Demand for Composites Continues to Rise

“By 2020, approximately 65 percent of U.S. composites growth by value is expected to be driven by the aerospace, transportation and construction industries.”

—Composites Manufacturing Magazine, 2015
Expense of Composite Processing
Where Do Manufacturers Spend Their Money

COSTS OF PRIMARY SOLID LAMINATE PART FABRICATION

% OF TOTAL COST

Material: 35%
Kitting: 5%
Layup: 20%
Cure: 5%
Milling: 20%
NDI: 9%
Finish/Post-Ops: 4%
Recurring QA: 2%
Expense of Composite Machining
Trim & Drill of Aerospace Composites

High production costs and expenses associated with:
• Initial tooling (part holder fixtures)
• Storing/maintaining large fixtures
• Frequent, regular replacement of worn cutting tools
• Machine maintenance/down time
• Scrapped parts

Plus increasing volume demands, tight tolerances, advanced materials…

The commercial aerospace industry wants to drive costs down!
Many of the “standard” tool geometries used throughout the cutting industry are utilized in trim & drill of composites, such as:

- Drills
- End Mills
- Routers
- Countersink bits
- Abrasive cutoff wheels
- Hole Reamers
## Current Solutions

Specialized Cutting Geometries for Composite Laminates

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>WHAT IT IS / WHAT IT CAN AFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Double Helix</strong></td>
<td>Two opposed helixes to create compressive force on laminate</td>
</tr>
<tr>
<td>a.k.a. Compression Router</td>
<td>• Axial force on laminate top &amp; bottom surfaces (compressive in Z direction)</td>
</tr>
<tr>
<td></td>
<td>• Cutting forces (compressive toward laminate, X and Y directions)</td>
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<tr>
<td></td>
<td>• Tool entry/exit forces of tool (smoother than other cutters')</td>
</tr>
<tr>
<td><strong>Grooved Tooth</strong></td>
<td>Creates small helix angle on each tooth by adding small nicks</td>
</tr>
<tr>
<td>a.k.a. Nicked Router</td>
<td>• Axial force (reduces to approximately null)</td>
</tr>
<tr>
<td></td>
<td>• Cutting forces (reduces fluctuation of feed and normal cutting forces due to helix; tensile force away laminate in Y direction, likely due to increased cutter/laminate abrasion)</td>
</tr>
<tr>
<td></td>
<td>• Noise of cut (reduced)</td>
</tr>
<tr>
<td><strong>Burr Router</strong></td>
<td>Opposing spirals ground into tool body, simultaneous pull/shear cuts fibers cleanly</td>
</tr>
<tr>
<td></td>
<td>• Have been used at relatively high speed/feed rates</td>
</tr>
<tr>
<td></td>
<td>• Uneven number of up/down spirals → overlapping cuts, clean surface cut</td>
</tr>
<tr>
<td></td>
<td>• Can cut honeycomb core sandwich panels</td>
</tr>
<tr>
<td></td>
<td>• Possible disadvantages: premature cutting tips fracturing, easily clogged</td>
</tr>
</tbody>
</table>

(...these are just some examples, there are many more!)
Current Solutions
Conventional Cutting Technologies

- Despite thorough understanding of conventional cutter tools, surface finish and integrity issues common to machining CFRP include:

<table>
<thead>
<tr>
<th>Fiber pull out</th>
<th>Fiber Breakage</th>
<th>Matrix smearing</th>
<th>Delamination</th>
</tr>
</thead>
</table>

![Images of fiber pull out, fiber breakage, matrix smearing, and delamination.](sme.org/smartmfgseries)
## Current Solutions

### Conventional Cutting Technologies

Traditional cutting tool geometries that significantly affect cutter performance in trimming CFRP laminates:

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>WHAT IT CAN AFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake Angle</td>
<td>• Cutting forces</td>
</tr>
<tr>
<td></td>
<td>• Chip formation</td>
</tr>
<tr>
<td></td>
<td>• Quality of machined surfaces &amp; edges</td>
</tr>
<tr>
<td>Clearance Angle</td>
<td>• Cutting forces</td>
</tr>
<tr>
<td></td>
<td>• Bouncing of fibers on clearance face</td>
</tr>
<tr>
<td></td>
<td>• Quality of machined edges</td>
</tr>
<tr>
<td></td>
<td>• Quality of exit hole (drilling)</td>
</tr>
<tr>
<td>Tool Nose Radius</td>
<td>• Chip formation</td>
</tr>
<tr>
<td></td>
<td>• (“Sharp” = nose radius &lt; fiber diameter)</td>
</tr>
<tr>
<td>Helix Angle</td>
<td>• Negligible when laminate thickness &lt; 5% of helix pitch</td>
</tr>
<tr>
<td></td>
<td>• Axial force on laminate (can lead to surface ply delamination)</td>
</tr>
</tbody>
</table>
Current Solutions
Diamond Cutting Tools

- Common applications of diamond in cutting tool technologies:
  - Diamond Coated Carbide (DCC)
  - Abrasive Diamond Grit
  - Polycrystalline Diamond (PCD)

- Diamonds offer long life, high abrasion resistance, and consistent performance when used in machining composites

- Cut primarily through grinding action against the material
Current Solutions

Diamond Cutting Tools

Diamond Coated Carbide (DCC)
- film coating of pure diamond crystals is grown directly on tool surface
- many technologies exist regarding how diamond deposited, coating with multiple layers (CVD, PVD, etc.)
- unlimited geometries possible, can coat complex tool shapes
- increase life significantly compared to uncoated tools of same geometry

Abrasive Diamond Grit
- bonded to the surface of carbide cutting tools via electroplating or brazing
- used with helical, straight, or no-flute geometries

Polycrystalline Diamond (PCD)
- synthetic diamond, made by fusing diamond grit together with metal matrix powder via high heat and pressure
- brazed to carbide tools in separate process; sometimes formed directly as “veins” in carbide tool
- can be re-sharpened
- highest-cost option (usually many times more expensive than a diamond coated tool)
Current Solutions

Diamond Cutting Tools

Cross-section image of CVD coating on carbide tool's cutting edge

sme.org/smartmfgseries
Current Solutions
Diamond Cutting Tools

- Coating delamination from tool substrate is one of the primary wear characteristics observed in industry (rounding of uncoated cutting edge occurs rapidly)
**Current Solutions**

**Diamond Cutting Tools**

- CVD coatings still far behind PCD in overall wear resistance—but can do complex geometries far better than PCD

![Image of diamond coating delamination](image_url)

Above—Diamond coating has delaminated. Cutting edge would round very quickly with continued use.
Current Solutions

Diamond Cutting Tools

Many studies of diamond tool performance have been conducted, confirming its advantages. For example:

• Drill flank wear evolution with the number of holes drilled (graph) illustrated superior wear resistance of diamond tool

• Holes were drilled through Composite/Aluminum stack
  • 7mm thick CFRP
  • 14mm thick Aluminum

• Both drills started with same geometry when new

Diamond coated tools offer longer life, lower cost, better abrasion & slide-wear resistance when used in machining composites (compared to uncoated equivalents)

Expense of Tooling
Trim & Drill of Aerospace Composites

The unit cost of a PCD tool is:

• 3x to 5x that of diamond coated (CVD) equivalent
• 6x to 10x that of non-coated carbide equivalent

Choice of cutter technology should not be solely-based on individual tool unit cost!

A well-known example: Lockheed Martin case study of tool selection for drilling F-35 composite parts

• PCD drill originally specified, production process change led Lockheed to consider alternatives
• National Center for Defense Manufacturing and Machining (NCDMM) asked to evaluate process & solutions
• Complex drill geometries tested, perfected; these new tools then diamond coated via CVD (not possible with PCD)
• The new drill's geometry and diamond coating allowed for huge reductions in cost and process time:

<table>
<thead>
<tr>
<th>Tool Life (# of holes)</th>
<th>Impact of New Diamond Coated Tool on F-35 Drilling Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCD drill 275</td>
<td>Span time 75% Reduction</td>
</tr>
<tr>
<td>Diamond Coated (CVD) drill 1200+</td>
<td>Tool Life (holes per tool) 450% Increase</td>
</tr>
<tr>
<td></td>
<td>Feed Rate 12x Faster</td>
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<tr>
<td></td>
<td>OVERALL TOOLING COST 97% Reduction</td>
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</table>
Current Solutions
Dealing with Constant Change

So why not just use conventional cutting tools (with PCD / diamond coating / etc.)?

• Cutting tools work as intended on some composites—but fail to produce quality cuts on other composites
  • partially due to differences in laminate construction, part geometry, features being cut, fixturing of part, etc.

• Highly-abrasive nature of composite laminates
  • functional solutions still often entail frequent replacement of cutting tool(s), leading to very high cutter costs

• Tool performance is potentially sensitive to the many interacting process parameters

• Changes in a laminate’s construction, design, or materials can mean finding a new cutting solution
  • often happens without warning, must quickly adapt to industry trends
  • as a result, cutter tools require frequent inspections/replacement

• No “one-size-fits-all” answer or approach, especially with traditional machining methods and solid cutting tools
On The Horizon
For Trim & Drill of Composites

• Big leaps through applying new processes/technologies
  • Disruptive technologies could bring major change to how the trim & drill process is approached

Cutting technologies and strategies currently being developed for use in composites industry include:

• Water Jet Cutting
• Laser Cutting
• Robots, robotic arms for use in cutting & fixturing
• Flexible tooling (fixtures), ultrasonic cutting, part location (metrology), etc. …
On The Horizon

Water Jet Cutting
On The Horizon

Water Jet Cutting

Recent industry examples:

- **BMW i3** manufacturing procedure incorporates automated water jet process to cut precise contours and openings in the composite side frame.
On The Horizon

Water Jet Cutting

• AWJ cutting used in manufacturing hundreds of GFRP train doors
  • Clean edges
  • No airborne dust
  • Stack and cut 4 panels simultaneously
On The Horizon
Laser Cutting
On The Horizon

Laser Cutting

- Laser cutting of composites has potential to be high speed, high tolerance process
- YAG, CO2, fiber lasers used (depending on application)
- Can be used to cut preforms (dry fabric) and cured laminates

Advantages:

- Tight tolerances (~0.003"-0.005")
- No cutter tool wear
- Capable of handling complex geometries
- Good for very thin/delicate laminates
- Non-contact nature, work piece requires little clamping
- Smooth edge finishes
- Used for through-cuts and surface ablation (prep for bonding)
On The Horizon
Machine Design
On The Horizon
Incorporating Robotic Arms
Unique Challenges
Still Facing Composites Trim & Drill Industry

• Stack drilling – multiple materials, configuration-dependent, cutter-intensive

• Tolerances achievable

• Capital investment involved in emerging/new technologies (still unproven on industry-wide scale)

• **Constant change** will continue as the composites industry keeps growing, challenge of using new technologies to solve new problems