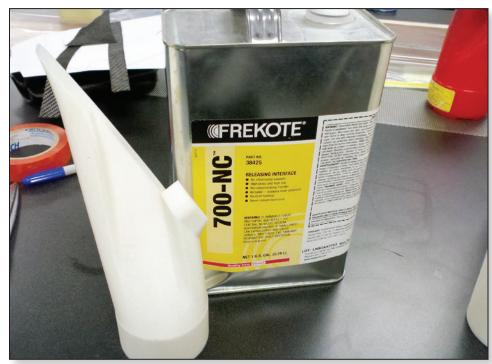


Figure 15: Coat core with a water-based release agent after applying sealant (SR-30 white).

6.4. Seal surfaces.

When composite resin impinges on the surface of the soluble core, it will not dissolve completely. If this happens, the composite part will have an irregular “lining” of undesired material.

Brush or roll sealant on the surface of the core.

Note: If the soluble core contains permanent features (Section 3.4), avoid applying sealant or release agent in the areas that bond with the composite part.

6.4.1. Sealant and release options:

- Composite tool sealant and release agent (Figure 15)
- Mold release wax (as sealant and release)
- Release-coated shrink tape/shrink tubing (as sealant and release)
- Release bagging system (as sealant and release)

Zyvax® QuickSkin® is a high-build sealer that can be applied in coats and sanded to improve surface finish.

Note: A non-water-soluble sealant such as QuickSkin will likely remain in the part after the core is dissolved and must be cleaned away.

Wax provides an adequate seal for low temperature and pressure applications.

The wax, tape, tubing and bagging options will seal the surfaces while acting as the release agent that allows the core to separate from the cured composite.

7. PART PRODUCTION

7.1. Lay up composite.

Perform composite layup or winding (Figure 16). No special considerations are needed for soluble core tooling.

Figure 16: Wrap composite cloth around the core (SR-30 white).

7.2. Consolidate composite.

- Vacuum bagging (Figure 17)

  To minimize wrinkles and seams in the epoxy caused by bag bunching, pull the bag taut and tape its edges to a rigid surface with duct tape. In an ideal case, the only artifact left by the bag will occur where the top and the bottom bags meet.

- Clamshell tooling

  Hollow, thin-walled soluble cores can be used in conjunction with clamshell, open-faced tooling. Outward pressure is exerted on the core, pressing it into the clamshell mold, by running vacuum bagging through the core or by using an inflatable bladder inside of the core.

  Consider using elevated temperatures to soften the core and aid in the transmission of pressure to the composite material.

- Shrink tubing

  Shrink tubing works like shrink tape but comes in a tube/sleeve form and is placed around the layup like a sock.

- Shrink tape

  Wrap shrink tape around the layup. Once applied, heat the tape to apply pressure to the core.

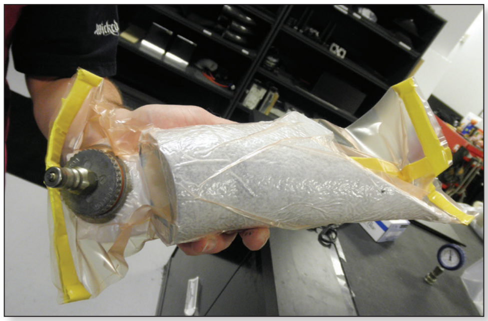


Figure 17: Consolidate composite (vacuum bagging shown).

7.3. Cure composite.

As previously noted, do not exceed a curing temperature of 121 ˚C (250 ˚F) for SR-100 cores or 93 ˚C (200 ˚F) for SR-30 cores. Do not exceed a consolidation pressure of 550 kPa (80 psi).

If using a resin system with a higher cure temperature, use a two-stage approach:

- Perform an initial cure at a lower temperature.

- Remove the core (Section 7.4.2).

Optionally, the core can remain in the layup during post-cure, provided the temperatures do not burn or char the core.

- Complete the cure at the higher temperature.

7.4. Remove core.

7.4.1. Remove capping layers.

If capping layers were not removed in the file preparation (Section 4.4.3), break open the ends of the core to expose the sparse fill structure to the WaterWorks detergent. This accelerates the dissolving cycle. One option is to drill several holes through the capping layer with a large diameter bit.

Next, manually extract as much of the core as possible (optional).

7.4.2. Dissolve core.

Immerse the composite part in a heated, WaterWorks detergent bath (Figure 19). Do not use ultrasonic tanks because they are ineffective at core removal.

To accelerate the process, raise the temperature of the solution bath to the maximum possible temperature if the bath contains only composite-wrapped soluble cores. If other FDM parts are processed in the same bath, limit the temperature to that recommended for FDM model materials to prevent distortion.

Note: Good circulation of the fluid is important. In some circumstances, an auxiliary pump may be needed to increase the rate of circulation. Common configurations that require increased circulation are long, narrow passages and passages with multiple or tight bends. If possible, pump fluid directly into the core using flexible tubing. This can reduce dissolving time by 75% or more.

Monitor the process and remove the part when the core has completely dissolved (Figure 20). Complete the process with a thorough rinsing to remove all of the soluble support solution.

Alternatively, mounting hoses on the ends of the core and circulating the WaterWorks detergent bath through the composite has proven to significantly reduce the required exposure duration when compared to an immersion technique.

7.4.3 ULTEM 9085 resin support core removal.

Squirt acetone on the core until saturated. Then, mechanically remove the core with picks or other suitable tooling.

Figure 18: Cure composite parts below 93 ˚C (200 ˚F) if using SR-30.

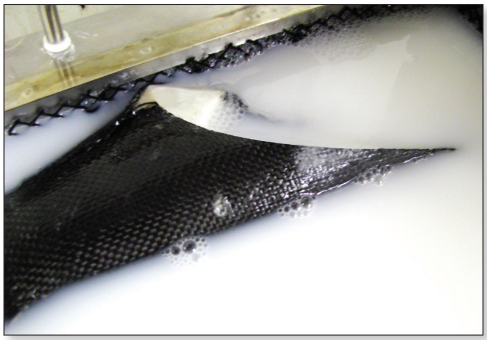


Figure 19: Place part in heated tank and allow core to dissolve (SR-30 white).

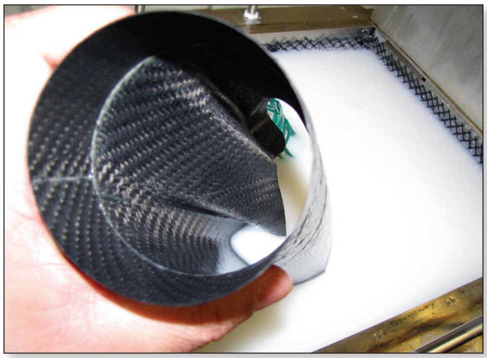


Figure 20: Remove composite part from tank after core has dissolved.

8. KEY PROCESS CONSIDERATIONS

The following table presents common obstacles to implementing FDM sacrificial cores for composite layups and recommended solutions.

Table 1: Common obstacles and resolutions

Obstacle		Resolution				
		Lights-Out Operations	Design for FDM	Process Control	Secondary Processes	Part Orientation
Build Time	Throughput not competitive with machining.	✓	✓	✓		✓
Porosity	Resin wicks into core resulting in poor surface quality and core removal problems.		✓	✓	✓	
Accuracy	Dimensional accuracy does not meet specifications.		✓		✓	✓
Surface Finish	Visible layers and toolpaths result in poor quality part surface.			✓	✓	✓
Material Cost	Raw material cost is too high.		✓	✓		
Material Properties	Core strength does not withstand process temperature or pressures.		✓	✓		

8.1. Resolution details:

- Lights-out operations
  - Increase throughput and efficiency by managing job scheduling to leverage “lights-out,” automated operations.
- Design for FDM
  - Design cores to optimize the FDM process: self-supporting angles, offset surfaces, variable density, material removal and wall thicknesses.
  - Use advanced toolpath settings to seal the core: multiple contours, linked contours, and negative air gaps.
  - Design cores considering build orientation.
  - Design cores to withstand consolidation pressures and curing temperatures.

- Process control
  - Use advanced Insight software program tools for fill styles and custom groups (strength, porosity, material expense and build time).
  - Select appropriate slice heights for feature size, surface finish and build time.
  - Adjust curing temperatures and modify consolidation parameters.
- Secondary processes
  - For surface smoothness: sandable surface sealers (Zyvax QuickSkin).
  - For porosity: epoxy coating or face coating with sealers (Zyvax QuickSkin).
  - For accuracy: secondary machining.
- Part orientation
  - Position part to improve feature accuracy, surface finish and strength.

9. TOOLS & SUPPLIES

9.1. Required items:

- Tools and materials for:
  - Composite layup (Figure 21)
- FDM SR-30, SR-100 or ULTEM 9085 resin support materials
- WaterWorks detergent and heated agitation tank
- Sealer/release agent:
  - Release agent (e.g., Frekote® 700-NC)
  - Release-coated shrink tape (e.g., Dunstone or 3M™)
  - Release-coated shrink tubing (e.g., Soller Composites)
  - Flexible-release bagging system (e.g., Stretchlon®)
  - Sealer: (e.g., Zyvax QuickSkin)

9.2. Sources:

- Frekote: www.henkel.com
- FDM SR-30, SR-100 and soluble solutions: Stratasys.com
- Composite supplies: www.sollercomposites.com
- Bagging systems: www.airtechonline.com

Figure 21: Composite layup materials.

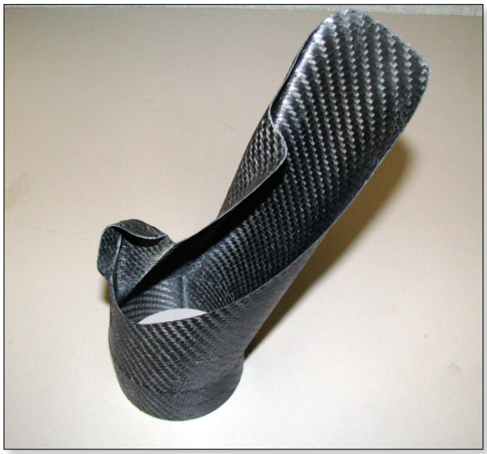


Figure 22: Final product, a composite brake duct, ready for use.

10. RECAP - CRITICAL SUCCESS FACTORS

10.1. Actions:

- Composite material:
  - Compatible resin system and curing cycle
- Soluble core:
  - Sparse - double dense interior fill style
  - Invert build materials
  - Seal surfaces
- Core removal:
  - Thorough application of sealer and/or release agent
  - Heated solution with good circulation

10.2. Eliminate adoption obstacles.

- Material selection:
  - Understand your process to select the right soluble release (SR) material to meet the process specifications.
- Adopt FDM best practices and design for FDM guidelines.

CONTACT:

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