MOULD TOOLING FOR FIBRE-REINFORCED POLYMER COMPOSITES

A Good Practice Guide

Composites UK Trade Association

NATIONAL COMPOSITES CENTRE

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1. INTRODUCTION

Good mould tooling for composites is intertwined with process selection and critical to manufacturing repeatable and accurate parts. Göte Strindberg, a former technical director at Saab, is reported to have said "Ninety-nine per cent right can be one hundred per cent wrong in a composite manufacturing process" [1] and nowhere does this apply more than in good practice for tooling, where minor faults can lead to expensive failed parts or substantial delays.

Tooling choices are an important part of reducing the environmental impact of parts, potentially reducing energy use and material waste, both in process scrap and failed parts, as well as enabling faster, more cost-effective manufacturing of parts which contribute to our pathway to net zero in transport, renewable energy, construction and other sectors.

Readers new to the subject may find Appendix 1: Glossary & Terminology a useful reference. A basic understanding of composites is assumed in this guide. The Composites UK 'Composite Materials' pages briefly describe what composites are and the materials and processes typically used.[2]

1.1 Scope

This document addresses good practice for designing, specifying, making and maintaining mould tools for the manufacture of composite components. It does not cover cutting tools for the machining of composites. Text and images cannot replace years of experience, but this guide aims to inform, introduce and explain the necessary thought processes and questions to ask when setting up to manufacture composite components, rather than be a comprehensive engineering reference document.

The guide covers tooling design principles, tool materials selection, and tool types for different manufacturing processes, component geometries and part qualities. The focus is on the tools themselves, independent of end use sector application, computer aided design and software, manufacturing processes or component materials.

A composite material is composed of at least two materials, which combine to give properties superior to those of the individual components. This good practice guide refers primarily to fibre-reinforced polymer (FRP) composites, usually with carbon, glass, aramid, basalt, polymer or natural fibres embedded in a polymer matrix, which may be thermoset or thermoplastic.

1.2 What is a mould tool?

Composite manufacture is an *additive* rather than a *subtractive* process. Near net shape components are created by adding sequential layers of materials and creating a part tailored for both shape and function, rather than being machined out of a block of a single substance.

The mould, or tool, defines the shape to layer the material components onto or into. It can also determine the surface finish of visible surfaces, act as the containment vessel for liquid components, the heat transfer medium for curing the materials, as a pressure vessel to resist consolidation forces, and contain indicators and sensors allowing closer control of the manufacturing process.

Composites are materials of choice for many applications based on their lighter weight, corrosion resistance, superior specific stiffness, or freeform shape. To make the composite concept or design a reality and plan for product launch, a good understanding of costs and production methods is necessary to build the best business case.

[1] Grankäll, 'Tooling and processing for efficient and high tolerance prepreg composite manufacturing', Doctoral Thesis in Aerospace Engineering, KTH Royal Institute of Technology, Stockholm, Sweden 2022 https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1657504&dswid=1682

[2] 'Composite Materials', Composites UK https://compositesuk.co.uk/composite-materials/

A tool can range from a cheap disposable means to make a single one-off item, to a robust piece of precision engineering designed to produce thousands of accurately replicated components, reliably and at high rate. Selecting a tooling strategy is arguably the most important consideration when adopting composite materials for a product or component.

1.3 Tooling selection considerations

The first questions to ask are how many parts are needed, how soon, and what budget is available to get the first product to market. Then there is a need to consider whether the tooling and process that made sense for prototyping and market entry still makes sense for larger orders and higher volumes. Will a low volume process be acceptable while product demand ramps up? …or is it necessary to be ready to launch at high rate to a volume market right from the start?

These are questions of technical feasibility vs. commercial feasibility. What is technically possible may not be commercially sensible and vice versa. Both need to be satisfied to create a successful project.

Answering as many of the key questions below before starting to commission or manufacture tooling will go a long way towards the right solution.

- *Where are you starting from and how good is your source data? Are you 'copying' an existing shape, working from a simple concept, or perhaps you already have a set of good 2D engineering drawings? If you have a 3D computer-aided design (CAD) model, what format is it in, how good is it, and will it integrate with other software for design and simulation or machining?*
- *Has the part design been carried out with an understanding of the manufacture of composite materials and components?*
- *Is the aesthetic appearance paramount, or is mechanical performance and functionality the overriding priority?*
- *Will your component/product have one cosmetic 'A' surface and an invisible 'B' side, or need to look good outside and in, or front and back?*
- *Do you require a self-coloured finish out of the mould? Or will it always be painted afterwards?*
- *How important are thickness control and geometric accuracy? Will you need a closed mould process that gives two accurately spaced surfaces, or will a single-sided tool be sufficient?*
- *What process temperature will be required? What is the allowable coefficient of thermal expansion (CTE)?*
- *What are the component materials, and is the tool compatible? E.g. for a phenolic composite part, will the moisture release during cure degrade the tool?*
- *How big is your product? Can you make it in one piece, or will you need to break it down into multiple components?*
- *How complex is the shape? Is it hollow? Will it require inserts or cores? Does it have complex curvature, or must it have ultra-flat surfaces and tight, sharp corners to fit alongside traditional machined elements?*
- *Is the composite component working alongside other materials and systems as part of a more complex assembly? Can you integrate these other functional elements into a single component, or perhaps you require a modular or 'design for disassembly' approach?*
- *Do you have ethical, corporate responsibility, sustainability, environmental, waste efficiency, or carbon footprint goals that need consideration from the outset?*
- *How fast do you need your first part? And what compromises from the list above can you make for speed?*

With any new design or product, the earlier you tie down the answers to these questions, the easier it will be for the composite manufacturing supply chain to give you the costs and timescales you need to plan and finance your launch successfully.

2. TOOLING TYPES AND SPECIFICATION

One of the key factors in the widespread adoption of composites in its traditional market sectors is the ability to set up production relatively quickly and with minimal capital outlay. The discovery of room temperature curing thermoset resins meant that it was possible for almost anyone to copy a shape, make a simple tool, and rapidly replicate that shape in a durable and attractive material. Traditional carpentry skills and the purchase of relatively cheap resins, curing agents and reinforcement fabrics, were enough to get started. These traditional methods survive today, especially in the leisure marine, motorsport and architectural and construction sectors.

Good practice in these techniques produces high quality products, but technology has moved on. New consumables formats, advanced materials, supporting software, sensors and automation, offer tooling methods that allow for quicker time to first part, and more accurate and consistent production quality. Moving away from open mould processes has improved manufacturing health and safety by reducing emissions of volatile organic compounds (VOCs) to the environment. Simulation in digital design and manufacturing techniques are increasingly replacing more traditional skills-based patternmaking.

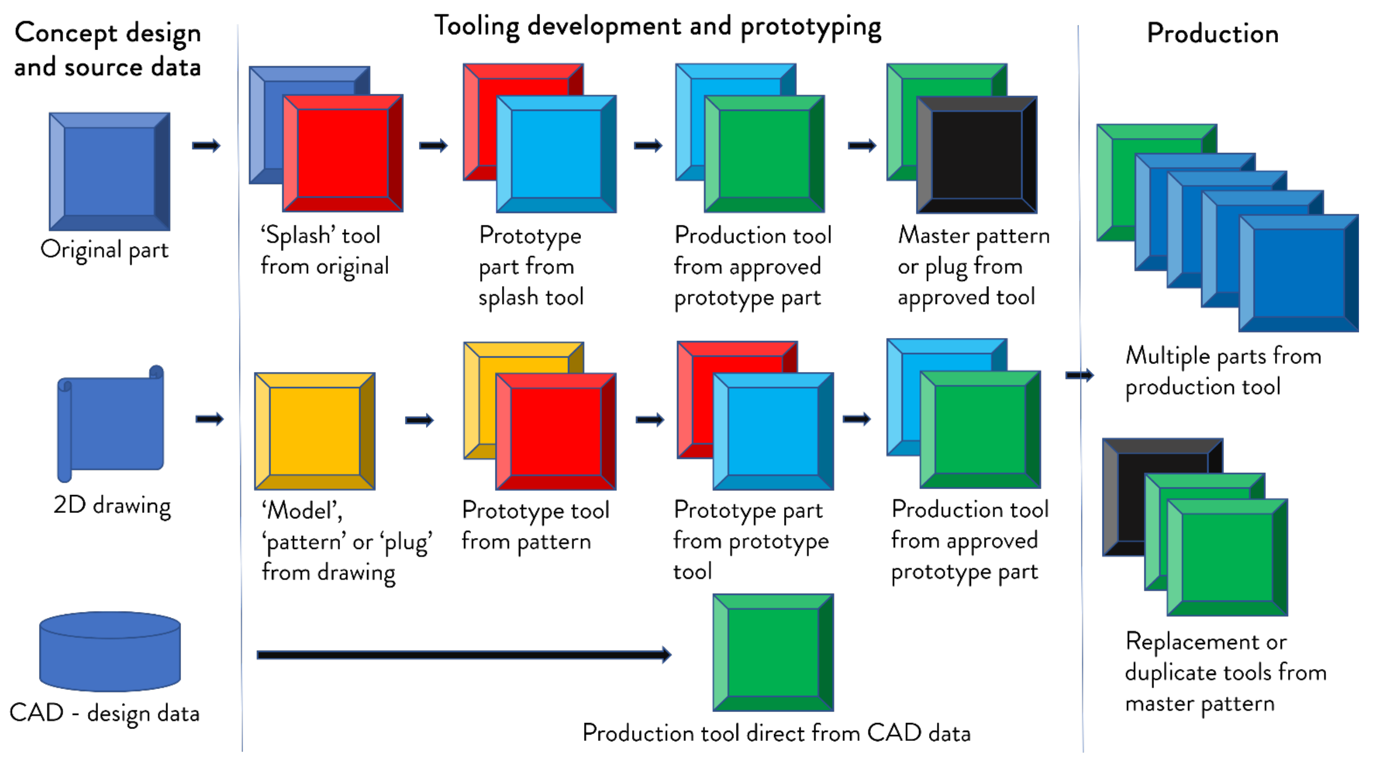


Figure 2.1: Design concept to production parts

2.1 Traditional FRP tool making

'Traditional' FRP composite tooling methodology works back from the final desired design shape, either by copying an original shape, or translating a set of 2D drawings into a full-scale 3D model. The model specifies the dimensions of the components required to realise that product, and the tooling needed to produce and assemble each component into that final shape is made from the model. The model produced from these drawings is called a 'pattern' (or 'plug' or 'model') and used as a 'tool to make the tools'.

Pattern makers use carpentry techniques and typically start with wood (especially jelutong), foam, medium-density fibreboard (MDF) board, clay etc. to make the pattern, adding additional features around the component shape to aid production. Depending on the process being used, additional area can be added around the component pattern for clamping top tools, sealing of vacuum bagging materials, or as additional run-off where excess material can be deposited, and edge defects can be removed.

The pattern is then ‘filled and faired’ using an easily sandable filler to remove imperfections such as cover joints in the woodwork and holes in foam and provide smooth radii in corners. The filler can be used to build up the pattern to just above the correct dimensions, so it can be sanded back close to tolerance, allowing for coating thickness. The pattern is primed, and painted with either a hard enamel, which can be polished to a high gloss, or with a wax containing topcoat, depending on the final finish required, and once again sanded and polished to tolerance. It is always best to achieve the final desired surface finish on the pattern, rather than attempt to sand/polish the tool to achieve it. This means as little work is done on the tool as possible, extending its life.

Figure 2.2: Mould tool for the tail end of a UAV camcopter, being released from male master pattern. The pattern is made from epoxy tooling block with black gloss surface coating. Photo supplied by Toray Advanced Composites, courtesy of Legatec Gmbh

Tools with multiple elements to make a single component are known as split tooling. To make split tooling, the pattern is ‘sectioned’ and tools for each component are taken from the pattern. Allowances are made at each ‘split line’ for assembly flanges, so that different elements of the tool can be joined back together accurately. For large components, such as ship hulls, modular tooling has the advantage of making the different tooling sections easier to handle and manoeuvre. Part geometry that does not allow release from the tool in a single direction will also need to be sectioned.

Once the tool set is complete it is waxed or treated with an appropriate seal and release agent and the first part(s) are produced. Laminating or layup techniques and FRP materials specific to making tools are used to make the tool. These are selected according to the maximum service temperature expected during production, expected durability or service life, or by speed, time and cost to first part constraints.

In traditional series build e.g. for boats, sports cars or caravans, the first part, or first ‘pull’ was fully checked and dimensioned, any minor adjustments made to the tool set, and once a fully acceptable part had been achieved, then a ‘master pattern’ was made from that toolset and put into storage as a physical archive. Subsequently if production tools become damaged beyond repair during service, then replacements could be made from the master pattern as required, rather than going back to square one or taking a splash from a part. This is only usual where the product design is expected to be long-lasting, as there are cost, time and storage space penalties to providing this physical hard copy as a back-up. Nowadays it is much more likely that the ‘master’ will be in digital format.

2.2 Direct tooling

Direct tooling eliminates the need for a pattern and is often used where the design data and part geometry allow for accurate machining of the tool shape straight from CAD i.e. where the data source is digital rather than physical. It is the method used for all metal tools, and for many short-run designs and prototypes. Direct tooling is the preferred method for composite processes using prepreg materials and, as computer-aided design replaces traditional drafting methods, direct tooling by CNC machining is replacing traditional pattern making and becoming the norm rather than the exception in many sectors.

2.2.1 'Soft' tooling

Soft Tooling is used to describe any tools *not* made from metal. Motorsport fabricators typically use easily machined epoxy or polyurethane syntactic foam, known as tooling block or tooling board. Tooling block can be sealed and finished sufficiently to act as a short-run direct tool. High quality tooling board even allows relatively high temperature autoclave cure. It should be noted that tooling block can have a relatively high CTE which needs to be taken into account. (CTE is explained in section 4.3.1.)

Increasingly large tooling such as boat hulls are also directly machined, especially where a male tool is preferred for prepreg. Specialist companies have evolved that have gantry mounted machining heads in large machining bays, with excellent dust extraction. They provide either patterns or tools and machine both male and female hull shapes. For tools, the support framework and substructure are built on a base, clad in a laminate to provide structural integrity to the tool surface, and then a machinable putty is applied. This is machined close to tolerance, and then a tooling topcoat and release system applied and finished. While this route is potentially more expensive, it eliminates the cost of a pattern, reduces opportunities for variance from design tolerances, and speeds up time to first part.

2.2.2 'Hard' tooling

Hard tooling refers mainly to metal tools designed for longevity in production, depending on the industry. In aerospace, an aluminium tool, more rapidly machined for a short-run or prototype part, could be considered a 'soft' tool, in comparison with a 'hard' tool from steel or from Invar. However, hard anodised aluminium tooling can produce significant numbers of parts (>20,000) at high rate in RTM and press moulding processes.

2.3 Digital imaging and 'virtual' tooling

The use of digital techniques can take expertise, time, and state-of-the-art equipment, software, and sometimes significant data storage and processing time on high-speed computers. The cost and time to first part of the digital approach can be off-putting, but enables key decisions to be made without 'cutting metal' or using up materials on multiple prototypes, and should end up producing accurate, 'right first time' tooling.

2.3.1 Shape capture

Digital techniques, such as laser, blue light and 3D visual scanning can be used to accurately dimension and copy existing shapes, to create digital source data that can form an alternative start point to CAD-driven design. For example, a classic car body panel be captured by a portable scanner into a point cloud data set, a surface created from that, cleaned up digitally, then imported and used as the start point for adding the functional design features in CAD.

2.3.2 'Virtual' tooling

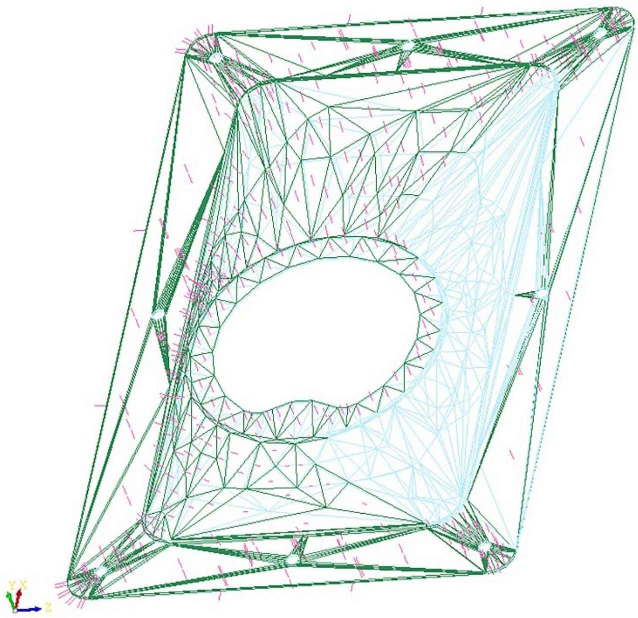
The finalised CAD models, tolerancing and instructions for layup and/or machining the tools make up a 'virtual' tool, i.e., a set of documentation describing the tool and how to build it, which can be stored and moved digitally. In this way the supply chain for manufacturing can be quickly expanded globally, and it is no longer uncommon for this to be the case, especially with less complex and easily machined materials and components.

Case study: Using digital technology and a distributed manufacturing model to significantly improve the tooling procurement process

Kiran Jones, Plyable

Plyable has leveraged AI and machine learning to produce an instant cost and lead time for any tooling project based solely on the final component CAD.

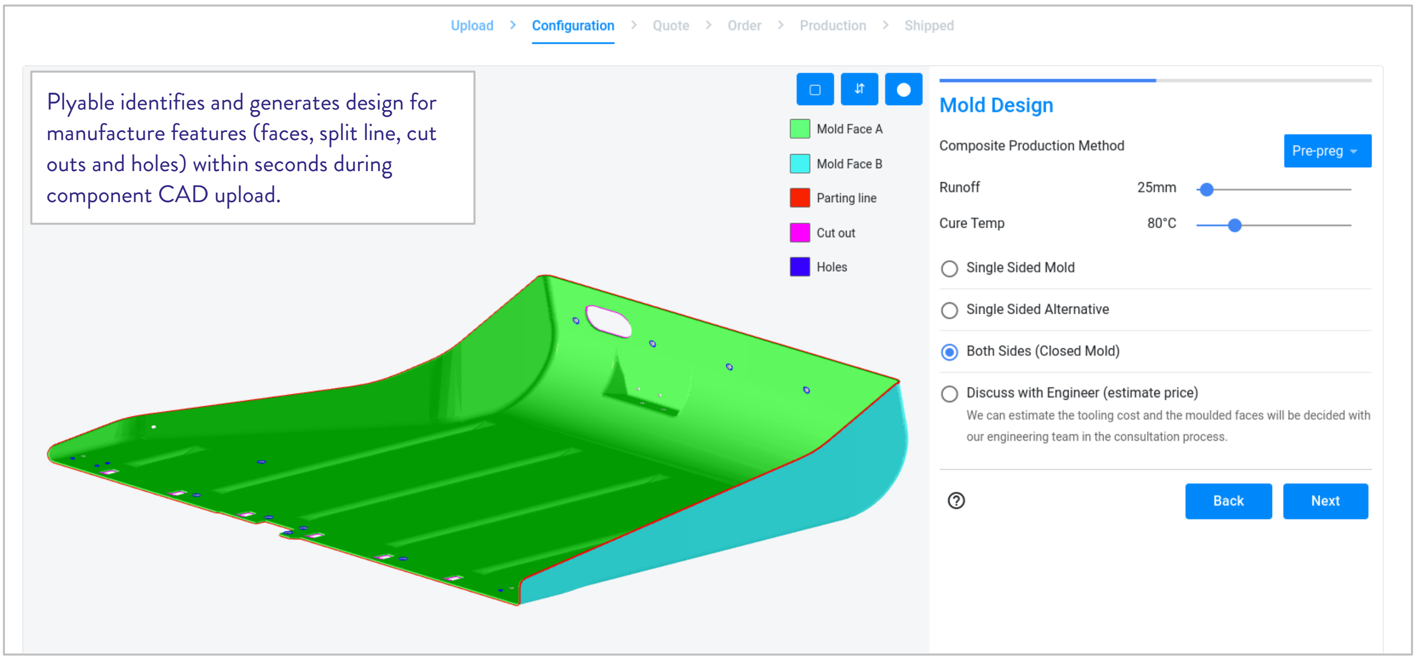
When a user uploads CAD for their composite part, the machine-learning Plyable algorithm finds the ideal mould solutions for its manufacture. The technology can also detect features in the part that need to be considered in the tooling design such as low draft angle, holes and most efficient split line amongst others. This analysis then feeds into a pricing algorithm which calculates for volume of tooling material, complexity of design and network capacity to produce a high-fidelity cost and lead time for the project. This design for manufacture feedback also acts as a starting brief for the tool designer, significantly reducing time and making the design process considerably more efficient with a reduced risk of error.



Visualisation of the Plyable algorithm assigning data points for analysis and meshing on uploaded geometry

Plyable technology works with all types of composite manufacturing process, RTM, prepreg or wet lay as examples. The signed off tool design is distributed via Plyable's manufacturing network, enabling multi-part projects to be built simultaneously, inspected and collated before delivery to the end customer offering valuable time saving. This distributed model allows Plyable to act as a front-end to small machine shops around the world, reducing their sales outreach and enabling their work to reach a wider audience. The RFQ (request for quote) system is also a proprietary platform, enabling manufacturers in the network to both receive their RFQs digitally and to view available upcoming jobs, which assists in levelling out seasonal peaks and troughs.

During 2022 Plyable delivered over 2000 composite tools, jigs and fixtures to 40+ global customers spanning the aerospace, automotive and marine industries, seeing a particular uplift in interest from the relatively new eVTOL industry. Customer GKN Aerospace reported that using Plyable had proved 40% faster and 20% more cost effective than their traditional supply chain.



2.3.3 Digital inspection

Digital imaging techniques can also be used to verify and quality check tools and parts once fabricated. The images can be manipulated to allow viewing of the virtual tools, parts and assemblies on screen, or in 3D via a virtual reality (VR) headset. The user can 'fly through' and zoom in on complex features. The inspector or machinist with the right equipment can now look at the physical tool part and the VR image simultaneously, with discrepancies highlighted with an overlaid tolerance colour spectrum which can be accurate to micron rather than millimetre accuracies.

2.4 Tooling specification

Once the decisions on component geometry and manufacturing process have been set, then tool specification and documentation should ideally include.

- Final part geometry and tool geometry including designed allowances for thermal effects such as CTE and spring back:
  - Essential component functional tolerances e.g. for assembly fit, closures and moving elements.
  - Essential tool functional tolerances – e.g. for component release, mating to other tool fittings, inserts, closures etc.
  - General tolerances – radii, thickness, min/max dimensions for less critical areas
  - Requirement for a co-ordinate measuring machine (CMM) report
  - Surface finish requirements
- Location of production aids within the tool:
  - Trim / scribe lines
  - Injection and witness ports
  - Clamping / closure hard points and x-y-z location hard points, targets for laser-based systems / automation
  - Mounts for drill jigs and assembly aids
  - Seal line rebates, sealing materials, moulded in vacuum couplings / ports
  - Heating / cooling system
  - Pressure, temperature, or dielectric sensor positions
  - Part ejection components
  - Tool identification plates or tags
- Support frames, handling points, provision for press mounting, mobility or safe transport
- Process temperature specifications and tolerances
- Tool materials:
  - Materials quality assurance (QA) or specification verification criteria
  - Supply chain traceability requirements
  - End-of-life options and life cycle assessment (LCA) data for the tooling
- Tool surface treatments and finish specifications, including inspection criteria
- QA acceptance criteria and sign-off method
- Tool design and copyright ownership
- Physical tool and ancillaries ownership, transfer, insurance and handover agreement

Figure 2.3: Portable Measuring Arm Laser Scanner. Photo courtesy of the National Composites Centre

- Documentation, data security, encryption requirements and data transfer protocols
- Export controls

3. TOOLING AS THE KEY TO PROCESS SELECTION

Tooling is inherently linked to process selection, especially in relation to the number and rate of parts to be manufactured. Size, shape and complexity are also limiting in terms of the practical application of different types of tooling, and surface quality from the tool is a critical factor in many applications. Another important question is how soon the first production parts are needed. Tool complexity and material choice affect lead times, as well as cost. Cheaper tooling may be available more quickly, but will not last as long in a fast production cycle.

3.1 Numbers off and rate

The first question determining a tooling strategy is, "How many parts are needed?" This helps to determine a target takt time or cycle time for each part based on the working time available divided by the numbers required.

Short takt times, which for composites means anything under 10 minutes, and high volumes, say above 10,000 p.a., are likely to require high-rate processes. In this case, investment in quality tooling and automation to reduce labour and improve part uniformity might therefore be the right way to go.

Where high production rates are needed process optimisation should be deployed to maximise the use of capital equipment. Examples include smart use of available tool area to make multiple parts from a single pressing, co-curing multiple pieces in a single autoclave or oven cycle, shuttling multiple tools to a press, or setting up to resin inject multiple tools from a single injection machine.

Working with competent supply chain partners and sub-contracting production can significantly reduce time to first part and per part costs, but it may be worthwhile to consider an intermediate rate development stage product on the way to full volume production.

Short-run, or one-off, development products will often require a fast turn-around tooling approach. The tool may need to be modified as designs are improved on, and so cost of repeating tooling must be kept low. Product value and volumes play a part – it will not make sense to spend lots on complex tooling for a set of parts for a short-lived product that will generate only small profits.

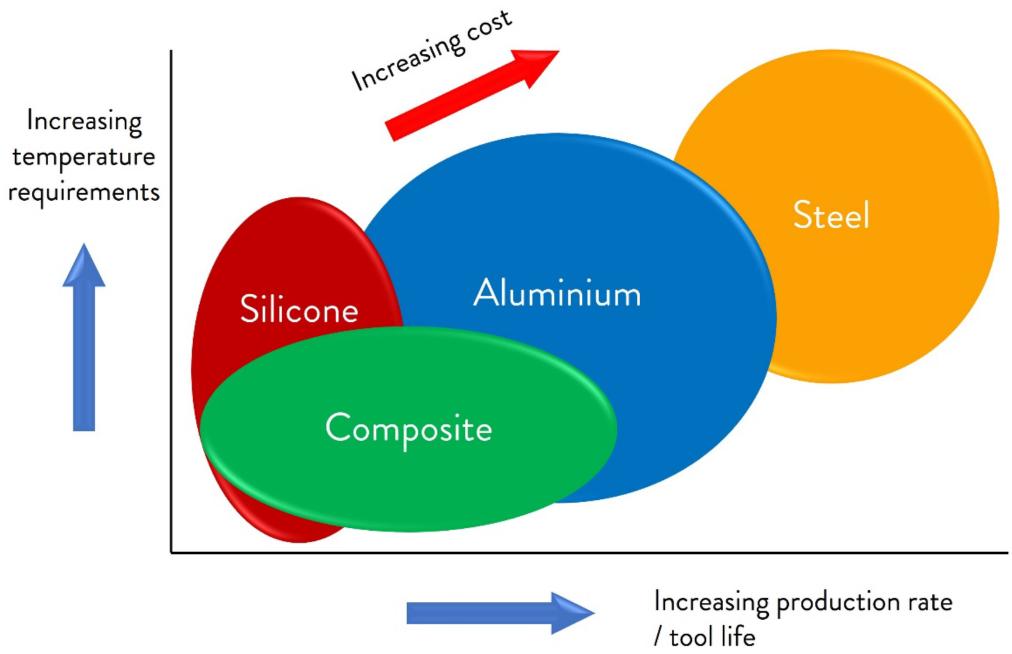


Figure 3.1: Tooling materials: Temperature requirements vs production rate / tool life, with cost trend.
Based on diagram from Composites Integration.

3.2 Rate of process

The chemistry of thermoset resin systems is a major factor in determining timings within the production cycle, with gelcoat cure and resin cure often the rate determining steps. Removing the gelcoat process might be a route to faster production, but adds a paint stage later, creates extra wear and tear on the tool surface, and potentially creates more defect rectification work both before and after painting.

3.2.1 Liquid resin

Time must be allowed for mould preparation and materials layup before the liquid resin enters the tool, wetting time, before gelling stops further flow within a cavity, and time for the resin chemistry to work, the peak exotherm to pass, and the part to harden to at least a 'green strength' sufficient to demould the part, and finally for demoulding, tool cleaning and release system application. It is usually better to allow a part to cure almost fully before demoulding, but some systems might release better when green, then be allowed to cure on, still supported by the tool to keep shape.

Large vacuum-infused components with thick structural laminates, such as boat hulls and wind turbine blades can take upwards of a week to turn around depending on the complexity and thickness of the fibre pack, even though the actual resin infusion step is only a few hours. This can still be faster than hand or spray lamination for very thick parts, which may have to be cured relatively slowly or in several stages or intermediate steps to avoid pre-release.

Open moulded, mid-sized parts with a gelcoat finish and relatively thin structural laminate, e.g. in truck and bus applications, can typically be turned around twice a day in an eight hour shift. Cycling an FRP tool more than twice a day works a soft tool quite hard and puts time constraints on tool cleaning and maintenance turnaround between shifts. Some production set-ups prefer to have duplicate tools and cycle them only once a day, so they stay better prepped and maintained to last longer. This also builds some resilience and flexibility into the system reducing risk of production delays.

A multiple tool, LRTM (light resin transfer moulding) production cell might realistically aim to cycle 4-6 times a day, depending on part size, layup complexity, and manpower. An RTM press tool could have a 10-15 minute cycle time, producing 3 to 6 parts an hour, with the rate determining step often being how fast the fibre preform can be made and laid up into the tool. In this case multiple tools going to a single press might be a good option. Another option to increase rate and press utilisation might be a static bolster tool, permanently mounted in the press, and multiple skin tools, that cycle through the off-press process steps.

3.2.2 Moulding compounds

Thermoset SMC and BMC press moulding cycle times, even for quite complex components are typically 5-7 minutes. These processes also lend themselves well to automation, with the SMC charge or 'blank' automatically cut, and robotically placed in the tool, or the BMC charge robotically dispensed into the tool. Tools and presses that can inject an in-mould coating by partially opening and injecting a liquid into the gap between the just cured part and the tool surface can reduce or eliminate the need for post-paint processes. These processes are best suited to high volume manufacture, producing products such as electrical sockets in the hundreds of thousands per annum very cheaply.

With thermosets, high-pressure resin transfer moulding (HP-RTM) and wet press techniques cycle times can be sub-five minutes. The 'part a minute' or 60 second takt time that would make high-volume automotive 'body in white' production economic in thermoset composites is a clear target for these processes, but it must be borne in mind that the parts produced often replace multi-component assemblies, and process speed should be evaluated in that context.

3.2.3 Thermoplastics

Thermoplastic composites do not require time for reaction chemistry to work but do have to be heated and cooled quickly. Production processes such as injection moulding, injection overmoulding, and stamp forming using reinforced thermoplastic composites have the potential to be faster than those using thermoset resin systems. The rate-determining step and future challenge in developing these processes has now become the accuracy and reliability of robotic preform assembly, rather than the press cycle time.

Figure 3.2: Vacuum bagging for de-bulking plies (usually the first and every third ply depending on material and prepreg resin system) and final consolidation during the autoclave process. Photo courtesy of Pentaxia

3.2.4 Prepreg

For safety-critical, high-performance, applications e.g. in civil aviation and F1, rate of production is considered secondary to guaranteed and fully predictable performance. The materials of choice, carbon/epoxy prepregs require relatively long cure cycles in autoclaves, meaning a part a day per tool is about the rate limit. High-performance applications where prepregs are deployed usually require high pressures to drive out porosity, and high temperature conditioning to cure the high Tg resin systems. With the increasing use of carbon-fibre structural elements in aircraft, and a push for higher production quotas towards 75+ single-aisle aircraft per month, improving production rate with these materials is a high priority for the sector.

In contrast with liquid resin processing techniques, requiring time for a liquid to wet out the reinforcement, flow throughout the mould cavity, and chemically harden, prepregs and other intermediate product formats already contain the resin and reinforcements in the right ratio and intimate contact, and this can potentially help with production rate as well as quality and performance.

Automation of layup using robotic deposition in techniques such as ATL (automatic tape-laying) for tapes or AFP (automatic fibre placement) for narrow tow 'fibres' helps in getting accurate preforms onto big tools more quickly, but cure and quality requirements still generally demand autoclave cure, unless a part is of a size and geometry to be accurately pressed. Out-of-autoclave (OOA) cure prepregs, have improved rapidly in recent years. Better localised heat control and consolidation at the robotic heads may offer a pathway to faster production for some geometries. As robotic techniques develop, fine motor positional control of not just the deposition head, but also the orientation of the tool-face has become part of the challenge. The importance of accurate datum points on tooling, so that the robotic control systems can see and recognise surface features and check and adjust themselves in real-time has become a new factor in designing advanced tooling.

3.3 Component size and handling

Size really does matter. Processes requiring enclosed machinery, like presses, autoclaves, ovens etc. have a tipping point where investment in oversize equipment is just uneconomic. For example, the laws of physics mean that the closure force on a press is proportional to the pressed area, so the cost of equipment ramps up significantly as parts increase in size. Even if simpler processes such as vacuum infusion are used, the area under vacuum will still determine how stiff and bulky the tool needs to be to resist closure forces, and the scale of equipment needed to manipulate those tools in the production environment.

Size of tooling may also determine how a production unit is set up. With large components, such as wind turbine blades, it makes sense to bring all the process equipment to a static tool, but for other scenarios the tools themselves may move between equipment stations around a process loop. In an open moulding process this might be tool prep, gelcoating, kitting or preform assembly, layup, cure, demould and trim, looping back to tool clean and prep, while parts go on to assembly or final finish. The factory layout needs to accommodate this with clear flat passageways, or floor or overhead trackways between stations, and the tools will need to have the necessary wheels, lifting points etc. to assist mobility. The tools may require marking to accurately locate them within each production cell, and perhaps radio-frequency identification (RFID) or bar code scanning to enable tracking of progress through the production cycle.

3.4 Component shape and complexity

There are very few part geometries that are truly un-manufacturable and there is a wide range of options in process and tooling. Simple shapes, such as pipes, beams, and sheets with fixed cross-sections, can be made continuously, through pultrusion dies, continuous sheet forming, braiding and pipe winding etc. and these processes all have very specific tooling requirements. (See section 10.2.)

Composites manufacturing copes very well with double curvature geometries that are difficult to fabricate in metal. It can be better with composites to design a shape with curves and ribbed features that add stiffness and aesthetics, than to make a perfectly flat sheet and put stiffening features onto it later. Many complicated looking pieces can be made from single part tools, e.g. a bus front or rear panel can include rebates for windows, light fittings and moulded-in grills, as well as an aesthetic aerodynamic shape. As soon as return edged flanges are needed, or features that will not release from a single pull direction, then while the component can still be made in a single piece, split tooling will probably be needed. Hollow shapes without a constant cross section may also require split tools, and/or an insert, bag or bladder to provide the necessary internal consolidation pressure during manufacture. Some highly complex shapes, with multiple cavities or internal passages are made using sacrificial tooling inserts. These either stay in place, or are washed, dissolved or melted out once the part is cured. (See sections 4.5.5 for design and 7.6 for materials for bladders and sacrificial tooling.)

It should be noted, however, that complex tooling solutions to manufacture complex parts have an impact on takt time and tooling cost, lifetime and maintenance. Consideration of part design and geometry to reduce tooling complexity and cost is a vital part of the overall tool design process.

3.5 Surface quality and visible surface aspects

In composite manufacture both the aesthetics, the function, and the environmental protection can be built into the surface of a component to some extent, and the best quality parts often have an out of mould finish, one that requires almost no additional work, other than a visual inspection and a wipe down. The surface texture will mirror the texture of the tool. A highly polished tool can provide a high gloss finish, or alternatively the surface could be rough in parts as an anti-slip, or have a specific aesthetic texture.

On the downside, a scratch or defect on the tool will also witness on the part, so another option is to not worry too much about surface finish. Keeping a tool finish consistently perfect between parts, particularly if it is being cycled frequently with manual handling for demoulding, may not be practical for some processes, and the refinishing effort more cost effectively applied later, perhaps even after final assembly. If the part will always need a paint finish or is structural and largely invisible, then a semi-gloss or matt finish may be easier to manage consistently in production.

A popular choice, even where a paint finish will be applied, is to use a primer gelcoat, that gives the structural composite beneath some opacity and ultraviolet (UV) light protection, some protection against knocks, and some depth to play with for sanding and refinish before it starts to abrade the fibre beneath the surface. A primer gel can be neutrally coloured, match the final paint colour, or contrast with the paint colour to visually help the paint sprayer.

A part may have more than one surface aspect with different finish requirements, perhaps an edge that will carry a foil trim, a topside that will be visible and coloured, and a back surface that needs to be touch smooth but can be ‘self-coloured’ as it will not be exposed to light or any potential UV degradation.

Figure 3.3: Epoxy tooling materials provide a high-quality surface finish for carbon fibre composite applications. BE769 epoxy tooling material from Base Materials. Photo courtesy of Base Materials

3.6 Time to first part and capital cost constraints

The world is increasingly looking to virtual concept development, and creating the right images, design, and modelling the various tooling and production options is usually time well spent. However, putting a physical prototype on the table in front of a customer can often be a more powerful way to sell a concept, so long as it is representative of what will ultimately be produced at the volumes and price required. Choosing to present to potential backers or investors a concept, however well engineered virtually, or being able to present a prototype and say that *x* more can be made at *n* per month for an investment of £*y*, will depend on the business model and will determine where initial cash and time outlay will be placed.

4. TOOLING DESIGN

The preceding chapters have shown that design of tooling for composites has many factors. This chapter seeks to summarise key factors in design for tooling, beyond geometry and structural performance. The implications of choosing single or double sided, open or closed mould tools are discussed, as well as dimensional considerations, especially in relation to thermal effects. Several methods for managing part release for increasingly complex geometries are outlined.

Several features which can be incorporated in design to help with part definition are described, followed by a summary of issues around tool supports and handling. Some pointers related to designing for 3D printed tooling are given. Practical features to enable efficient manufacture are included throughout.

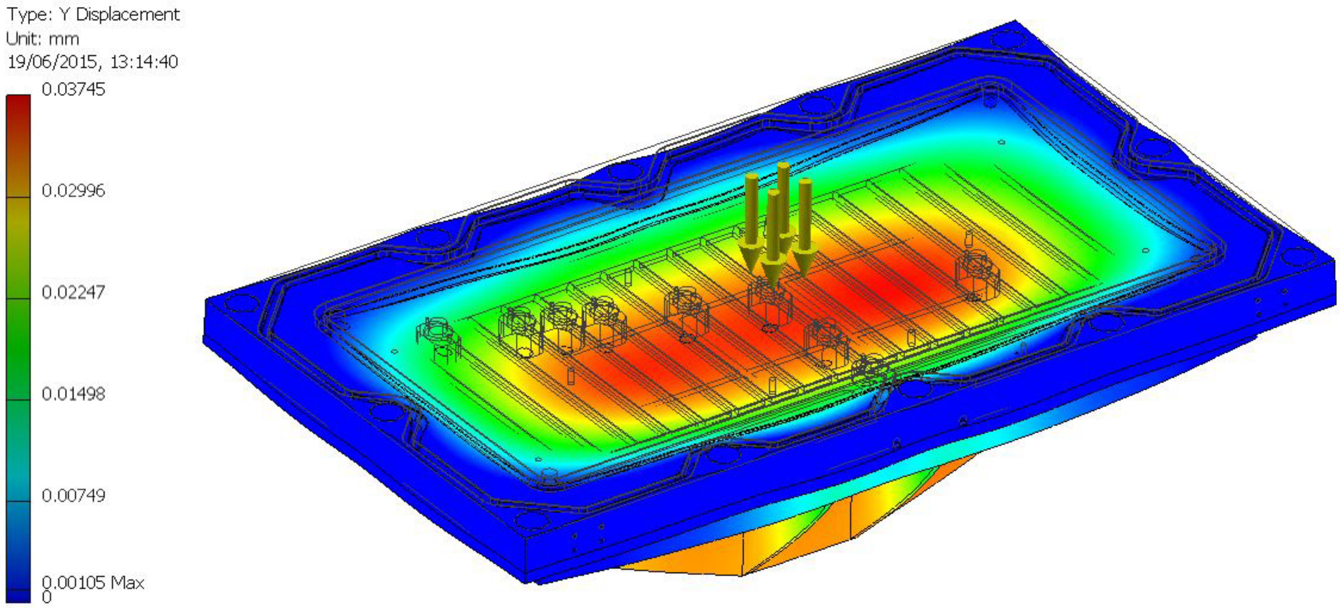


Figure 4.1: Typical FE analysis of tool design under injection pressure. Image courtesy of Composite Integration

4.1 Single and double sided tools

Many composite components and applications have an ‘A surface’ which is visible and exposed to the external environment, and a ‘B surface’ which is not, but remains largely hidden and protected within the product as it is assembled. Typical examples might be a boat hull, a truck wind-deflector, a door skin, or a seat back.

The aim is to have an accurate, functional and aesthetic surface on one side, while the back side can remain relatively unfinished. Sometimes, provided the part is stiff enough or strong enough, the tolerance on the thickness of the component may not be critical, except at certain fixing points or key features. The thickness of the part will then depend on the reinforcement content, fibre volume fraction (FVF) and the degree of consolidation. It may be specified by the number of plies of a certain nominal weight in the layup plan, and/or a minimum thickness, with a generous tolerance. On a single sided tool, extra thickness, structural elements and insulation can be added where required using core materials, and over-laminated to produce ‘sandwich’ structures.

These types of components suit single sided tooling and simpler open mould processes like hand-lay or chopped spray layup. Lower tooling cost and shorter time to first part are the primary reason that these processes remain popular.

4.1.1 Open moulding tools

Open mould tools can be made close to net shape, with small overspray or run-off flanges. Design of the tool should ideally be an integrated part of the global design process. Materials selection will have an effect too. Fabrics need to drape effectively around tool features, ply by ply. Access for accurate placement of either prepregs or dry fabrics needs to be considered, allowing for fabric loft and drape characteristics to avoid unnecessary cuts, fibre breakages, creases or overlaps.

The tool needs to be at least stiff enough, relative to the part to resist bending moments from shrinkage forces that would otherwise cause the tool to bow or warp. This usually means the tool needs to be stiffer than the part itself. The tool must resist such forces throughout the production process, and across the full temperature and pressure cycle. A low void content is particularly important in achieving this in high pressure autoclave cycles. For metal or syntactic foam direct tools this is usually achieved simply by having sufficient thickness prior to machining.

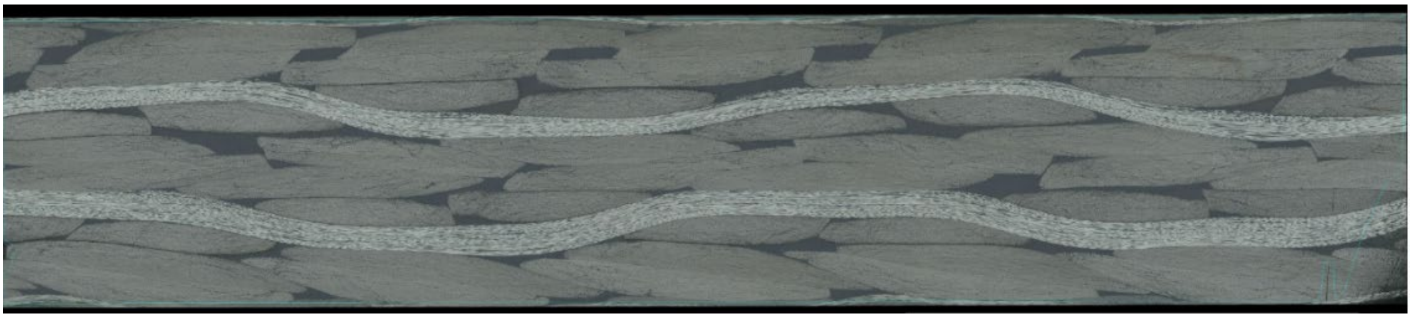


Figure 4.2: Typical 5-6mm thick laminate tooling prepreg microscopy image, showing very low void content. Image courtesy of Toray Advanced Composites

For FRP tooling, the stiffness is achieved by having a shape and reinforcing structure. The primary tool laminate will be thicker than the part, and a balanced layup, but the global stiffness will often come from the backing structure, often applied as an 'egg box' type arrangement of slotted ribs within a box, bonded and over-laminated to the back of the tool surface laminate whilst still on the pattern. When a tool will be oil or water heated/cooled an alternative to ribbing is to use a shrink-controlled casting resin, with sand or even metal fillers to improve heat transfer, and cast this around the pipe-work. Finally, handling, transport and storage needs to be considered, and arrangements designed to attach a lifting frame, stand, trolley or 'dolly'.

A useful addition to the tool set for gelcoating and chop spray processes is an overspray shield, that protects the edges of the tool and limits the extent of any overspray – either during spray gelcoating or spray-chop. This can reduce the feathering out of the part edge, gives a more robust edge trim, and allows easier demoulding, as well as preventing overspray getting into handling features or onto the floor.

The decision to spray or hand apply gelcoat, and whether to move to the tools between processes will also decide whether the tool will perhaps need to be rotated vertically or stay horizontal. Open mould, wet-lay processes rely to some extent on gravity to assist air release during consolidation, so a horizontal orientation with the A surface facing down can help trapped air rise more quickly to the back of the laminate. Larger tools can be difficult to reach into with a brush or roller, or even with a spray gun head (unless it is on the end of a gantry mounted robot arm). In this case, moulds bigger than say 1.5m (two arms lengths) across may need to be rotated vertically for gel and spray chop application, then perhaps returned to the horizontal for consolidation.

Resin systems such as polyester or vinyl ester contain reactive monomers like styrene and cure can be inhibited by puddling of these heavier than air vapours within a concave tool. With deeper tools it can be an advantage to rotate them once consolidated and gelled, to avoid vapour puddling in deep parts of the mould during the initial cure stage, an alternative is to arranging local extraction using flexible hoses suspended into the tool.

4.1.2 Closing the mould - vacuum bagging

Single sided tools are often used for the simplest 'closed process' where a bag or film is used to cover the back surface of the laminate, and by applying vacuum under the bag, atmospheric pressure (or autoclave pressure) can evenly consolidate the part. The tool itself will need to be air-tight, especially at any split lines, and requires a wider flat flange or run-off area around the part geometry to allow space for bag folds and tape sealing.

Vacuum bagging on single sided tools is typical in several processes:

1. Prepreg – where the reinforcement is already wet with resin and in the right ratio with a minimal excess resin
2. Resin film infusion (RFI) – which uses dry reinforcement and a resin film which mobilises at temperature
3. Wet bagging – where dry reinforcements are wet-out as in open moulding, then vacuum bagged to consolidate more evenly and control FVF better
4. Vacuum Infusion – where dry reinforcements are placed, the bag and vacuum applied to evacuate air from the reinforcements, then the resin introduced under vacuum.

In typical prepreg or simple wet vacuum bagging process, adhesive tape is used between a flat flange and the bagging film. (The term 'bagging' originates from the scenario where the whole of a small tool is placed inside an airtight bag). The volume under the bag is evacuated using a vacuum pump, then capped off to retain the vacuum before being placed in an oven or auto-clave to cure. For prepreg autoclave processes, vacuum is usually applied through the bag, using ports that clamp to the bag materials. Placement of these ports can be important, as any excess resin movement beneath the bag will be towards this point, and the port must remain clear until the part is fully consolidated and resin movement has ceased. The port can be placed on an area that will be subsequently cut out, placed centrally on a part, when it should be protected by a resin trap, or by placing some flow media and peel ply beneath it to allow excess resin to puddle, but not remain on the finished part. Alternatively, the exit port can be placed peripherally, and a 'race track' arrangement created to pull vacuum equally from all around the part geometry. For complex parts with areas of significantly varying thickness, multiple ports can be used, opening in sequence. Care should be taken to ensure the vacuum port is off the part so as not to imprint the components laminate.

Figure 4.3: Vacuum drop tests are undertaken and recorded to ensure the level of vacuum is to specification. Photo courtesy of Pentaxia

Autoclave cure is expensive, and it is usual to run cure cycles overnight, often with multiple components all stacked into the same autoclave. This means a component will often be 'bagged up', and vacuum applied and tested, some time before the tool is taken to and placed into the autoclave. It may be clamped off at that point, but in most situations the vacuum will remain on the part/tool throughout the curing cycle. The tape material and bagging films are selected according to the maximum cure temperature, as they must retain flexibility as well as vacuum integrity through the cure cycle, while having limited shrink. For high temperature, multiple stage autoclave cures a part might be 'bagged' more than once, with different materials, to ensure vacuum integrity throughout the cure cycle. Effective sealing and clamping are important, as a break in vacuum integrity during the cure cycle, especially before the part has set, can cause serious defects or result in a scrapped component.

The bags and tapes are not the only 'consumable' or single use element in such production. The B surface of a film bagged component will often have witness marks from the many folds the bags make as they collapse under vacuum, which is where resin permeable peel ply or texturing films help. These are applied beneath the bag to control the surface quality of the B surface and avoid witness marks from bag creases. Peel ply may also be added where bonding will be required, to minimise surface preparation later. Over the peel ply a breather layer, often a mesh or open felt type fabric, is used to assist flow of air above the part but beneath the film. For vacuum resin infusion, flow media such as helical tubes and open mesh fabrics are often used , to direct resin and gas escape flows, and prevent resin flow sealing off areas prematurely. See Figure 4.4.

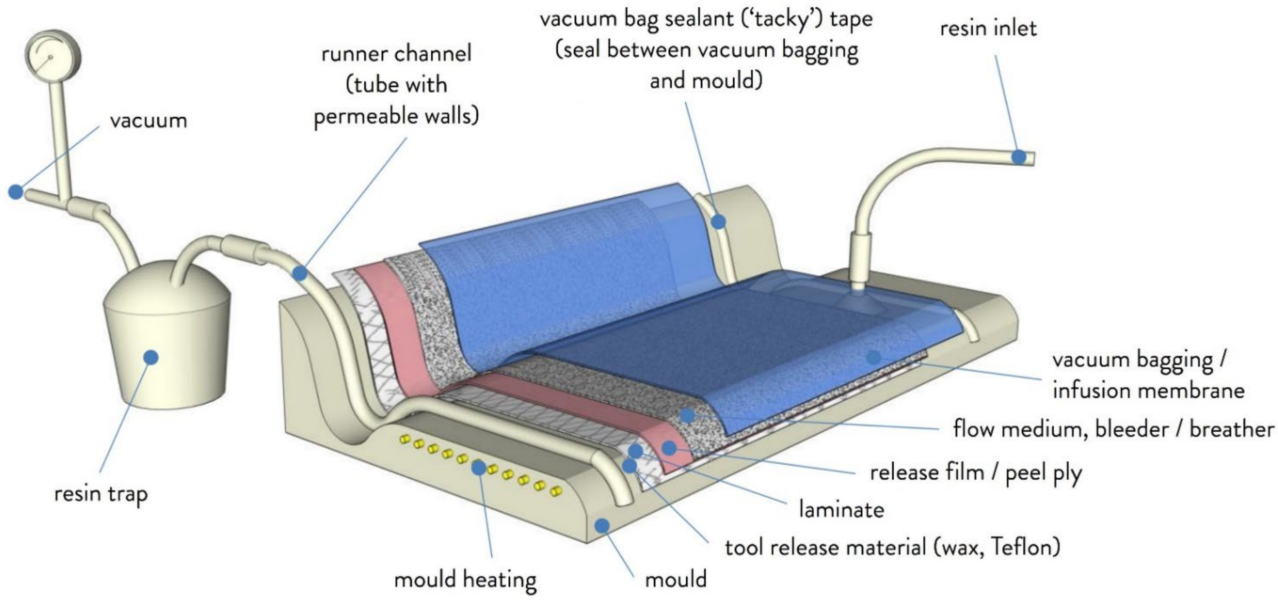


Figure 4.4: Aids for vacuum processes. Image courtesy of Rogier Nijssen, Inholland University of Applied Sciences (fonts edited). CC BY-SA 4.0[3]

The aim in all cases is to have a bagging regime that allows all parts of the component to wet and consolidate evenly and in correct sequence, allow excess resin to bleed away without blocking gas flow and causing porosity, especially in cosmetic witness areas, and to ensure even cure by avoiding excess thickness build up e.g. in corners.

4.1.3 Light RTM and flexible membranes

Vacuum infusion under a flexible membrane or LRTM laminate top tool uses two flexible seals, and vacuum is used both to hold the top bag/membrane in place as well as to draw resin into the component and consolidate the part. The vacuum force clamping the top membrane to the main tool is proportionate to the surface area between the inner and outer seal, consideration must be given to the necessary seal compression force, the stiffness of the tool and the resin injection pressure during the process to ensure available clamping force is not exceeded.

The seals in such an arrangement can be built into the bottom tool by making a rebate into which a standard section seal can be slotted securely. The rebate itself can be facilitated by using a flexible extrusion glued to the pattern.

Alternatively, and one of the advantages of flexible membrane top-tools, is that the double seal vacuum track, and vacuum ports can be built into the top or flexible tool, leaving the flanges on the main tool flat, which in turn makes tool fabrication simpler, and tool cleaning and maintenance easier too.

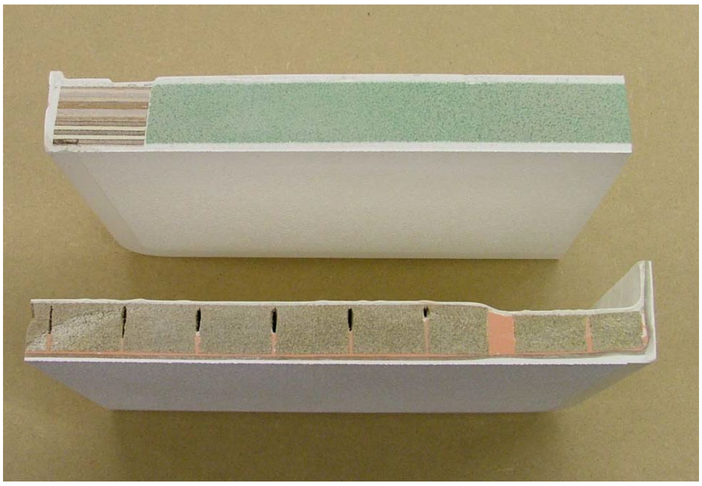
The surface quality of the 'B' side of an LRTM component will mirror that of the top tool, and will generally be more consistent than if a bag is used, having no creases or fold marks.

[3] R.P.L. Nijssen, 'Composite Materials - an Introduction', Inholland University of Applied Sciences, 2015 https://compositesnl.nl/wp-content/uploads/2019/10/Composites-an-introduction-1st-edition-EN.pdf

Case Study: Double sided VRTM tooling for marine table application

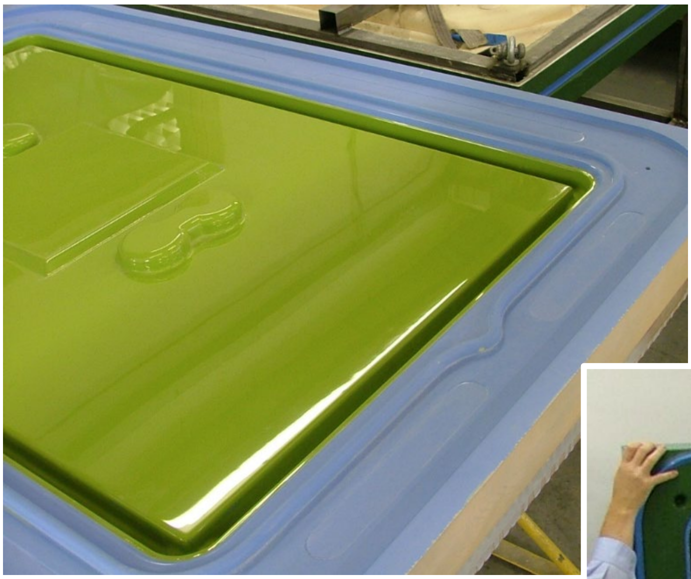
Richard Bland, Composite Integration

Double sided components can present particular challenges when made by hand-lamination, infusion or silicone bagging due to the requirement for high quality surfaces on both sides, and accurate dimensional tolerances. This issue is often overcome by manufacturing two separate mouldings and bonding together with an appropriate core. This is still an imperfect solution due to the additional time required for manufacture, joining/joint repair, and also the longer-term issue of joint stability and risk of voids expanding when exposed to temperature variations.



Comparison of VRTM section (upper) vs hand lamination section (lower)

The use of a double sided VRTM tool provides benefits of excellent A/B surface finish, low void content and the lack of a bonded joint. In addition, specific features can be incorporated including cores, fixing inserts, seal grooves etc.



CNC machined model board pattern for B surface tool, finished with a two part polyester surface coat. The blue primer layer seals the pattern for moulding and provides a base for the green topcoat used for aesthetic areas.

It is important in pattern manufacture to achieve as near final tool surface requirement as possible at the pattern stage to reduce work on the final tool surface. At this stage, all details from tool design can be incorporated into the pattern including seal profiles, inlet ports, inserts etc.

Tooling was manufactured from vinyl ester tooling gelcoat, with 125°C heat distortion temperature (HDT) and elongation of approx. 3%, followed by a vinyl skin coat, then built up to a tool skin thickness of approximately 15mm using low shrink Rapid Tooling System (RTS). A simple frame provides additional strength in the flange area to support seal compression and provide a point for handling fittings.

Care must be taken at the pattern/tooling stage to ensure accurate location points are referenced across from pattern to tool for final X-Y-Z location of the two completed tool surfaces.

Finished VRTM tool and part

4.1.4 Double-sided tools – 'matched tooling'

Some components may have more than one aesthetic 'A' surface, or the rear surface geometry significantly differs from the front, or precise thickness tolerance is critical to the function of the component. Such shapes will require matched tooling, where two or more tools are assembled to create a cavity defining the part geometry precisely.

Consolidation of the laminate, to drive out porosity and excess resin, is still required. In out-of-press RTM the consolidation pressure comes from the resin injection pressure acting against tooling that is sufficiently stiff and uses edge clamping, with multiple threaded bolts or mechanical clamps, sufficient to counter the internal hydrostatic pressures. RTM tools can be mounted into a press, where the additional stiffness of the press platens acting across the whole tool, rather than reliance on tool stiffness to transfer loads from edge clamping, means that the tool itself can be lighter and less stiff.

Figure 4.5: Finished double-sided component installed (see case study on previous page). Photo courtesy of Composite Integration

'Open moulding' processes can potentially still be used on each mould segment prior to assembly, but additional consolidation will be required to ensure correct reinforcement distribution. Components can be made using prepreg hand laid into matched tooling, but where these tools are fully closed, they will need to be oven or hot-press cured, as autoclave processing requires an opening for gas pressure consolidation. For hollow parts consolidation pressure can also be applied outwards via an internal inflating bladder, an expanding core material or solid mandrel.

Design of matched tooling is significantly more complex than single sided tooling, and needs to consider the required movement between the mould segments during closure and release, how the tool segments will locate together accurately, where the entry ports for resin injection, vacuum attachment, gas venting and witness holes for excess resin will be located. Because the manufacturing process within the tool is no longer visible, features may then need to be added that allow for tracking that process better to ensure repeatability. If the component has a balanced amount of reinforcement either side of a core, insert or hollow space, then ensuring accurate location of these elements can also be important.

Matched tooling is always required for resin transfer moulding RTM, thermoplastic injection moulding and overmoulding processes, where hydrostatic injection pressure drives part consolidation and low porosity. In these processes the tools, seals, and clamping or press arrangements act as a pressure vessel to counter the forces pushing the tool halves apart. The tool must be stiff enough to avoid tool distortion, as well as contain fluid pressures safely. Significant closure and clamping forces may also be needed to compress dry fabric reinforcements against the natural 'loft' or springiness of the fabrics.

4.1.5 Envelope bagging

Envelope bagging can be useful for small parts, or where the tooling is not airtight, e.g. MDF or plywood tools, or flanges are too small. This can either use a reusable silicone envelope bag, or tube bagging, or can seal down onto a vacuum tight table, i.e. the table becomes part of the 'envelope'. This may use more bagging material (not in the reusable envelope case) but may also reduce the need for flanges and backing structure on the tool and may reduce the amount of sealant used.[4]

[4] See 'Introduction to Vacuum Bagging – Envelope bags', Explore Composites! 31/5/20 https://explorecomposites.com/articles/lamination/basics-vacuum-bagging/#envelope

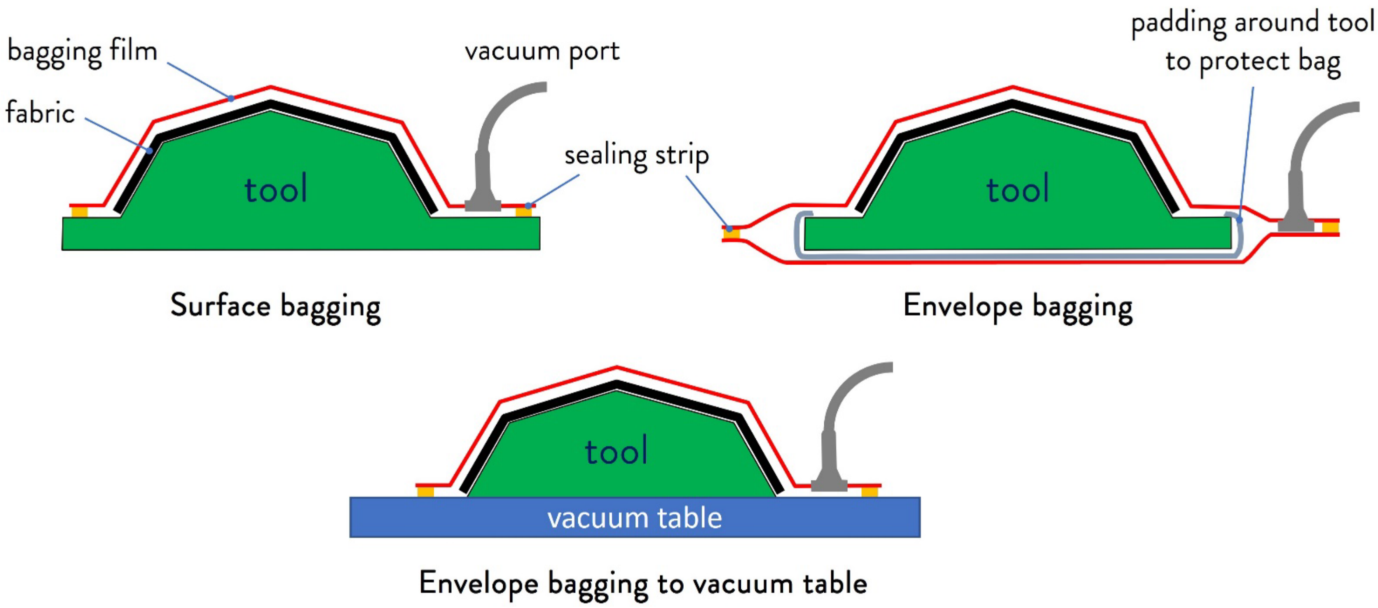


Figure 4.6: Comparison of surface and envelope bagging (other process aids not shown for simplification)

4.2 Tolerances and part dimensional accuracy

Starting between the wars in the early age of mass manufacturing, a whole science and methodology, and universally accepted international standards have built up around how to determine, explain and describe critical dimensions and acceptable manufacturing tolerances. This is known as geometric dimensioning and tolerancing (GD&T). The premise is that manufacturing processes all introduce some variation to the idealised or nominal design dimension, but each dimension does not necessarily have to be exact for a component to work. GD&T has its own rules, language and symbolic notation for use on engineering drawings whereby the acceptable tolerances and limits for key dimensions on a component can be described, labelled, inspected, and controlled during manufacture. ensuring that the critical functions and fit of components is maintained.

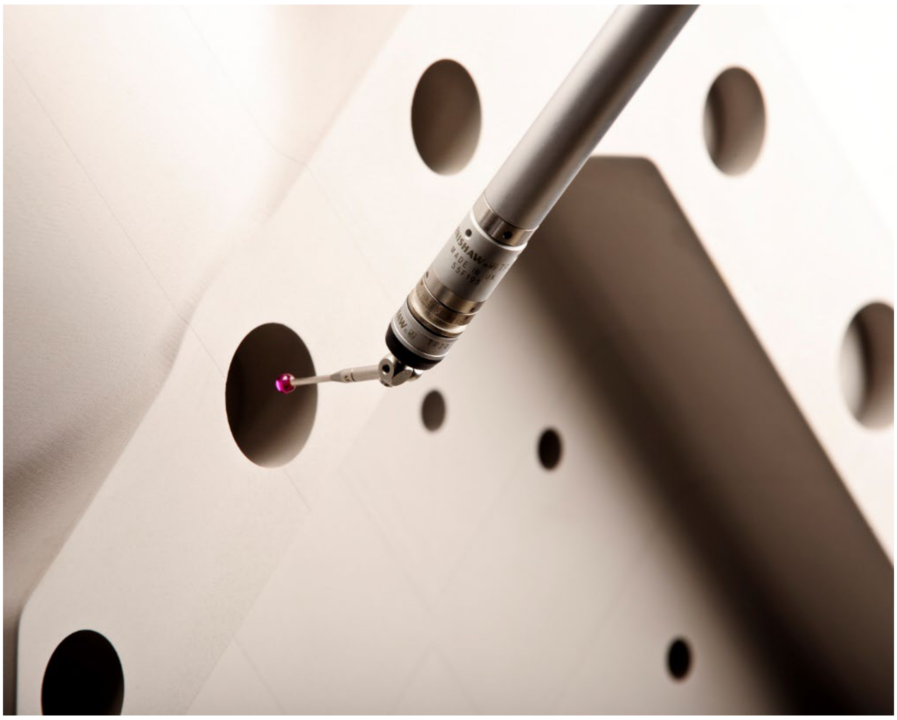


Figure 4.7: FaroArm testing of Base Materials tooling board. FaroArm measuring devices provide accurate dimensional surveys. Photo courtesy of Base Materials

GD&T principles are now used to form lists of instructions and grouped features that are the communications link between the computer aided design (CAD) model, and computer aided manufacturing (CAM) instructions. Thus a STEP File describing each feature and its tolerances can be translated into a set of tool path instructions for a computer numerical control (CNC) cutting machine.

On a simple composite component for example the critical functional dimensions might simply be the fixture points for bolting the part to a larger assembly. They will need to be spaced to always match, within tolerances with the mating fixtures on the attaching part. They may also critically need to be a specific minimum distance from one flush mounted end of a component to allow for fit, and less than a certain maximum distance from the same end to meet gap tolerances. One way to achieve accurate location of fixings might be to machine sockets for inserts into the tool, such that the part is formed around these, rather than bond the fixing points to the rear of the finished component, or drill holes for fixings post manufacture – both of which introduce extra process variables.

It has long been assumed that the very tightest tolerancing is beyond most composite manufacturing processes, without additional machining, and indeed many processes require that features on tools for fibre-reinforced components have more generous tolerances than for a tool dealing with conventional isotropic materials. Engineering fit tolerances (shaft and hole), draft angles and other sliding fit clearances ideally will need to allow for the fact that multi-material components containing fibre, core materials and reactive resins that shrink as they cure may NOT always be exactly the designed nominal shape once cured.

Predicting and simulating this variability is a constantly developing science rather than a matter of simple physics and predictable material properties, but it is now true to say that all the major software houses for CAD/CAM have products and modules that support composites manufacture, within the International Organization for Standardization (ISO) framework, and linked to ever improving simulation tools. Recent work on simulation of composite manufacturing processes and developing reliable automated manufacturing solutions for composite processes is highlighting not only how accurate composites manufacturing can be, but also throwing up new questions about how good conventional precision manufacturing processes are.

4.3 Thermal effects and their associated problems

When a thermosetting resin system cures, it shrinks as it turns from a liquid to a solid state. The degree to which it shrinks depends on resin chemistry and the speed of cure, which in turn depends on temperature. Understanding these factors is an important part of manufacturing and designing with and for composite materials. Embedding sensors to monitor the temperature, both for monitoring the cure process and for safety reasons, may be required – this is discussed further in chapter 8.

4.3.1 Shrinkage allowances and CTE

Resin manufacturers will often quote linear or volume shrinkage % under a standard cure regime, but a single number will not capture all the variables seen in a real build. Other factors are in play. FVF can vary across the part, with resin rich areas of the part, or thicker sections that get hotter during cure, potentially shrinking more. Knowing these factors and making allowances for them can be critical for final part accuracy.

The coefficient of thermal expansion (CTE) is an important concept to understand as it determines the relative change in size of a material with temperature. (CTE is usually used referring to the coefficient of linear thermal expansion (CLTE). However, thermal expansion can also be measured as the change in volume, i.e. the volumetric CTE, which is more relevant for fluids.) Table 7.1 in the 'Tooling materials' chapter includes CTEs of typical tooling materials.

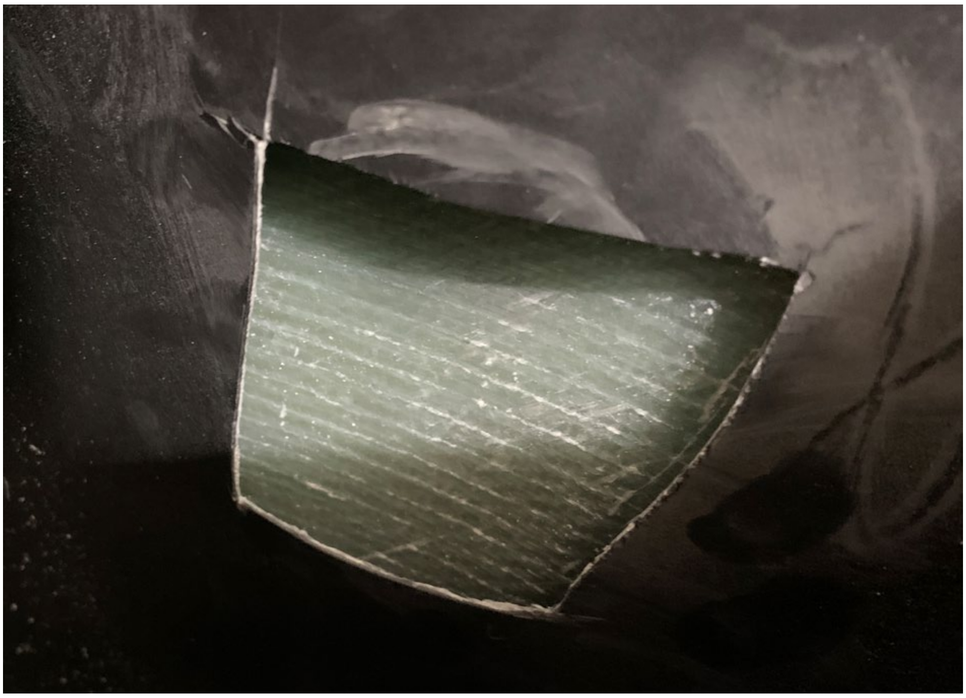


Figure 4.8: Cut out section of high temperature glass/epoxy composite tool showing blistering and delamination at temperature due to thermal expansion

The increased length with a given temperature change can be calculated using the CTE (linear):

$$L_n = L_0 (1 + \alpha * \Delta T)$$

Where:

L_n = increased length at temperature (m)
L_0 = initial length of object (m)
α = coefficient of thermal expansion (m/m°C)
ΔT = change in temperature (°C)

The CTE of the tooling needs to be considered, especially when hot processes and metal tools are used. An aluminium tool will expand more when taken to 90°C than a steel tool, and a composite tool will expand much less. (See Table 7.1). When a part cures, i.e. transitions from liquid or semi-solid state to a solid, and is then cooled back down to room temperature for demoulding, the difference in CTE between the tool and the part, and therefore the part length at room temperature, can cause significant stresses at the interface. The part will typically 'set' at close to the maximum dimension of the hot tool. As it cools a metal tool will usually become smaller than the composite part, an effect that can aid release of the part from the tool but equally can become a problem with larger parts, or certain part geometries. These factors must be accounted for at the design stage, and checked again when specifying, designing and putting into commission new tooling.

One way to minimise or effectively ignore these effects is to use tooling materials that are very similar to the part materials i.e. glass fibre tools for glass fibre parts, and carbon tools for carbon parts, but this is not always the best productivity option.

The CTE of Invar is unusually low for a metal and close to that of carbon fibre, hence its use in high performance tooling, but the CTE increases as temperatures rise, especially above about 200°C, see section 7.4.

Carbon fibres are anisotropic in their response to temperature. They typically shrink along their length with increase in temperature and expand slightly in width, but glass fibre is the same in both directions. Natural fibres have a much more anisotropic response, often with a negative longitudinal CTE -8 μm/m °C. Aramid fibres are also very anisotropic, but CTE is still positive transversely. These are the CTEs of the fibres, which is not the same once fixed into a matrix. This is discussed further at section 7.1.2 Anisotropy of fibres.

4.3.2 Springback

Springback is a term used to describe the degree to which a desired shape or angle may be off-true due to a thermal shrinkage factor. A good example is where a rib or flange is made at a nominal right angle to the moulding surface. It is not uncommon to find that on demould, the flange is neither at the correct angle, nor flat. This is firstly because control of FVF in tight corners applied layer by layer is not always easy, and secondly thermal mass effects mean that heat is retained longer in thicker parts of the tool structure, e.g. at the base of a flange. Both of these effects can result in resin cure being hotter and faster in these areas, causing more shrinkage.

4.4 Compatibility of materials

Compatibility between the tooling materials and the moulding materials needs to be considered. For example, if moulding with phenolic resin systems, stainless steel mould fittings/inserts must be used to prevent oxidisation from moisture release during the curing phase. Also, epoxy resin systems can have a detrimental effect on silicone seals or flexible silicone membranes. For composite tooling, tool colour should be considered to ensure a good visibility contrast if applying gelcoat.

4.5 Part release

Many tolerances are process critical, rather than functional, and these can often be neglected by designers, particularly if the composite component is replacing a conventional metal or plastic component. Key amongst these are draft angles and other features that allow part release. Release relies on breaking frictional, electrostatic bonds between the part and the tool, aided by release agents applied to the tool, or sometimes additionally incorporated in the matrix material.

4.5.1 Draft angles and radii

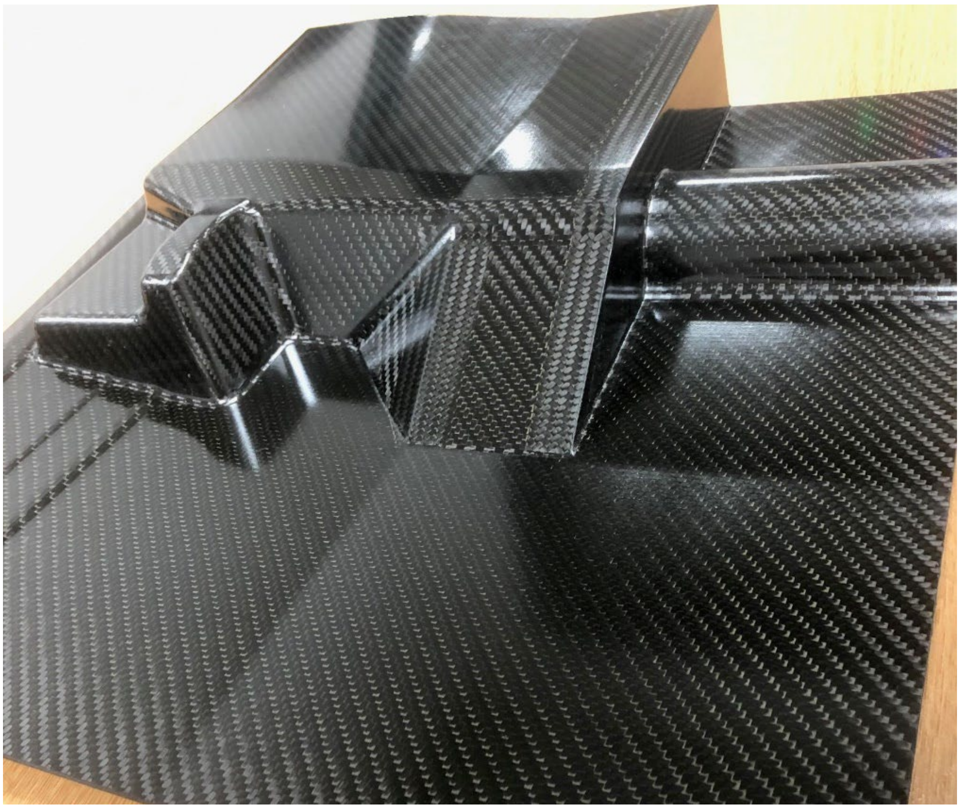


Figure 4.9: Complex tool with deep drafts, compensating angles and small radii.
Photo courtesy of Toray Advanced Composites

A part must be able to move freely against the tool in at least one direction in order to release successfully. In an ideal system the force to be overcome during release are weak, interfacial, electrostatic or van der Waals forces. The parting force perpendicular to the pull direction will be proportional to the surface area in this plane, surfaces at an angle will have a shear element and be more easily overcome. Surfaces too close to parallel to the pull direction, i.e. entirely in shear, and large flat surfaces entirely perpendicular to the pull direction and entirely in tension will be the most difficult to release. As soon as a draft angle is introduced an element of tension as well as shear is introduced which is better able to break the interfacial forces. The bigger the draft angle, the easier the release. In composites design a minimum 1° draft angle is considered essential, but 3° will make release significantly easier. Another factor to consider, especially for FRP rather than direct machined tools, is that a 'nominal' 1° draft angle on the tool design may get reduced through springback or shrinkage effects, and this could lead to the draft angle virtually disappearing or even becoming negative, preventing release.

Radii are equally important. Too tight a corner may not be manufacturable, because the reinforcement fabric cannot drape or comply to it without fibre breakage. A thick ply may 'bridge' the corner leading to a weaker resin rich area on the outside corner, and a fibre rich, possibly improperly wet-out area against the inside radius. A corner that is more generously curved will likely be much stronger, and more repeatably manufacturable than a sharp one. This is often counterintuitive to metals designers, who have the mind-set that machining a generous rad is wasteful of material, and perhaps aesthetically does not look as 'sharp' or 'precise'. When specifying radii it is important to think about the fibre ply layup, how thick and conformable or drapable it is, how physically accessible is the location for multiple ply layers, and how the reinforcements or plies will be placed. In addition, sharp edges, or small radii, are particularly susceptible to tooling damage.

4.5.2 Pre-release

Pre-release occurs when a part shrinks excessively, perhaps in a resin rich area, and the interfacial stresses due to shrinkage and CTE differences overcome the forces holding the mould and part surface together. This can cause a cosmetic witness line or ripple on the surface which will need repair or can even cause a part to be scrapped. The tool may well also have to be cleaned and release coated too before reuse.

4.5.3 Stick-up

Stick-up is a term used to describe any situation where the part will not release from the mould. This could be because of the release angles or minimum radii being too tight, shrinkage onto a complicated detail in the mould, or it could be due to a failure of the release system on the mould surface, perhaps due to exceeding the heat tolerance of the release system during cure.

Case Study: Large scale multi-part infusion tools

Ned Popham, Engineering Manager, Norco Composites & GRP

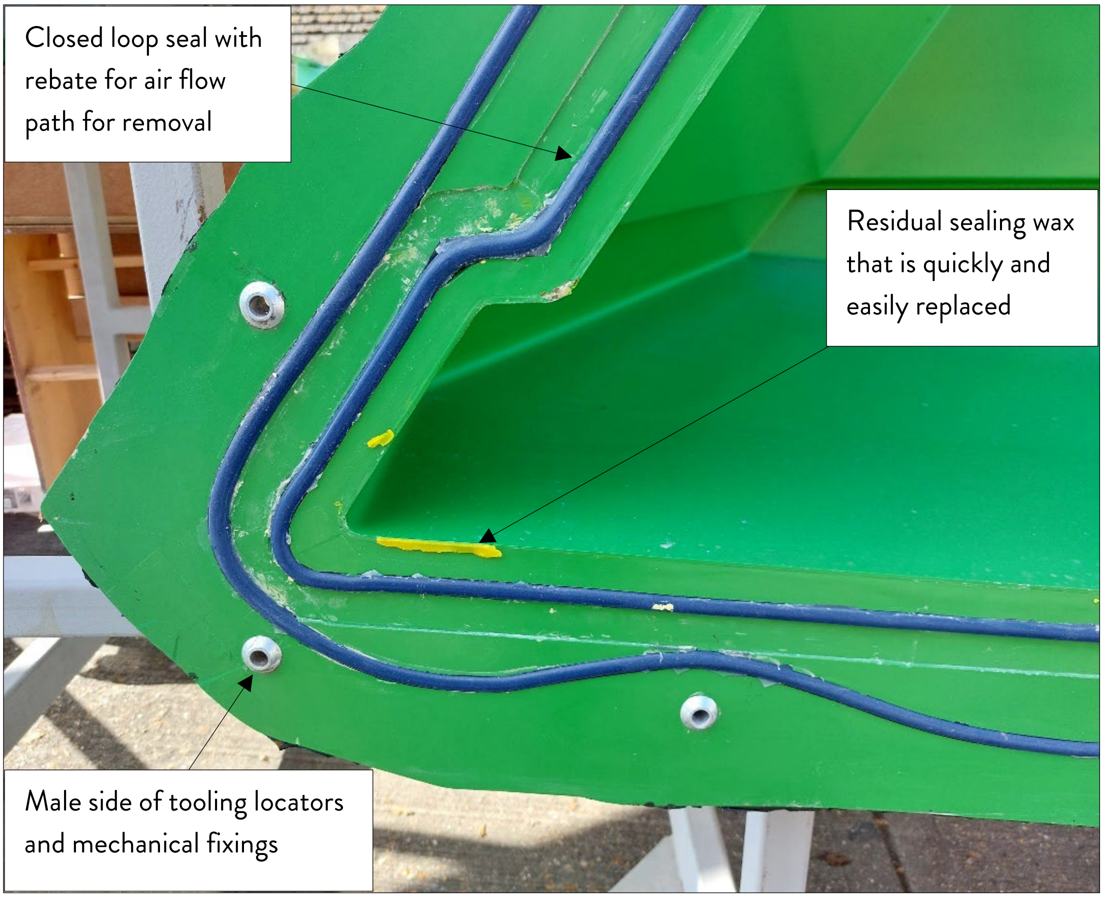
Multi-part tooling is an effective way of achieving large complex composite structures that require negative draft angle surfaces without splitting the parts into a subassembly. Thus, reducing production time, labour, and material cost.

The goal of manufacturing with an infusion technique of any multi-part tool process is to ensure good quality repeatable, cost effective manufacturing. To do this a good vacuum, quick tooling turnaround and high tolerance of the completed component are required.

Closed mould processing with multi-part tools can pose challenges when ensuring vacuum integrity. Methods such as external bagging around each split, sealing the gap with tacky tap or silicone sealant, or even mechanical gaskets can be used. The challenges with these methods can lead to poor sealing between flanging, difficulty splitting the tool due to the use of adhesive tapes or sealants and the additional post-processing associated with removing and reapplying these sealants. All of this leads to wasted time on the production line.

Norco's preferred method is to integrate seals into the tool flanges to ensure reliable vacuum sealing while eliminating the time associated with applying and removing temporary sealing materials.

The integrated seal arrangement provides not only vacuum integrity but also a clamping force to secure the tool sections. Mechanical clamps can also be used, and the seal can be arranged to allow flanges to be through bolted without compromising the vacuum performance.



Male-female locating features are laminated into the tool during manufacture, allowing repeatable and reliable tool alignment with minimal tool wear. These features are also threaded to allow mechanical fastening. Once the tooling is finally assembled wax, plasticine or flash breaker tape can be used to close the small gap in the split, producing a near seamless finish with minimal repair work to the component.

This process allows for repeatable, consistent, high tolerance and good vacuum processing, with minimised risk and productionised manufacturing.

4.5.4 Split and multi-part tools

Sometimes a vertical flange is a functionally necessary design feature, or the geometry of the part is such that release from a single direction is not possible. Examples include parts with all around return flanges for bolting flush to adjacent components, cylindrical shapes with no taper and flat ends, and hollow parts that are larger at the end away from the opening, rather than tapering conveniently. If it is not possible to obtain a release angle within the part geometrical tolerance, then these will require split moulds that will disassemble and release from the part separately. When designing for split tooling, the decision on where to put the split line is key. Ideally it will be in a location that is not too critical to the visual aesthetic, as the split line will usually require some level of refinish once demoulded, but in many cases the split line will need to be right down the middle of the component symmetry, so it may be worth thinking again about whether the reverse flange is the best method of attachment. Split tooling also inevitably adds complexity and risk to the moulding process, particularly where seals are required e.g. RTM or vacuum RTM.

FRP split tooling is made by taking multiple tools from the pattern, by attaching a temporary profile plate at right angles to the pattern aligned to the split line, making one tool that includes this as a flange, then removing both, repositioning the temporary plate the other side of the split line on the pattern and repeating. The mould sections will then be mated back together and joined on the flanges using sturdy removable bolts. It is good practice to also provide some form of interlock profile, in addition to the bolt holes, that ensures repeatable accurate reassembly each time. This is often done with mating bosses or cut outs on the flange plates.

Once assembled the split line itself will need to be sealed to prevent resin leakage and minimise witness marks. This is most simply done with plasticine putty, which can be easily removed from the part prior to the finishing process. Tailor-made silicone split line profiles are a more elegant option, they can be accurately located in the split line recess, give a consistent profile to the split-line witness, which can perhaps be more easily polished off. They also have the advantages of being reusable and so more environmentally sustainable as well as less messy.

More complex multi-part tools, especially direct machined tools can have appropriate rubber, thermoplastic urethane (TPU) or other high temperature resistant seals permanently mounted within a machined slot.

4.5.5 Bladders and single use inserts

Hollow parts, especially those requiring good surfaces inside and outside, provide a challenge in achieving part consolidation from the inside. If there is an opening sufficient to allow gas pressure, or a pipe to access the inside then an inflatable bladder can be used. There are companies that specialise in making bladders, inserts and bags that are rigid enough to lay up onto, have a controlled expansion to aid consolidation, soften or shrink for removal at a certain temperature within a cure cycle, then be reinflated and cooled to room temperature and reused, all while maintaining repeatable dimensional accuracy.

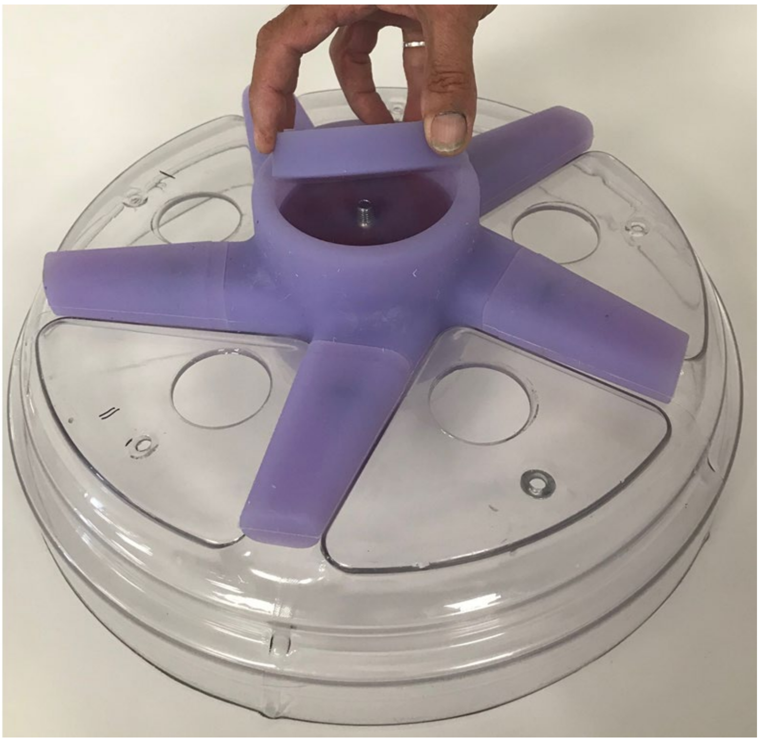


Figure 4.10: Multi part removable silicone bladder. Photo courtesy of Composite Integration

Some part geometries are extremely complex, and have no single direction, nor even multiple directions from which a tool element can be released. Examples include complex ducting and conduiting for aero engines and air ducts in Formula 1 cars. Soluble tool materials might provide a viable option to these geometries as well as those that could be achieved only with multipart clamshell tools and bladders or expanding inserts.

Sacrificial cores can either be machined or 3D printed and then smoothed and sealed, by dipping in some cases. The dry fibre or preform elements can be assembled into and around the insert, wrapped around it and even threaded right through it. The assembly is placed into a closed mould cavity, or if the interior dimensions are more critical than outside aesthetic, wrapped in a shrink wrap film, which will act as both the exterior tool face and compression/consolidation method. Once processed and cooled, the soluble core removal is usually via wash-out or chemical dissolution. The part could be placed in a water bath, or dissolution of the core may involve a hole or holes being drilled into the core or insert through the part at a non-critical point, suitable for flushing and drainage. The resin system used needs to be sufficiently water resistant to cope with this – so is usually an epoxy. For more on materials for bladders and single-use inserts, see 7.6.

Using a 3D printed, single use, sacrificial tool at one per part can seem illogical except for prototyping, but its advantage, once the design work is done, is that it is fast and repeatable, and compared with time to manufacture of very complex hard tooling, can be cost effective up to a surprising number of parts. (See also section 4.8 Tools, patterns and sacrificial inserts using 3D printing.)

4.5.6 Flexible tooling

A flexible top tool can sometimes negate or reduce the need for split tooling. An example is a simple return flange, where a flexible top tool can be essentially stripped out of the recess, where a rigid tool could not. Silicone tooling can be built quite quickly, building up layer by layer, and can incorporate fabrics for toughness, stiffeners to act as aids to handling during bagging and demoulding, or as local intensifiers e.g. in corners. Pre-made patches assembled with vacuum and resin ports can be accurately placed and incorporated in the flexible tool build, likewise surface textures, sealing features and resin distribution features. This means that bagging consumables can be practically eliminated from production for all but the highest temperature prepreg processes.

Aerospace and motorsport manufacturers are accustomed to rigorous procedures to ensure that 'free' silicone chemicals are banned from clean rooms to the extent that workers are expected to refrain from using silicone containing hair conditioner etc. This is due to fear of interlaminar adhesion, or 'kissing bond', failures from surface contamination with non-stick, 'slippery' chemicals. It has now been satisfactorily demonstrated that, using the best formulations and modern platinum catalysts there is minimal risk of uncross-linked silicones remaining in or on well-made flexible tooling, although it is still good practice to isolate the flexible tool production area if it is being spray dispensed, and institute good anti-contamination procedures from wet/uncured silicones, e.g. on footwear and PPE.

Another barrier to use of silicone membranes has been that the surface release properties break down over time (around 25 uses) when used with amine cured epoxy resins, polyurethanes and DCPD resin blends. However proprietary surface treatments now exist which can be painted on to recover the membrane's self-releasing properties.[5] Silicone membranes can be used with polyester, vinyl ester, methyl methacrylate (MMA) and phenolic resins up to around 600 cycles without the need for additional release agents.

For vacuum infusion, or wet-bagging, the flexibility and shape memory of silicone membranes are also being used to create resin reservoirs that self-distribute, via self-sealing capillary channels, and close themselves off as the part is fully wet out. This is very effective for low permeability fabrics such as high density multi-axials, removing the need for flow mesh with traditional vacuum bagging. See case study below from Alan Harper Composites demonstrating the "flow field" technology.

The resin distribution network can also be built into the top so that a single measured dose of liquid resin can be poured under the bag or into the reservoir and will essentially automatically self-distribute under vacuum. These methods have the potential to reduce cost, saving labour, resin and energy usage, eliminating both metered pumps, and use of single use consumables such as flow coils and other flow media.

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[5] E.g. SILFLON, see https://alanharpercomposites.com/silflon-125g-102163-2/ or Marbocote SB4 https://www.ecfibreglasssupplies.co.uk/user/TechnicalDataSheet/5739.pdf

Case study: Multiaxial high-density fibre, glass and carbon, gets easier to infuse

Alan Harper, Director, Alan Harper Composites

It is common practice and necessary to use single use flow mesh and release film when infusing high density multi-axial fibre due to its low permeability. The new "flow field" concept eliminates this costly unsound consumable approach through permanently building multiple flow channels into a reusable silicone vacuum membrane.

Not only are these channels reusable but the good news is that they eliminate the wasted unused cured resin consigned to land fill with the former single use consumable system.

The savings are not only through elimination of wasted material but more so significantly the labour cost of tailoring, fitting and disposal of the one-time contaminated consumables cycle use.

RS Sailing' new RUSH electric powered RIB uses the system to make the large 6 m^2 structural battery bank containment box. This 5m long laminate with high density multi axial either side of perforated foam core takes only 9.5 kg resin. There is no flow mesh or release film employed. Instead "flow fields" are present in the form of 17 individual flow channels all of which are external pressure operated to open and close as required to fill the mould cavity. After 95% fill all surface flow channels are closed to eject their resin volume which finally completes the infusion to the edge without waste.

The system saves at least 4 kg of resin and considerable labour as all flow aids are always installed and totally reusable. It is recorded that the savings in materials, labour, and waste management costs amount to £240 per cycle.

The reusable membrane weighs 63 kg and is simply stored hanging above in the roof space and manipulated by one operator using an electric single phase €100 hoist.

Photo courtesy of Alan Harper Composites

Flexible tooling can also be considered to replace films in bladder moulding of hollow parts. Once again the advantage is the precision to which the reusable bags can be made, compared with complex bagging procedure for thin films, which introduces more variability, and so requires more highly skilled layup operators.

Semi-flexible materials are also available for processes such as filament winding that apply significant pressure to the mandrel. these can be tailor made and set rigid at room temperature, be designed to expand or inflate to consolidate a hollow part at processing temperature, have a trigger temperature at which they collapse and soften for removal, and can then be reinflated for reuse.

4.6 Part definition and net shape components

4.6.1 Scribe and trim lines

In most open mould processes, and closed processes where accuracy of kitting and placement is of lower integrity, then it is usual to make the component oversize, and trim it back once released. Component edges are frequently the most likely to show imperfections, such as ply or fabric wrinkles, insufficient reinforcement, or porosity and high resin content. A generous overspray or run off area can help ensure the part has the correctly wet out ply content at the part trim line, but does require that edge trimming is part of the production process, and generates waste.

Tooling can contain features specifically designed to define the part edge and improve accuracy and sightliness of cut edges. Typically these features are a thinning, and/or a change of angle at the part edge, but they can be simply a line scribed across a flat area that will witness clearly on the part once released.

4.6.2 Net shape components

A 'net shape' component is one that as released from the mould is already the correct size and shape requiring minimal or no post-machining. Closed mould processes and tooling lend themselves well to this, with the key being the capability to accurately cut the ply kit and place the reinforcement, especially up to part edges. To aid layup into the mould for net shape components it can be useful to have a change of angle, and/or a sharp change to a tighter gap at the part edge, such that it is easy to place the preform or dry fabric layup accurately. It also helps if structurally the part edges themselves need not be highly loaded needing highly aligned fibre content, i.e. the part of the component right at the 'nip' can be relatively resin rich and cosmetic without detracting from the part function.

In press moulding, with tight tolerances and relatively viscous moulding compounds, the nip is such that a thin 'flash' is all that remains. This can be brittle enough to simply rub or tumble off after cure, or in some cases a separate cutting downstroke of the press with a cutting blade will trim the part prior to part release.

4.6.3 Fabric crimp and clamping

In high pressure RTM the extreme flow speeds and pressures will tend to move or 'wash' the fabric within the cavity. Tooling for HP-RTM is therefore designed to clamp a deliberately oversized or specially tabbed fabric preform in the run-off area to prevent movement, and so true net shape components are not possible. However, HP-RTM tools can still be designed to define the part edge such that the 'flash' and fabric tabs are easy to trim off. Tool features such as shallow ribs can also be used to restrain the reinforcement in place within the part geometry where there might be a tendency for wash movement with resin flow.

4.6.4 Witness flow holes

RTM and vacuum infusion and variants of these closed mould processes normally have an entry and exit gate for resin. With peripheral injection the exit point(s) are typically central, perhaps located on a part cut out or area where the rear aesthetic appearance is not critical. With central injection the resin flow front tends to be radial, but may travel at different rates across irregularly shaped parts, making it usual to vent at corner points. Witness vents in a top tool can be a way to track this flow process and ensure the tool cavity is fully and evenly filled, with the vents being sealed as soon as the resin reaches them. Resin flow to a mould area can thus be controlled in sequence, which can be useful in bigger components or those with large changes in component cross-section. Peripheral injection also creates a much larger flow front, significantly reducing fill time for a fixed injection pressure, but this is often limited by process/tooling type).

4.6.5 Intensifiers/caul plates

Wherever flexible tooling or bagging is used there is a risk that the material will not stretch or conform closely enough to the front face tool in tight corners or recesses, but will 'bridge'. This will result in poorer consolidation pressure on the reinforcement in those areas, causing them to be more resin rich than ideal, or where there is insufficient excess resin, to leave space for porosity. One solution is to stiffen these areas with shaped pieces of tooling material, metal plates or even a clamped frame to ensure the bag is fully tucked down into the corners, and that any bag shrinkage or movements during cure do not open up the space between bag and front face across those features. These 'extra' pieces are known as caul plates, or intensifiers. Caul plates may also be used to assist, for example, geometry, surface finish or insert location in specific areas in flexible tooling/bagging applications.

4.7 Tool supports and handling, heating and process monitoring

A tool must resist both global forces that might distort the whole tool, creating a twist or bend, and local forces such as hydrostatic pressure that might distort the surface and change the shape locally. The tool surface material must be stiff enough to take the local forces and transfer them to the backing structure without distorting, and the backing structure must be able to resist the global forces. For most small to medium tools the minimum thickness of the main tool face will depend on size, and the expected pressure regime from processing, whereas the backing structure will need to stiffen the main tool against global twist or bending, provide support bridging to avoid tool bending across the width or length.

The simplest backing structure is none at all, just a thick enough tool and base plate. This is fairly common with direct tooling from lightweight tooling board and tooling block, and metal tooling machined from billet.

The tool may be a 'benchtop tool' or require stand-alone mounting to achieve a comfortable working height for ease of layup. Manoeuvrability is a consideration, which may lead to requirements for wheels, a pallet base or mounting points for lifting, or clamp and bolt insert points for mounting to a press. Lifting and handling is discussed further at section 8.4.5. Tools may also need to incorporate access for plumbed in vacuum or resin hose feeds, or electrical cabling plugs.

The method of heating the tool should be determined at an early stage as this will affect the materials used. Heating and cooling lines (fluid-filled) or electrical heating elements can be incorporated in the design. Points for sensors may be required for temperature, pressure and potentially other cure parameters such as dielectric sensors. These aspects are described in sections 8.1 and 8.3.

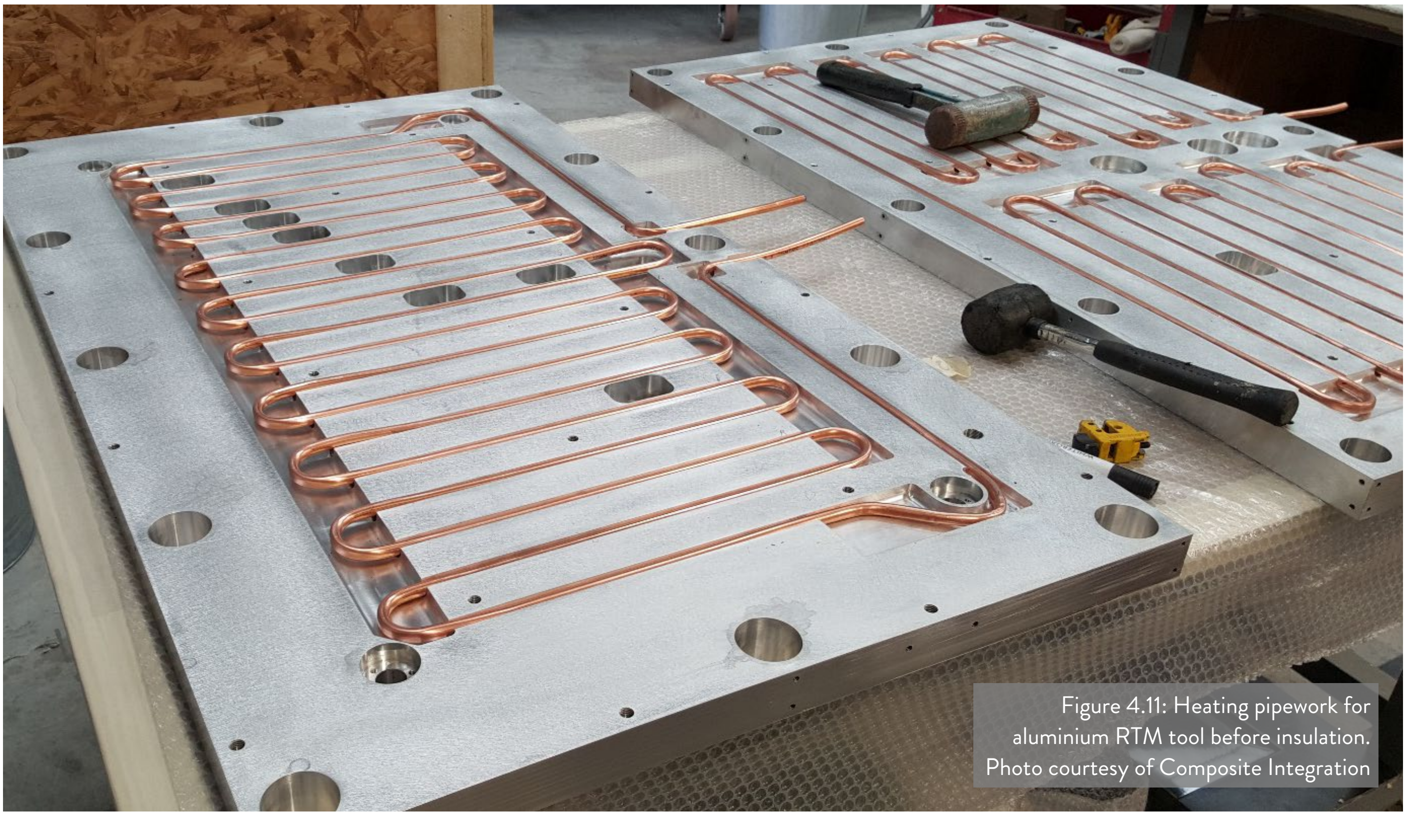

Figure 4.11: Heating pipework for aluminium RTM tool before insulation. Photo courtesy of Composite Integration

4.8 Tools, patterns and sacrificial inserts using 3D printing

Several companies are now printing moulds, patterns and jigs using fused deposition modelling (FDM) with thermoplastic resins. While 3D printing is not suitable for all applications, it can outmatch traditional CFRP tooling methods in terms of cost, time and geometry possibilities, as well as producing very little scrap material and being potentially recyclable at end of life. Mould life and durability where unreinforced thermoplastics are used are still greatly reduced compared to traditional CFRP tooling. Using carbon fibre filled FDM compounds can lead to longer lifetimes, and better CTE matching. The FDM process has some inherent porosity, so parts usually require sanding of the surface followed by application of an epoxy sealer or film to create a vacuum tight surface.[7] (See section 7.5.)

Large format additive manufacturing (LFAM) machines are typically used for larger tooling, up to several metres. See Airtech case study at section 7.5. In LFAM the part is first printed at high speed slightly larger than needed, then trimmed on the same machine to the final size and shape. This is the fastest, most efficient method of 3D printing large structures, and produces a fully fused, vacuum tight finish.[6]

3D printed moulds are capable of more extreme geometries than pattern-made moulds, as the printer is not limited by where an endmill would or would not be able to reach. This allows greater freedom over geometry. 3D print techniques can tackle complex shapes that would be difficult, costly, or impossible to machine. For instance, it is possible to build channels beneath the tool surface to tailor heat control across a part. 3D printed tooling inserts can also carry specific threads or shaped cavities to aid location of functional fixtures across the tool, e.g. to locate sensors or thermocouples that might need to be regularly replaced. 3D printed ceramic inserts have been suggested for extremely high wear areas of tooling for example where there is potential for movement against the dry tool of abrasive fabrics in high FVF HP-RTM parts.

Tool design should primarily focus on printability: Does it have a suitable orientation both for print efficiency and mould surface finish? It is not ideal to have an important mould face in the vertical print direction, as this will suffer a 'raster' effect from a printer's build lines that is difficult to sand or machine back. Mould geometry can often be adapted to accommodate an easy print by doing things such as extruding the B surface down to meet the print bed. As it will be printed sparse (i.e. with open, lattice structure for material efficiency), it uses little, if any, more material than filling the same area with supports. This will also have the added bonus of ensuring the mould can lie flat while being laminated.

Wall thickness on all mould faces should be sufficiently thick to allow a successful seal, too thin can not only lead to sealer and resin leaking into the mould but can also cause the moulded surface to deform. This limit can vary significantly depending on the job.

Expansion rate / CTE is an important consideration. 3D printed moulds will contract post-cure more than the carbon fibre, which will have set while the mould had expanded under heat. This can lead to moulds becoming stuck on parts if they are not designed to come off easily. For this reason, 3D printed moulds are also required to be much thicker than an equivalent mould from CFRP tooling to give them a similar rigidity. 3D printed resins are anisotropic due to the nature of the build process, so properties of the 3D printed material can also vary significantly with the build / deposition direction, especially if fibre filled compounds are used. This variation needs to be factored into the engineering, but capability in design for 3D printing has grown significantly in recent years. .

Scribe lines can be printed even with FDM machines, a scribe diameter of around 3x layer height will produce a visible groove but will only work effectively if printed as a negative in the mould, producing a positive on the part. In LSAM scribe lines would be introduced at the machining stage.

3D printing can also be very useful for jigs and fixtures, or robot arm tools. In many cases a support structure can be printed in one shot with the tool, using a lattice design to save material.

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[6] 'LSAM - Large Scale Additive Manufacturing', Thermwood https://www.thermwood.com/lsam_home.htm (Thermwood's proprietary system uses the term "large scale" rather than "large format", which is used more widely.)

Stratasys has produced design guides for using FDM for composite tooling[7] and for sacrificial tooling and mandrels[8] which are useful references.

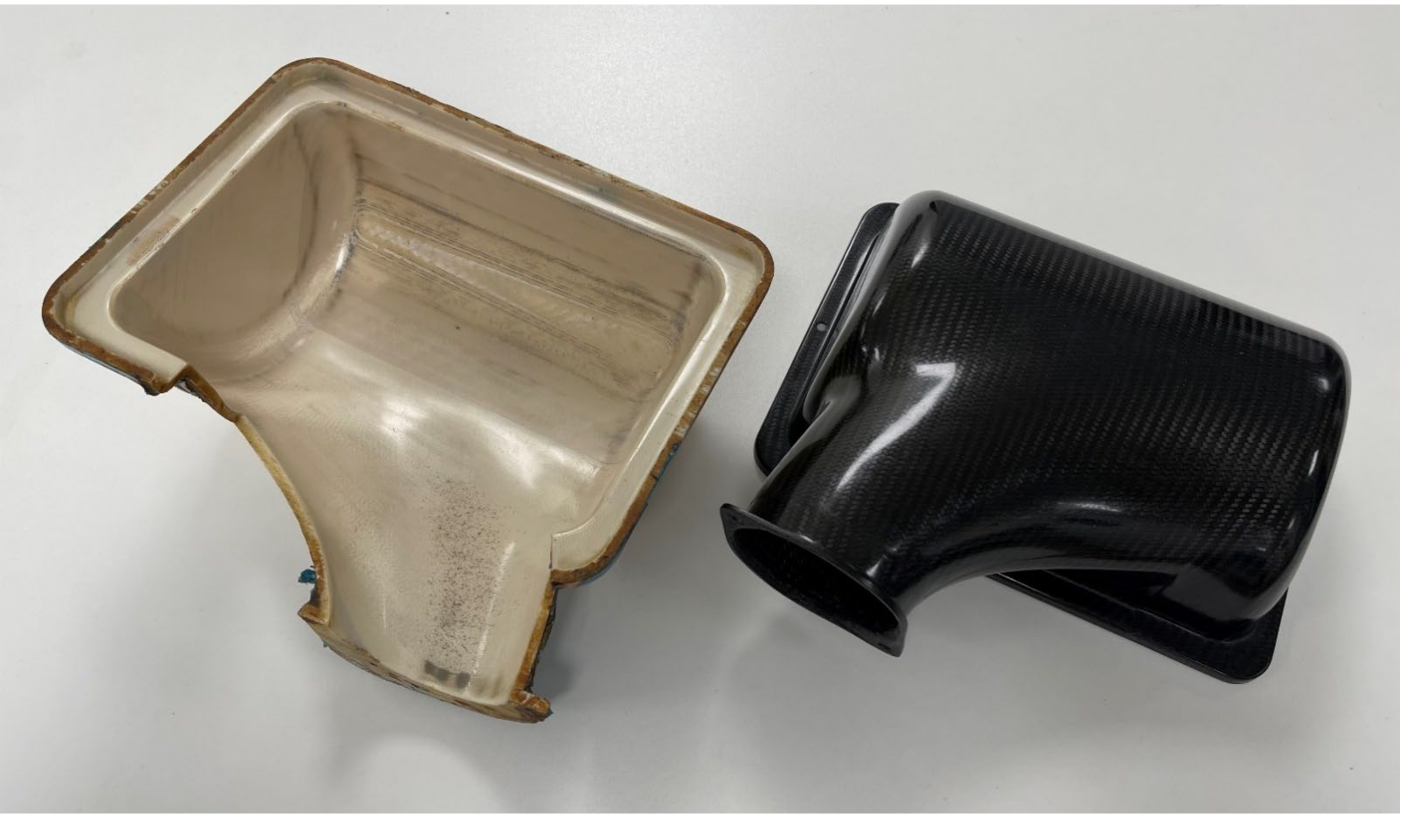

Figure 4.12: 3D printed tool using ULTEM™ 9085 and resulting carbon fibre part. Photo courtesy of DASH-CAE

[7] 'FDM for Composite Tooling Design Guide 2.0', Stratasys, 2020 https://www.stratasys.com/en/resources/resource-guides/fdm-composite-tooling/

[8] 'Sacrificial Tooling and Mandrels for Composite Part Fabrication: Design Guide', Stratasys, 2016 https://www.stratasys.com/en/resources/resource-guides/sacrificial-tooling/

5. AUTOMATION AND PRODUCTION / PROCESS LINE INTEGRATION

It is challenging to say that there is a 'typical' composite part production line as both the materials and the manufacturing techniques employed are many and varied. There is however a constant process of converting raw materials via a moulding process, completed normally with some part finishing. This process often contains a number of typical elements.

Tooling design plays a vital role in supporting both automation and production rate, encompassing a number of elements including the following.

5.1 Preform/material loading

How will the material be prepared into the correct form to load the tool at a rate able to support the moulding process? There is a wide range of methodologies and processes which can support this, all of which are very dependent on the manufacturing process itself i.e., RTM, pultrusion, filament winding etc and the nature of the materials themselves i.e., random fibres, multiaxials, core materials, inserts etc. There is no one solution and many companies evolve a range of techniques to meet the need of their particular product. Automation of complex fibre preforms can be a particularly challenging area, requiring significant specialist automation systems, but where possible, simplicity is key.

Figure 5.1: Automated RTM cells for service covers – single button operation. Photo courtesy of EJ Ireland Ltd

5.2 Tool release systems

Whilst most application of release agent is done manually in existing processes, automated spray bars or internal release agents added to, or pumped with the resin system can improve productivity and reduce risk of operator error.

5.3 Tool heating and cooling

In virtually all composite manufacturing processes, accurate temperature control (typically +/- 2 °C) is an essential element of process control for automation. Due to the exothermic nature of many resin systems, cooling is often required once automated processes are up to rate, rather than heating. As previously discussed in this guide, there are multiple heating methods, but fewer cooling methods, being normally chilled water supplied either directly into the tool, or indirectly to cool existing heated water/oil via a heat exchanger.

5.4 Tool handling/closure/clamping

For high-rate production, this area can be dealt with through various means, but typically, hydraulic presses with sliding beds or mechanically actuated tooling (motor drive, hydraulic actuation or pneumatic actuation) with hydraulic clamping are common methods.

5.5 Injection/infusion inlets/vents and material flow paths within the tool

Assuming tool design has been completed correctly to provide a correctly moulded part each time, automating a discrete process often brings the challenge of ensuring resin feed and vent points are cleaned ready for the next moulding cycle. Automated inlet/vent valves with solvent flushing systems provide this. In addition, depending on the process, both to reduce waste and improve productivity, consideration should be given to non-vented tooling, removing both the waste and cleaning process from that element. Continuous processes can often run for long periods before any cleaning assuming careful material management.

5.6 Process control and part cure monitoring

The list of variables which must be controlled in an automated moulding process can be significant, with the key requirement being to understand the effect of variance of each element, and the means needed to maintain it within specific bounds. These variables may include material temperature, viscosity, mix ratio, flow rate, pressure, vacuum level, clamping pressure, temperature etc.

There are a variety of methods to monitor part cure status in an automated manner. On a well resolved automated system, where all parameters are carefully controlled, this can be as simple as 'time', but is often further supported by temperature data from in-mould thermocouples and/or dielectric sensors. The collection of multiple points of data to form a 'decision point' allows minimisation of tool close time, and aids productivity.

Figure 5.2: Use of vacuum lifters for part handling. Photo courtesy of EJ Ireland Ltd

5.7 Part demould/ejection

Most people involved in composite processing have at some point seen parts 'stuck' into tools, due to release issues, part shape or shrinkage. Tool design for automation needs to consider all these areas along with the inclusion of either mechanical, pneumatic, or hydraulic part ejection to ensure consistent part release.

Figure 5.3: Service cover in operation (relates to Figure 5.1 and Figure 5.2 above). Photo courtesy of EJ Ireland Ltd

5.8 Part finishing

In automated systems, CNC trimming is a standard first step with a wide variety of equipment available in the market. There is also the opportunity for long production runs to develop in house trimming processes to reduce capex whilst still providing a high level of automation. Equally, part polishing, painting etc have a wide range of commercially available solutions from individual machines to complete automated lines, particularly for painting.

5.9 Robotics

Robot arms come in a wide variety of sizes and capabilities, but with correct end effectors, can be extremely efficient for material loading/unloading/trimming/polishing and other handling requirements throughout the process.

5.10 Overall system control and Industry 4.0

A key element in integrating multiple technologies within an automated production line is to bring together both the process control and the process data into a single place. This is normally done by connecting all items of equipment via ethernet to a SCADA (Supervisory Control and Data Acquisition) system. This is a PC based system, communicating constantly to each controller on the production line to ensure process parameters are kept within tolerance, and to record all process data into accessible and historical formats for either further analysis or quality data. This data can also provide pertinent information for feeding into a digital twin to enable offline experimentation. The use of modern secure remote management gateways permits production line support from the equipment manufacturer in real time regardless of where they are located.

Figure 5.4: Use of robots in an automated RTM cell with preform braiding. Photo courtesy of Composite Integration.

5.11 Health and safety

When integrating a number of items of equipment together into an automated system, safety is a key factor which is not always well understood. Whilst every individual element may meet CE/UKCA requirements, and have all necessary safety measures in place, once two or more items are assembled together, it must be assessed as a new system. 'BS EN ISO 11161:2007+A1:2010 Safety of Machinery. Integrated Manufacturing Systems. Basic Requirements' is a good starting point. Key considerations include for example, the fact that all relevant emergency stop systems must be linked at the appropriate performance level (PL) so that any can be operated to stop the entire system regardless of location. Equally, guarding requires special additional consideration.

It should also be noted that one entity should take responsibility for the overall system certification to ensure accurate compliance.

6. SUSTAINABILITY CONSIDERATIONS

The most significant role that FRP composites have to play in sustainability is in enabling more sustainable solutions, such as renewable energy, lighter vehicles and more durable structures. Doing this at lower cost and faster rate enables the environmental benefits of composites to be seen in more applications, and tooling is a key part of that, but does not reduce the responsibility to design for products with lower impact at every level. Sustainability should be a consideration from the start of the design process, alongside cost, safety and manufacturability.

For a fuller resource on sustainability of composites please see 'Sustainability of FRP Composites: A Good Practice Guide' (Sustainability GPG) which is referred to throughout this chapter.[9]

6.1 LCA and trades

Awareness of life cycle assessment (LCA) is increasing, and many manufacturers are now compiling data to enable them to understand the trade-offs between the environmental impact of different parts of a product's life cycle. Different environmental impact factors may conflict with each other. For example, adding a novel surfacing technology to a tool may increase the embodied energy / emissions of manufacture and, perhaps, may make the tool more difficult to recycle, but it may also increase the lifetime of the tool (reduce the number of tools needed) and/or reduce the number of failed parts due to tool damage.

Some factors are easy to quantify, such as energy use, but others less so, such as recyclability, though that can be quantified by estimating a proportion of the material recovered multiplied by the impact of that material. Where improved tooling can reduce the weight of the part, e.g. by increasing FVF, the through life benefits in an LCA may be substantial, and understanding this and collaborating with the client can lead to significant sustainability benefits.

Chapter 3 of the Sustainability GPG gives more information on LCA, and there is a list of LCA tools in the appendix. Two useful, tools for simplified LCA for composites are:

- EcoCalculator, created by the European Composites Industry Association (EuCIA) and free to use.[10]
- MarineShift360, focused on the marine industry, but offers some composite LCA modelling for pattern and mould as well as composite parts manufacture. Starter version is free.

Generic LCA data found online enables a broad overview of impacts and where hotspots are, but where possible, accurate, peer-reviewed data from the upstream supply chain should be used. Upstream material impacts can be very high, especially for carbon fibre.

6.2 Material efficiency and waste

There are several areas where material wastage can be reduced, in manufacture of the tool and part, consumables, and, often overlooked, faulty parts and wrong orders.

A simple but useful calculation to do is to compare the mass of materials that are bought in to a company with the mass of product sold. Anecdotal evidence suggests that this may vary a great deal, e.g. between two GFRP manufacturers using similar processes, one wasted around 5% and another 30% due to differences in approach, quality control and staff training.

The opportunity to use carbon fibre scrap from composite processes in tooling applications is beginning to be realised, and much more work could be done in this area.

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[9] 'Sustainability of FRP Composites: A Good Practice Guide', Composites UK, 2022 https://compositesuk.co.uk/industry-support/good-practice-guides/

[10] 'Eco Impact Calculator for Composites', EuCIA https://ecocalculator.eucia.eu/

Case study: 11th Hour Racing Sustainable Design & Build Report

Amy Munro, Sustainability Officer, 11th Hour Racing Team

11th Hour Racing Team completed a full LCA of its new IMOCA 60-foot offshore race boat, with an in-depth interpretation and associated assessment of circularity, alternative materials and reduced impact scenarios. The study included the major composite components of the mould, hull, and deck and included the design phase, tooling, rigging, sails, and electronics. As a result, the study set a new high-resolution benchmark for a race-ready IMOCA.

MarineShift360 (Beta) was used to calculate the environmental impacts associated with the design and build process:

- Global warming potential (GWP) – 553 t $C0_2e$
- Mineral resource scarcity – 10,300 kg Cue
- Energy consumption – 15,900,000 MJ
- Water consumption – 7,500 m^3
- Marine eutrophication – 232 kg Ne

Photo courtesy of Amory Ross / 11th Hour Racing

Understanding the source and breakdown of these impacts is the crucial step in defining the correct action needed to reduce and mitigate the challenges in the marine boat building sector. Using 100% renewable energy across the supply chain could bring big reductions – the report suggests as much as 30%. Aside from renewable energy use and reusing the boat, the greatest potential reductions in GWP related to tooling.

At 171 t C02e, the plugs and moulds comprise more than 30% of the overall footprint. A study run by the team suggested pathways for reducing this footprint substantially. Prohibiting plugs (female mould only) could save 45.6 t CO_2e, while integrating recycled carbon fibre or flax in non-structural parts of the moulds would reduce impact by 23.6 or 16 t CO_2e respectively, and substituting all epoxy with bio-based resin could save a further 2.7 t CO_2e. Building the steel structure of the moulds for reuse and longevity could also save 6.8 t CO_2e and recycling production waste another 2.2 t CO_2e.

In this study 34.5 t of material was used to build an 8.6 t boat. Extraction and production of raw materials contribute more than 50% to most of the impact indicators due to non-renewable sources and energy-intensive manufacturing processes. Circularity is therefore a crucial factor, with carbon fibre comprising 80% of the material used. This emphasises the importance of integrating alternative materials such as recycled carbon fibre.

The biggest barrier to change in the marine boat building sector is time and confidence. While innovation is inherent to the advances made in the sector, any change is the result of careful trials and testing and requires long-term planning. None of this work can be done alone. The single most important thing is engaging the supply chain to address these challenges together.

Read the complete 'Sustainable Design and Build Report' here: https://www.11thhourracingteam.org/wp-content/uploads/11th-hour-racing-team-sustainabledesign-build-report.pdf

6.2.1 Material waste in tool manufacture

Machining metallic tooling from billet or machining from tooling board, especially from carbon fibre-reinforced block (since carbon fibre has very high embodied energy) produces a high percentage of waste. While metallic machining waste can be recycled, there are substantial losses in the process. Tools made by composite layup result in similar material waste as other composite parts, such as offcuts from ply cutting. 3D printed tooling results in minimal material wastage and is potentially more recyclable, though recyclability may be reduced on some 3D printed tools where epoxy coatings are needed for vacuum integrity or surface finish, or if resin penetrates the relatively porous printed surface.

For one off mouldings, it may be possible to go straight from CAD models to a mould tool, avoiding the need for a pattern, which can be a very substantial material saving, especially for large structures.

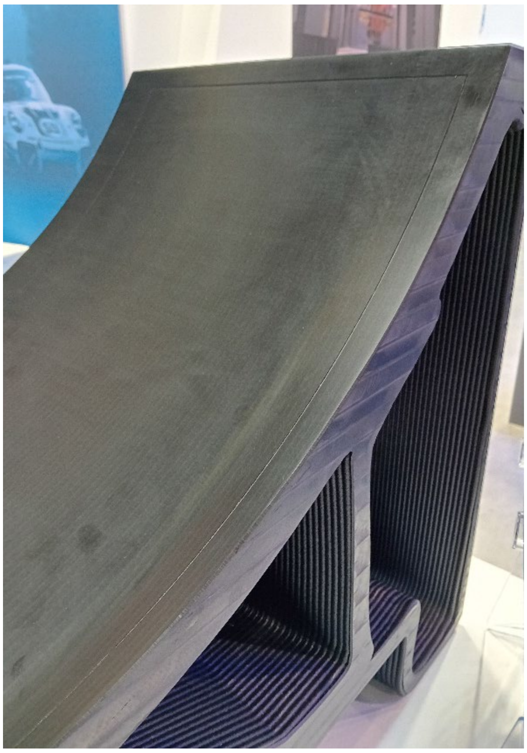

Figure 6.1: Recycled 3D printed autoclave capable tool. An Airtech Dahltram I-350CF tool was remanufactured from demonstration articles at the end of their life and tools reclaimed from customers that were no longer needed. Photo Stella Job

6.2.2 Process material waste in part manufacture

Good tool and process design and selection can reduce the amount of offcuts, trim, overspray, etc, saving both cost and material impacts. Using efficient resin mixing / feed systems limits the amount of resin wasted once infusion is complete. Nesting software limits waste in cutting fabrics.

6.2.3 Consumables

Single use disposable ancillary products such as bagging tape, bagging films, breather mesh, wipes and cleaning solvents can be reduced or eliminated with different tooling approaches. Silicone bagging systems are a great example, depending on the number of uses.

Solvents such as acetone can be recycled with in-house recycling equipment. Dartford Composites was able to demonstrate a complete return on investment within a year for the purchase of a vacuum collection tank and solvent recycling machine.[11]

Recycled silicone release paper is available for use in flat tooling, and where long lengths of used silicone paper are available on rolls, there may be potential to recycle them. [12]

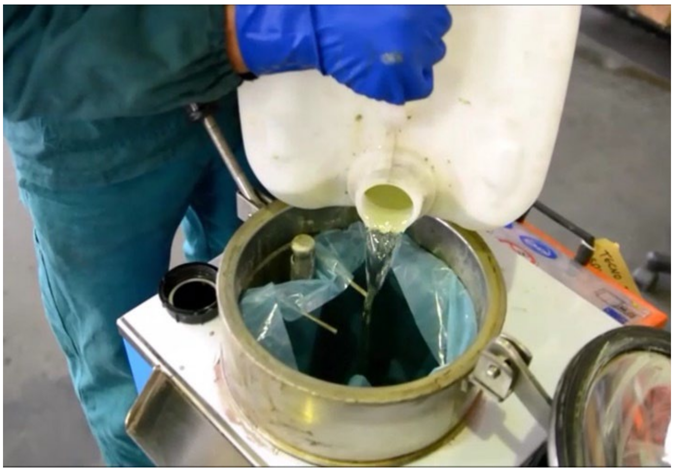

Figure 6.2: Solvent recycling using Ciemme K16 unit. Photo courtesy of Magnum Venus Plastics Europe

6.2.4 Faulty products and specification errors

People often think only of the waste that is inherent to the type of process, but waste from scrap parts can be substantial, due to human or machine error or especially in this case, poorly maintained or damaged tooling. Quality control, tool maintenance and staff training are all essential to reduce scrap rates.

Another substantial source of waste can be specification errors / wrong orders. It's important to work with the client to make sure specifications are fit for purpose, especially if the client is less familiar with composites.

[11] 'Case study – Dartford Composites: Recycling acetone for reuse in the rail industry', ReLondon, 2021 https://relondon.gov.uk/resources/case-study-dartford-composites-recycling-acetone-for-the-rail-industry

[12] Techlan https://www.techlanltd.co.uk/

6.3 Use of recycled or bio-based materials

Tooling represents an opportunity to use lower impact materials. This is especially true for carbon fibre, where matching CTE is important but optimal specific mechanical properties are not required, so it is an excellent opportunity to replace virgin with recycled carbon fibre (rCF). Several companies have demonstrated use of rCF in tooling. rCF can potentially be used in tooling in various ways including:

- Nonwoven mats produced by companies such as Gen 2 Carbon from either dry fibre scrap or fibres reclaimed by thermo-chemical processes, either infused or made into prepreg
- In-house dry fabric scrap, laid up and infused
- In-house prepreg offcuts, sometimes chopped and formed into a moulding compound to make a tooling block
- Compounding short rCF into thermoplastics to make filament for 3D printed tooling

Figure 6.3: Recycled carbon fibre tooling prepreg used in tool for hearse tailgate structure. Photo courtesy of Prodrive Composites

Tooling boards are now available using recycled and bio-based chemical feedstocks[13]. Flax, hemp or other bio-based fibres can replace glass fibre, and resins with bio or recycled PET content can be used. Sustainable (FSC certified) wood, such as jelutong for patternmaking, or recycled wood board products for tooling structures may also be an option. Recycled silicone release paper is available, as mentioned above.

Chapter 4 and 5 of the Sustainability GPG give more information on using recycled and bio-based material respectively, including a case study where Prodrive used rCF fabrics from Gen 2 Carbon for both body panels and mould tools for niche vehicles. Composites UK has a list of commercially available materials with recycled / bio-based content supplied by their members.[14]

6.4 Process energy

Minimising process energy is a clear win-win for environmental impact and cost, and often is associated with faster process times due to reduced heating and cooling requirements. Interest in heated tooling is gaining momentum, with some demonstrating 95%+ energy reductions compared to autoclave or oven. Heated tooling can also bring significant space and tool movement efficiencies if heated tools can remain static, rather than having to be moved. Planning time and costs to plan autoclave load/stack/unload can be reduced.

The number of parts to be made and the value of the parts will be a big factor in determining what is optimal for each situation. Factors to consider may include:

- Use of integrated heating and cooling in the tool
- Good insulation of the tool / autoclave / oven
- Planning so that autoclaves or ovens are only used at full capacity
- Use of secondary heat sources

[13] E.g. see Ru-Bix Envirocast™ Boards https://www.ru-bix.com/envirocast-boards/

[14] See 'Materials With Bio/Recycled Content' https://compositesuk.co.uk/industry-support/environmental/materials-with-bio-recycled-content/

- Moving to renewable electrical energy sources

General workplace energy management is also important, including insulation, use of heat pumps and solar photovoltaic energy generation, installing destratification fans in high-ceilinged workshops. A single fan installed in Far-UK's workshop saves around 2.7 t CO2e/year – equivalent to a year's gas use for a typical four bed home.

For more information see chapters 6 & 7 of the Sustainability GPG.

6.5 Designing for circularity

Understanding what will happen to the tool through its life and at EOL is important in designing for a circular economy. Designers should consider:

- **Reuse**: In some cases tools or support structures can be designed to be reused beyond a single application with some modifications, or modular or reconfigurable approaches may be appropriate.
- **Maintenance and repairability**: Keeping a tool in use twice as long will effectively halve the environmental impact compared to using two tools. Therefore, designing the tool so it can be repaired is key, as are procedures for good maintenance.
- **Design for disassembly**: Coatings and joining techniques can affect whether recycling a tool and its support structure is economically viable, so understanding how a part is likely to be recycled is important. Applying a PTFE coating before laminating the tool allows for separation of materials for recycling.
- **Product marking** - It is good practice to store information on materials used and ideally usage cycles as they may affect the value of a tool or part for recycling or refurbishment.

Figure 6.4: Demolition of a GRP yacht hull mould tool. Photo courtesy of Boatbreakers.com

6.6 Disposal routes

Where waste is unavoidable, it is good practice to follow the “reduce – reuse – recycle – recover” waste hierarchy.

Metallic tools will typically have scrap value at EOL, while there is likely to be a cost to dispose of composite tools. Commercial recycling solutions for cured, EOL composite materials are still limited, but CFRP can be recycled by pyrolysis or solvolysis, and GFRP has solutions through cement kiln co-processing, where the glass fibres are feedstock for cement clinker, or grinding for use in new products. Dry carbon and glass fibres are recycled.

Clean offcuts of film, breather mesh, etc made from commonly recycled materials such as nylon or PET may be recyclable. Suppliers may even have take-back schemes. However, for consumables which are contaminated with resin or silicone sealants, incineration with energy recovery may be the only economically viable route. As mentioned above, in-house solvent recycling equipment is a cost-effective solution for some companies, but there are also chemical or waste management companies who will recycle solvents as a service.

The growth of 3D printed tooling has significant sustainability benefits, as there is minimal material wastage and the tools are recyclable at end of life (EOL), though the effect of many thermal cycles on the polymer may reduce the quality of recyclate. As mentioned above, the need for epoxy coatings with some 3D printing resins limits economic recyclability.

See the Sustainability GPG chapter 2 ‘Design for circularity’ and chapter 8 ‘End of life and recycling’. For up-to-date commercial recycling routes, see the Composites UK page ‘What can I do with my waste?’ [15]

[15] ‘What can I do with my waste?’, Composites UK https://compositesuk.co.uk/industry-support/environmental/what-can-i-do-with-my-waste/

7. TOOLING MATERIALS

As can be seen from the previous chapters, material choices for tooling are critical to their function, the number of cycles they can endure, matching CTE, cycle time, heating and cooling rates, etc as well as affecting the labour involved in manufacture and having very different cost profiles. This chapter discusses the materials used for patterns as well as those used in production tools.

7.1 Material properties and testing

Material properties vary with several factors, and it cannot be emphasised enough that generic material data should always be backed up with testing. Simple testing and sample manufacture is a quick win and very instructive. Both mechanical and thermal properties vary by fibre orientation in composites, and vary with processing of materials – especially with annealing and work hardening in metals, and with fibre layups and cure cycles in composites. A high temperature post-cure can improve mechanical properties of composite parts significantly, and optimum cure cycles are usually recommended by materials suppliers in technical data sheets.

Table 7.1 provides some generic thermal and mechanical material properties for typical materials used in tooling, with a rough estimate of relative cost and the number of pulls expected through the lifetime of the tool, though this varies considerably with tool geometries, cure profiles and handling. This should be seen only as a guide, as materials vary significantly. Sources for table 6.1: [16] [17] [18] [19] [20] [21] [22] and various material data sheets.

7.1.1 Hardness

The hardness of the tool material surface is an important factor in the life of the tool, resisting scratches or defects. There are several hardness scales which can't be directly correlated.

For metals, the Rockwell scales are most common. The Rockwell C (HRC) scale uses a cone-shaped, diamond-tipped indenter with a 150 kg load. The Rockwell B (HRB) scale uses a 1/16-inch diameter ball indenter with a 100 kg load. The higher the number, the harder the material, but only relative to other numbers within a given scale. For example, an P20 tool steel might have a hardness of 30 HRC, while softer aluminium might have a hardness of 60 HRB.[23] Other tests / scales such as Brinell and Vickers may be used.

For polymers, Rockwell M or R scales can be used, but Shore durometer hardness scales are more common: Shore A for very soft materials such as rubber or silicones and Shore D for harder polymers. Shore D uses a hardened steel rod with a 30° conical point and 4.55 kg load. Barcol Hardness is also used to determine the hardness of both reinforced and non-reinforced rigid plastics.

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[16] Beckwith,'Tooling 101 for Composites Manufacturing', FSAMPE, CAMX 2020
[17] Yong Li, Yao Xiao, Long Yu, Kang Ji, Dongsheng Li, 'A review on the tooling technologies for composites manufacturing of aerospace structures: materials, structures and processes', Composites Part A: Applied Science and Manufacturing, Volume 154, 2022, 106762
[18] 'Material Guide', plyable https://www.plyable.com/materials/
[19] AZoM https://www.azom.com/article.aspx?ArticleID=6239
[20] Matweb https://www.matweb.com/
[21] Rogers, 'Machinable Tooling Boards', Explore Composites, 2021 https://explorecomposites.com/articles/tooling/machinable-tooling-boards/
[22] 'FDM for Composite Tooling 2.0: Design guide', Stratasys https://www.stratasys.com/en/resources/resource-guides/fdm-composite-tooling/
[23] See Palmer, 'Understanding the Hardness of Metals', Design News 2021 https://www.designnews.com/materials/understanding-hardness-metals

Table 7.1: Properties of typical materials used for composite tools and patterns. Sources listed at 7.1. Gaps indicate information not available. Last two columns are estimates based on experience. **Notes**: a. flexural or tensile modulus, not Young's modulus. b. values for X / Z orientation. c. No of components with carbon fibre/epoxy tooling may be increased with use of novel materials such as graphene fillers. d. Varies with resin, see 4.5.6.

Material	Max cure temp °C	CTE ppm/°C	Thermal Conductivity W/m·K	Specific heat capacity J/kg·K	Specific gravity	Young's Modulus GPa	Hardness, Shore D or Rockwell	No of components	Cost £ - £££££
Metals									
Aluminium	260	22-25	150-200	890-920	2.70-2.78	70	49-75 HRB	20,000+	£££
Steel (P20/mild)	500	11.3-12.8	52.0	420.0	7.85	210	30 HRC	100,000+	££££
Electroformed Nickel	288	13.1-13.5	61-78	420-500	8.90	207	15-40 HRC	20,000+	££££
Invar 36	250	0.5-2.0	10.4-15.6	510	8.1-8.2	150	66-88 HRB	20,000+	£££££
Composite									
Glass/Epoxy	125-210	11-20	3-4	900.0	1.8-2.0	41	75-89 Shore D	1,000+	£
Carbon fibre/epoxy	125-210	0-9	3.5-6.1	760.0	1.55-1.61	55 (cont fibre) 40 (short fibre)	85-90 Shore D	1,000-5,000 [c]	£££
Tooling boards									
Epoxy tooling board	120-150	35-45	low		0.63-0.74	2.1-2.2 [a]	65-80 Shore D	10-100	££
PU tooling board	40-50	45-55	low		0.60-0.72	~1	66-78 Shore D	10-50	£
CFP 360 (CF/PA6.6) tooling board	180	2.4-3.3			1.29	21	84 Shore D	50+	
3D printing									
ULTEM™ 9085 (PEI)	150	45-50	0.21		1.34	2.5 / 2.4 [b]	93 Shore D	100+ (with epoxy coating)	££
Dahltram® I-350CF (PEI 20% CF)	204	7.6 / 75 [b]			1.15	11.7 / 3.8 [a b]		1000+	£££
ABS	70	84-88	low		1.05	2.7 [a]	85-100 Shore D	(pattern only)	£
ST-130 (soluble)	121	106	low			0.003		1	
Other									
Carbon foam	550	2.3		710	0.56	3.5		<50	££££
Mass cast ceramic	899	0.7-0.8	0.9		2.57				
Silicone	288	80-360	0.2		1.27			20-500 [d]	£

7.1.2 Anisotropy of fibres and CTE

As noted in section 4.3, relative thermal expansion is a key material property to consider for tooling. Thermal conductivity is also important as it determines how heat is distributed through the tool. However, fibres and composites are anisotropic in their response to temperature as well as their mechanical properties. This also applies to 3D printing resins, where properties differ in relation to the direction of deposition.

Carbon fibres are typically dimensionally stable, or may shrink slightly along their length with increase in temperature, but expand in width. E-glass fibres are almost isotropic with small expansion in both directions. Natural fibres and aramids have a much more anisotropic response. Natural fibres such as flax, have a stronger negative longitudinal CTE than carbon fibre, i.e. they shrink in length as temperature rises.[24]

While properties vary for different grades of material, and natural fibres will also vary by plant type, Table 7.2 gives an indication of the variation, where E is the modulus of elasticity, α is the CTE and the subscripts L and T refer to longitudinal and transverse properties respectively. It should be noted that these are the CTEs of the *fibres*, which is not the same once fixed into a matrix.

Table 7.2 Comparison of reinforcement fibre thermoelastic properties at room temperature (fibres not fixed in resin matrix). Data from [24].

	E-Glass	Carbon	Aramid	Flax
E_L (GPa)	77	220	152	63
E_T (GPa)	68	14	4.2	1
α_L (μm/m °C)	5.0	−0.4	3.6	−8.0
α_T (μm/m °C)	5.0	18	77	83

This anisotropy needs to be taken into account in tooling design, especially where more fibres in the part layup are aligned in or close to one direction.

7.2 Materials for patterns

Selecting a modelling route is important, as errors made here can often perpetuate into the whole tool set, and cause issues later in production or in final part quality. For this reason, especially if the design will not be proved in the virtual space in CAD, inexpensive materials will often be required, which allow for changes to the pattern to be made relatively quickly and easily.

7.2.1 Structural elements

Timber can be used for the main structure, but care should be taken that it is dry and of reasonable quality to avoid gross distortions from changes in humidity. For medium sized patterns it is not unusual for the base structure to be a pallet with a sheet of thick plyboard attached to enable the pattern to be moved. Steel framing, usually made from tubular section welded together, is mainly used for larger structures that need to be moved. For example boat hull patterns that are contract machined in one location then shipped to the boat-builder fabrication yard.

7.2.2 Timber and sheet materials

Jelutong is a traditional pattern making wood from which very high quality multi use patterns can be manufactured from 2D drawings by traditional pattern makers. It is low density and very easy to work with using both hand and machine tools.

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[24] Thomason, Yang, Gentles, 'Characterisation of the Anisotropic Thermoelastic Properties of Natural Fibres for Composite Reinforcement', Fibers. 2017; 5(4):36. https://doi.org/10.3390/fib5040036

MDF (medium density fibreboard) board is useful for making cheap eggbox supporting structures. The material is relatively stable, has a uniform surface, and can be easily cut, glued and screwed to form shaped support structures or CNC machined to create underlying detail. Hardboard and lighter MDF boards can also be flexed across supporting ribs to create larger single curvature surfaces.

OSB (Oriented strand board) and other chipboard is stronger but more prone to splinter when cut. This is fine for eggbox structures, but with a random surface of varying absorbency its less useful for surface elements with detail or that will be painted.

Melamine faced chipboard is useful, especially for run-off areas and split-line flanges as the laminate surface can be used as a release surface without the need to prime and paint. It is used for flat areas that do not need a high gloss finish and can simply be waxed before moulding.

Glass can be used as either a pattern substrate or a tool for flat high gloss tool areas e.g. work-surfaces or table tops. Glass will take most release systems, and already has a high gloss but is not always as reliably flat as may be expected. It is fragile and not at all impact resistant, so toughened safety glass should always be used for safety reasons. A sufficient thickness should be used and it should be supported across any significant spans.

7.2.3 Adhesives and joining systems

Structural joints need to be secure against movement. Adhesives appropriate to the materials to be joined should be selected. Ideally, adhesives should be low shrink, and moisture resistant to avoid distortion of joints, or inaccuracies due to changes in humidity causing relaxing or expansion of the joint. Glue and screw fixing is appropriate for framing, glue and pin for boarding and surface sheeting. All screw and pinheads should be countersunk and filled/primed to avoid them witnessing.

Steel frames may be welded or bolted - bolted joints allow for easier reuse of materials, but this needs to be considered against the risk of joints loosening and causing a shape distortion at a critical stage. Extruded aluminium systems with bolt slots can be used and could be appropriate where disassembly and reuse of the structural elements is anticipated, but is costly. It is important to ensure that bolts or friction locking systems are stable and are not likely to loosen.

7.2.4 Expanded foams

Sheet or block foams have the advantage of being very lightweight and easily machinable. They support weight quite well, but do have compressive load limits, and can be easily dented or broken, so its usual to encase foams with a hard shell before applying the surface finish. Foam blocks can be assembled and glued together onto a base board, rough shaped with saws or blades, and then machined more accurately on CNC. For very large patterns blocks can be more accurately rough cut by e.g. hot wire cutting, and then assembled kit-wise on the base board.

Expanded polystyrene is the cheapest option for this type of pattern. EPS is highly prone to solvent attack, particularly from styrene monomer, so care must be taken with choice of glue, and to use water based or low VOC coatings to seal the surface. Polyurethane foams are also relatively inexpensive.

7.2.5 Syntactic foams

Syntactic foams are lightweight by virtue of containing glass bubbles, rather than being 'expanded'. This makes them denser, but also more stable, uniform and able to carry finer detail when machined. They can also be highly moisture resistant and temperature resistant, and so can often be sealed and used directly as the pattern surface.

Syntactic foams can come as block and sheet materials, known as tooling block, or in paste or liquid format that can be cast, trowelled or spray applied. Tooling board syntactics are predominantly epoxy matrix. Polyurethane and phenolic syntactics are available, but rarely used for patternmaking. Liquid syntactics can be made from urethanes, vinyl ester, or shrink compensated polyester resin systems.

Specific modelling clays are often used – especially by the motorsport and automotive sector, and these often also include glass microbubble fillers to reduce weight and improve machineability.

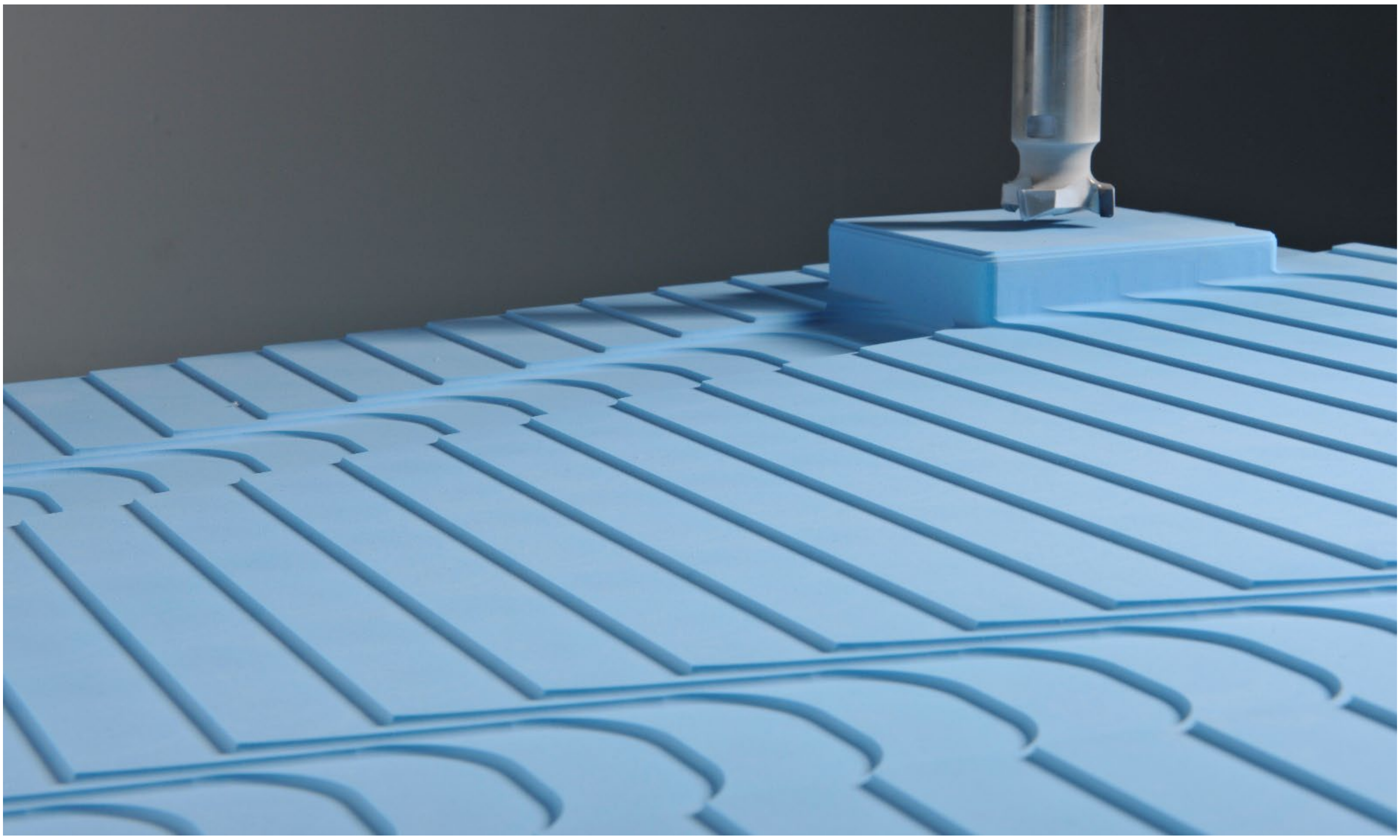

Figure 7.1: BE978 epoxy tooling material from Base Materials. Epoxy and polyurethane tooling materials are available in a range of board sizes and thicknesses. Photo courtesy of Base Materials

7.2.6 Machining pastes and spray syntactics

Syntactic foams and pastes can be applied by machine using a variety of dispensing heads. High viscosity putties and clays can be used to rapidly build up thicknesses between 1 and 5 cm without slump, extruded through a spreader head. Lower viscosity machining pastes can be sprayed, using airless spray heads with large nozzle sizes, and typically applied in thicknesses from 2-8 mm per pass.

7.2.7 Standard section profiles

Where seals and fixtures are to be a feature of the tool, then standard section profiles are a useful addition to the patternmaker's armoury. Mounted proud of the main pattern surface they create an accurate recess on the tool. Made from PVC, HDPE or silicone they self-release easily and can be glued lightly into a routed channel in the pattern, or surface bonded to stand proud of the pattern surface. Some care needs to be taken that these are perpendicular to the pull direction, but should they part from the pattern on demould, they should be easy to remove without damaging the tool. Profiles are also available for accurate radii in corners, and for creating location features on mating flanges to aid accurate tool closure.

7.2.8 Primer and sealer materials

A sealing layer is required on any material that is likely to be porous or highly absorbent. It should penetrate and seal off any bubbles, cracks or pores in the substrate, and when dried be resistant to and compatible with the topcoat system. A primer layer should be relatively flexible or sandable to allow minor surface repairs to be made easily prior to topcoat application. Low VOC epoxy or polyurethane based primer/sealers are the most universally useful. Primers typically have a matt finish to provide a receptive surface for gloss topcoats.

7.2.9 Pattern surface finish

The surface finish of the pattern will preferably be as close to final part finish requirement as possible, but if necessary, some final finish work can be done on the tool. The surface needs to take the release system and/or multiple layers of wax which will be polished. The better the pattern finish, the less work will be required for the tool finish, so judging the balance of labour input is important. It might be easier in terms of physical access to do the bulk of the finishing work on a male or positive shaped pattern surface, rather than the negative or female tool surface.

Surface finish coatings depend on the substrate and finish required but are typically a hard enamel, polyester or two-part epoxy or urethane paint.

7.2.10 Release systems for patterns

Hard waxes are the traditional method for creating a reliable release between pattern and tool. For room temperature laminating of GFRP tools a standard 60°C wax is adequate, but if a high exotherm is expected or an elevated temperature post-cure is required than a high temperature (80°C) wax should be used. Wax is applied in multiple layers, rubbing it on in a circular motion with a soft lint free cloth, polishing and allowing to dry between each coat according to manufacturer's instructions.

Where tool release is likely to be problematic, for instance where there is a deep draw on the shape with small draft angles, and where a high surface finish is to be applied on the tool rather on the patterns, then poly vinyl alcohol (PVA) is sometimes used beneath or instead of a wax coat as a 'fail-safe' release system. This is because, unlike wax, PVA is water soluble and in the case of a 'stick-up' then dissolving the release layer can recover the situation. In this situation PVA solution is brushed on to the pattern liberally taking care to avoid drips and repeated after the first coat is dry to ensure full coverage. The tool finish in this situation will be semi-matt one, but once washed off, dried, and lightly sanded can be refinished if required.

It is common to use semi-permanent release systems on patterns, which offer excellent release properties, but care must be taken to ensure the surface does not have too much 'slip' leading to potential pre-release during toolmaking. Hard wax can be added on top of a semi-permanent system to reduce slip and ensure a rigorous approach to protecting the pattern from potential damage during tool demould.

7.2.11 Textured finishes

Texture can be added to the pattern, or areas of it, in various ways, but a common one is to stick a textured film to a flat area – often within a defined border or recess. These films can be commercial self-adhesive texturing films, or sometimes bespoke textures cast in silicone from a desired surface and glued in place. The texture or detail will be accurately reproduced in reverse on the tool and replicated on the part.

7.3 Composite tooling

The majority of tools used by composite manufacturers for low volume products are made from composite materials, using the same fibres as the part, as the CTE will then match, and the skills to manufacture and repair the tools exist in-house.

7.3.1 CFRP tooling

Carbon fibre tooling is best deployed when making carbon parts, as it offers the best CTE match. Carbon tooling is most frequently made on a metal or tooling block master, and the layup normally designed to be quasi-isotropic, and balanced, with thinner surfacing plies, and thicker 'bulking' plies providing the majority of the stiffness. Resin matrix choice depends on the anticipated production cure cycle.

Specific prepreg materials designed for tooling are designed ideally to be relatively easy to work with, and the matrix materials combine heat resistance with toughness. Increasingly prepreg tooling matrix and surfacing materials are being enhanced with nano-additives such as graphene to improve toughness and heat conductivity (see Haydale case study), or silicon carbide to improve wear and surface hardness.

Matrix resins for carbon fibre tools depend predominantly on the process temperature requirements. A common 'rule of thumb' is that the Tg of the tooling resin, or the HDT of the tooling, needs to be at least 20°C above the maximum expected process temperature.

Case study: Graphene-enhanced prepreg for composite tooling

Simon Green, Sales Director, Haydale Composite Solutions

Haydale has developed and commercialised a graphene-enhanced epoxy prepreg tooling material after extended field trials with automotive composite parts manufacturer, Prodrive Composites, where it has enabled more than double the number of composite parts from a single tool.

Unlocking quality tooling

Using Haydale's HDPlas® technology, functionalised graphene is added to high performing tooling epoxy resin and then pre-impregnated onto a suitable carbon fibre reinforcement for use in tool manufacture. This gives extended tool life due to the better surface quality, leading to less frequent tool changes and reduced costs and environmental impact. The thermal nature of graphene also improves homogenous cure as it reduces the differentials between hot and cold spots, leading to tighter tolerance parts.

Extended tooling life

The tooling prepreg has been on trial for two years with Prodrive and they have been delighted with the performance they have seen.

> "We have been producing duplicate parts with both our standard and the nano-enhanced version and can say with confidence that the Haydale material has delivered more than 500 parts without any deterioration of the mould surface. Using the standard version, we would expect approximately 250 pulls from a tool before it is replaced," says Matt Bradney, Director of Business Development, Prodrive.

Ease of use

The graphene-enhanced prepreg requires no changes to standard processing for use in autoclave and out-of-autoclave (OOA) applications. The resin system is applicable to all standard carbon fibre reinforcements and is available in production quantities through a fully accredited and established UK supply chain.

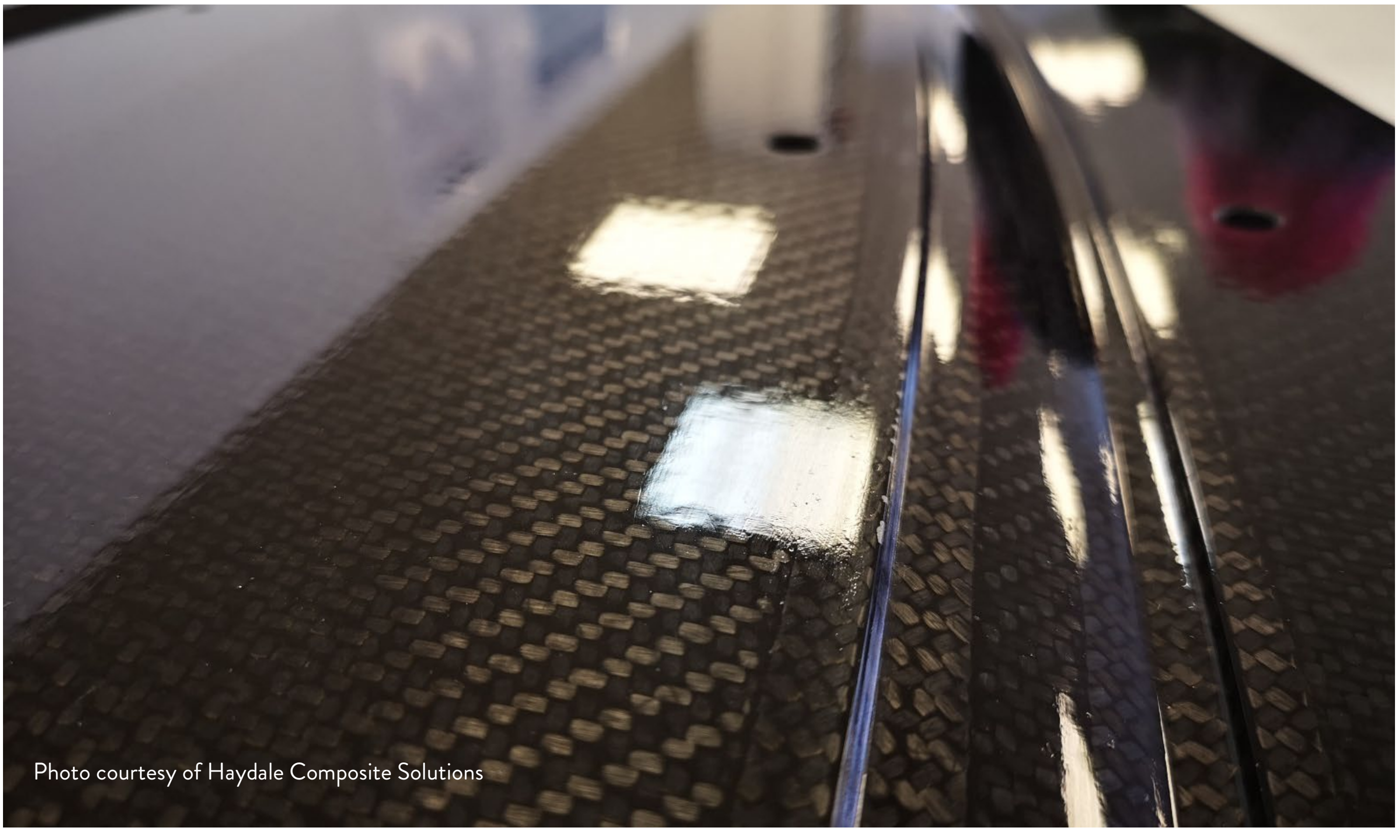

Photo courtesy of Haydale Composite Solutions

7.3.2 GFRP tooling

Glass fibre-reinforced tooling is predominantly used for glass fibre parts and low to medium temperature processes. Satin, plain or two ended plain weave fabrics can be used for smoothness on flat and low curvature tools, or twill grades for better drape. Often a discontinuous fibre tissue or surface veil is used to hide any 'print through' from the bulk fabric.

7.4 Metallic and hybrid tooling

Metallic tools are used to best advantage where durability and resistance to repeated hot cycling are essential for the manufacturing process. Metals generally have good thermal conductivity, enabling rapid heating and cooling, but also have higher thermal mass, needing more energy per cycle to heat both tool and part. Good insulation reduces energy wastage. Metals such as steel and aluminium and nickel will have mismatch of CTE with the composite component which will need to be managed within the tool design and the process to ensure dimensional accuracy of parts. Metals may be machined directly from billet or formed from a sheet, then machined and hand-finished.

Nickel-iron Invar alloys (typically Invar 36 or Invar 42, with the number representing the percentage of nickel) have very low CTEs, close to that of carbon/epoxy composites. The very low CTEs are due to a high-magnetic-moment frustrated ferromagnetic state reached at a nickel content of 36% (see Figure 7.2:). As the metal is heated it transitions from ferromagnetic to paramagnetic phases, determined by the Curie temperature (280°C for Invar 36). This causes the CTE to rise significantly above about 200°C.[25] A higher nickel content leads to a higher Curie temperature.

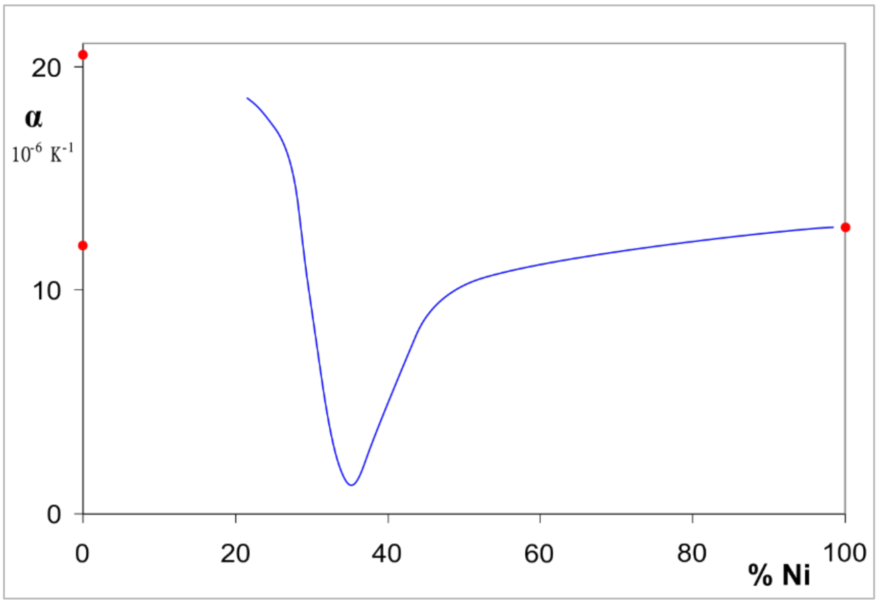

Figure 7.2: Graph of Coefficient of thermal expansion set against nickel content of nickel-iron alloy (Invar alloy). By RicHard-59, CC BY-SA 3.0

Invar is widely used for high performance aerospace composites, but expensive and less easy to form and machine than steel and aluminium.

Steel tools are hard wearing but take longer to machine than aluminium. P20 steel (high tensile pre-hardened steel) is often used for tooling, or sometimes stainless steel. Aluminium can be a very economic route for medium-run tooling, reaching higher volumes when tools are hard anodised (e.g. 5000-20,000+ parts) and prototype tooling, or where the CTE difference can be used positively for consolidation. A risk with aluminium is fibre damage to tool edges if crimped in a zero or low thickness region. Table 7.3 gives a brief summary comparing steel and aluminium tooling. There is a useful article with more information at Clinton Aluminum.[26]

Nickel shell tools are around 4-6mm thick and typically mounted on a steel frame. The nickel is electro-deposited onto a master model, or bath model, at a rate of 0.001 mm/hour in an electroforming tank. Care must be taken with electroplating to avoid thickness variations, especially on male and female radii, so the model is frequently taken out of the tank in order to measure the deposit and, if necessary, adjust the shields and anodes to obtain an even nickel thickness.[27] This is a time-consuming process, but material and energy use are low.

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[25] 'INVAR Alloys', Total Materia https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&LN=IT&NM=374
[26] 'The best aluminum alloys for molds', Clinton Aluminum, 22/5/17 https://www.clintonaluminum.com/the-best-aluminum-alloys-for-molds/
[27] 'Nickel Lay-up Tools', Corima Technologies http://www.corima-technologies.com/en/nickel-lay-up-tools.php#

An electroformed nickel-iron alloy, GalNiFe (similar to Invar), has been developed by Galvanoform for making shell tools with a low CTE, suitable for processing carbon fibre materials. The tools are usually mounted in steel frame structures, and enable compensation for the effects of spring back.[28]

Table 7.3: Comparison of steel and aluminium tooling

Benefits of steel	Benefits of aluminium
Lower CTE (steel ~12 ppm/°C vs. Al ~23 ppm/°C), but the CTE difference can be used positively for consolidation	Higher thermal conductivity (steel ~50 W/m·K vs Al 150-200 W/m·K) leading to faster heat transfer, reduced need for cooling water lines, more even tool temperature
Durability and hardness leading to much higher number of parts per tool	With the right alloy, no need for heat treating or stress relief - potential for hard anodizing (an electrolytic conversion to thicken the oxide layer)
Strength and stiffness	Much easier to machine and polish

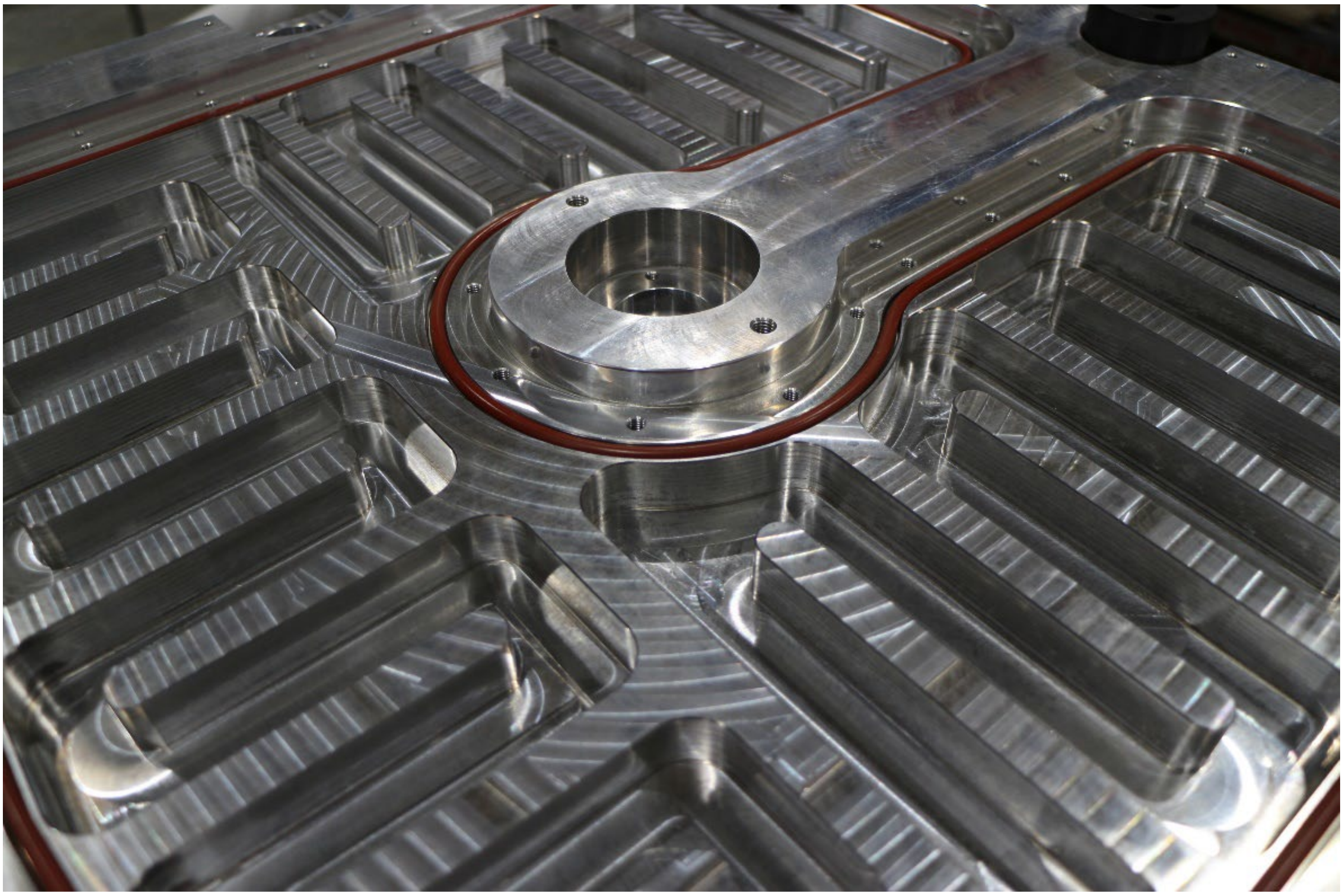

Figure 7.3: P20 steel RTM tool machined for oil heating. Photo courtesy of Composite Integration

[28] 'The future of molding' (Milestone 2), Galvanoform https://www.galvanoform.de/company/?L=1

7.4.1 Metal skin tooling

Putting a more durable metal surface onto a metal substrate is an additional way to enhance durability and reduce cost and mass. Two main methods are used:

- **Chemical vapour deposition**: This is a well-established method for creating a robust free-standing nickel-shell but because the master shape or mandrel must be heated to a high temperature to induce deposition, the technology is limited to depositing nickel onto metal masters.
- **Metal cladding**: This involves adhering a metallic foil or tack welding a metal sheet to a backing structure. These methods significantly reduce the material cost of a large tool and provide a durable surface, but are only suitable for tool surfaces that have low curvature, and not practical for those with compound curvature or complexity.

7.4.2 Metal faced composite tooling

Putting a metal surface on a composite tool can be a good way to improve durability, scratch resistance, and spread thermal loads more evenly across a tool surface, though the cost and lead times associated with these processes may not be worthwhile as compared to having two composite tools. A thin metal coating may also be subject to damage, and is not the same as a solid metal tool. Various methods are used to achieve this including the following:

- **Thermal spray coating.** As the name implies, this technology involves spraying molten metal onto the tool surface. However, when the melted droplets of metal fly through the air, they oxidize. Metal oxides tend to be brittle so the metal coating can be rough or even porous and have low strength. As thermal techniques and powders improve this technology may find a cost-effective niche. Similar techniques are used to create heat resistant ceramic surfaces on composites, which find uses in close to engine parts in F1 and automotive. These coatings have also been evaluated for specialist tooling applications, including for microwave transparent tools and wear resistant inserts.
- **Electro-deposition and electrodeless deposition**. These coating technologies have been developed in R&D projects[29] but there has been limited commercialisation. Methods include copper/chrome and copper/nickel/chrome plating, of glass fibre epoxy tools, but most processes do not produce a coating alloy that has thermal expansion low enough maintain a good CTE match with carbon/epoxy. A 'nanostructured' very fine grain iron/nickel alloy coating, Nanovate-NV (also known as Nanovar), effectively Invar electrodeposited on epoxy carbon tooling has been developed by Integran with Advanced Composites Group (now part of Solvay). The smaller metallic grain structure is much harder and more scratch resistant than forged Invar, though inevitably it is then harder to polish.[30]
- **Physical vapour deposition.** This technique creates coatings on a substrate via sputtering or the use of electron beam energy within a vacuum chamber. The techniques are best suited for forming very thin, accurate layers on small objects. They are impractical for use on larger composite tools.[31]

7.4.3 Composite faced metal tooling

A reverse methodology for hybrid tooling is to make the main structural and face elements of the tool from Invar using thinner plate to reduce cost, then lay up a pad of quasi-isotropic carbon/epoxy or bismaleimide tooling on the Invar, and machine this to give the tooling detail. This method can reduce the capital cost of aerospace prototype and short-run tools, compared with thicker Invar tooling.

Commercial practitioners of this have developed proprietary methods for ensuring good adhesion between the Invar base plate and the composite. The advantages are reduced mass and thermal mass, compared to an all-Invar tool, reduced and faster machining and ability to more easily re-machine the composite layer for tool adjustments, while retaining the better long term vacuum security of a metal surface in the run-off area. This approach also has the advantage that after the

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[29] E.g. 'Metal faced flexible composite tooling (MFCT)', Morganic Metal Solutions https://www.morganicmetalsolutions.com/metal_faced_flexible_composite_tooling.htm

[30] 'Why Nanovate?', Integran https://www.integran.com/what-is-nanovate-technology

[31] Sara Black, 'New metal coating to optimize composite tooling', Composites World, 1/5/08 https://www.compositesworld.com/articles/new-metal-coating-to-optimize-composite-tooling

component life or prototyping cycle is finished the composite elements can be burnt off, and the Invar base tool cleaned and reused.[32]

7.4.4 3D printed metal tooling

Metals are 3D printed in a variety of ways, for this context divided into powder bed and wire spool techniques.

Powder bed technology is still limited in size and further restricted by having to choose a single build direction. This is fine for small and medium sized tools and inserts, and powder techniques such as selective laser sintering (SLS) can create amazing detail and complexity.

Lincoln Electric have demonstrated large aerospace face plate tooling made using WAAM or ‘wire arc additive manufacturing’. This technique relies on a robotic welding head, either laser or metal inert gas (MIG), continuously placing beads of metal fed by wire spool. By tilting and rotating the base plate this technique allows the designer to shift the build axis during the build, and this allows much more freedom of size and shape. The procedure is complex and the cost case relies on the fact that Lincoln Electric Group can make their own wire alloy feedstock, have their own software for both deposition and machining, and large format milling machines to carry out the necessary refinishing to a high level of accuracy.[33]

7.5 3D printed soft tooling

3D printing techniques are continuously improving, as are the available materials and material formats required. Lower cost materials such as PLA or ABS can be used to make patterns from which to make a composite tool[34] and ABS is often used for low temperature tooling. Higher performance polyetherimides (PEI) are used for tooling for autoclave cured CFRP parts, e.g. ULTEM™9085 or 1010. Resins may be reinforced with carbon fibre such as the LFAM resin Dahltram® I-350CF. As noted in section 4.8, which gives some pointers on design of 3D printed tools, the properties of 3D printed material can vary significantly with the build / deposition direction, especially if fibre filled compounds are used.

3D printing has the advantage that it accurately reproduces digital shapes, and in general, because materials can be placed only where needed, it reduces the quantity and weight of materials used for the tool. The post print surface quality will typically be stepped or ridged, more so with LFAM than with FDM. This means that some post print sanding or machining is required. Different resins and printing systems have different requirements, so the supplier’s advice should be checked.

For smaller parts using FDM, it is usually advised to refinish and seal with epoxy coatings – these will improve surface quality and tool life, and are required if vacuum integrity is needed at the tool surface. Fluorinated ethylene propylene (FEP) film may also be used as an alternative to epoxy coatings.[35] The need for vacuum integrity can be avoided by using envelope bagging, in which case the epoxy coating may not be needed (unless required to improve surface finish or for longevity), though release agents and degreasers would be used as per the norm. There could then be some leakage of resin into the tool due to the porosity of the printed material, which ideally should be avoided.

Tools printed using LFAM are vacuum tight without the need for surface coatings. Machining is required post-print for dimensional accuracy and to remove ridges and add details such as scribe lines if needed.

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[32] Richardson, 'Tooling to mould and die for!' Aerospace Manufacturing 6/4/18 https://www.aero-mag.com/ascent-aerospace-hyvarc-hybrid-invar-composite-mould/

[33] See Lincoln Electric https://additive.lincolnelectric.com/

[34] ‘Making a Composite Mould from a 3D Print’, easycomposites https://www.easycomposites.co.uk/making-a-composites-mould-from-a-3d-print

[35] See section 4 of ‘FDM for Composite Tooling Design Guide 2.0’, Stratasys, 2020 https://www.stratasys.com/en/resources/resource-guides/fdm-composite-tooling/

Case Study: Large scale 3D printed tooling for BAE Systems

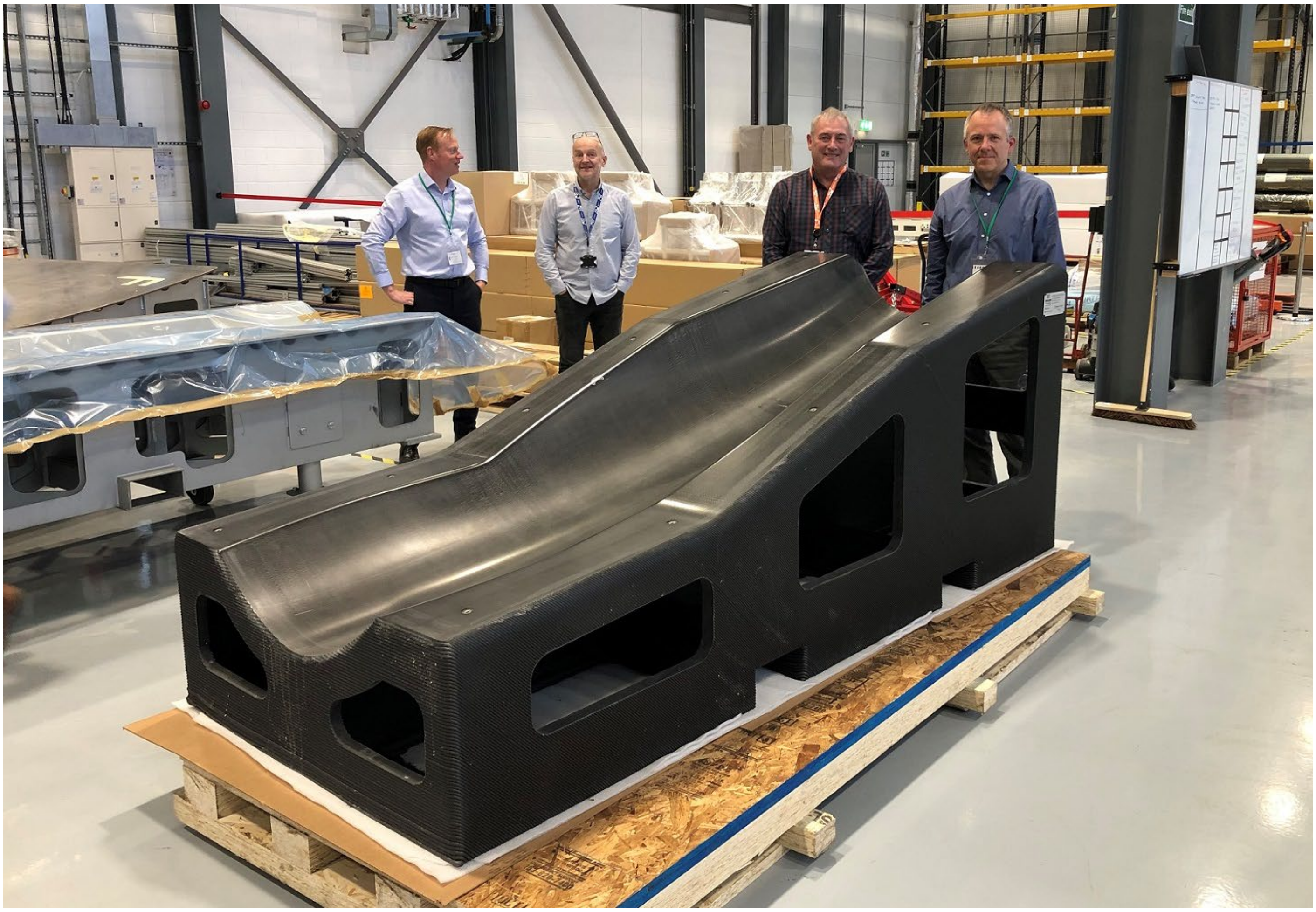
Airtech Advanced Materials UK

BAE Systems is using large scale 3D printing to produce high temperature mould tooling utilising Airtech Dahltram® I-350CF resin in the production of a manufacturing technology demonstration activity for exploitation in the Combat Air environment.

The Dahltram® I-350CF system is a high temperature capable, carbon fibre-reinforced, PEI based 3D Print resin, which has been adopted by the aerospace industry. BAE Systems has been working on the development of the manufacturing process with Airtech Advanced Materials Group and Ingersoll Machine Tools, Inc. who printed the mould tool on their MasterPrint large format 3D Printing platform.

This approach builds 3D near net shape tooling faster than any other process, reducing complexity, risk of delay and associated mitigation costs. Face skin and sub-structures can be fabricated simultaneously, and easily machined to accurate profiles, and there is a large reduction in material waste compared to the traditional subtractive manufacturing supply chain. All Airtech additive resins are 100% recyclable so printed scrap or retired printed moulds can be reclaimed: an AM CFR composite mould tool produced with Dahltram® I-350CF resin was recycled after use into usable pellet feedstock and then remanufactured into a new usable composite tool.

The Dahltram® range of resins are suitable for multiple print platforms, providing production flexibility with end use material approvals. Continuous thermal cycle testing, pressure leak testing, laser surface scanning and contact material testing have generated data supporting over 500 autoclave cycles, without degradation of the Dahltram® manufactured tooling. Airtech Advanced Materials Group has Dahltram® Additive Manufacturing Resins and Print-Tech® large scale 3D Printed tool manufacturing capability in the USA and Europe.



7.6 Flexible tooling

A tool that has some degree of flex is sometimes used to mould parts that have some undercut, but where a split or multipart tool is undesirable for reasons of aesthetic. This goes against most tooling design guidance. A well-known example is racing seats where to achieve a tight fit, the sides of the seat fold in a little over the legs, providing extra security and a better feel for the car. Since the tool has to be bent to 'pop out' the part from the tool every time and return to shape they are typically made with woven glass fibre for strength, and use a toughened or rubber modified vinyl ester or epoxy for additional flexibility and fatigue resistance. For such tools the B surface tool will also often be a flexible silicone membrane.

It is possible also to design tooling with a 'composite hinge' using rubber or urethane prepregs or films co-cured with stiffer prepregs, such that the fabric or fibre reinforcement maintains the dimension and shape across the hinge line, but the tool can flex there and open out to release the product. This is clearly best where the part has suitable bilateral symmetry.

7.6.1 Inflatable bladders

Bladder materials can be made from rubber – literally a balloon in the simplest case, but more often bladder inserts are fabricated from vulcanised rubber sheeting, Thermoplastic polyurethane (TPU) synthetic rubber sheeting, silicone membranes, or even epoxy prepreg tooling with flexible hinged elements (see above).

7.6.2 Silicone membranes

Silicone membranes are used in a variety of ways within the tool makers armoury as a replacement for bagging films, or as a reusable flexible top tool for a B surface.

The best silicone materials, cured with platinum catalyst technology, leave no detectable free silicone and are now routinely used in direct part contact without surface contamination issues. However, traditional concerns over the possibility of 'kissing bond' failure due to silicone contamination means aerospace and other safety critical components are still preferred to be separated from such membranes by breather and release films, although they are still used to replace the vacuum bag, reducing considerably the amount of consumable waste associated with prepreg manufacture.

Silicones are supplied in liquid formats of varying viscosity, for brush or airless spray fabrication techniques, or in pre-cured sheet form. The membrane can incorporate mesh, fabrics and plates to control stiffness, stretch and flexibility within a tool element made from the one silicone rubber matrix material.

It is also possible to create additional functionality within a silicone membrane, for instance, by moulding the silicone over a mesh or creating a specific volume void in the top tool it is possible to create a resin self-distribution system or "flow field". This can allow a 'fill and forget' process where the resin feed to the part is regulated entirely via vacuum, rather than via a metered pump. See also 4.5.6 Flexible tooling

7.6.3 Soluble and single use inserts

Several materials can be used in single use inserts or 'lost core' techniques, as an alternative to clamshell tooling or silicone bladders. These include low melting point metals, eutectic salts or sand patterns, ceramics, cast urethanes.

Alternatively mandrels can be 3D printed, either using sacrificial, soluble thermoplastics that dissolve in a basic (> 7 pH) solution[36], or using thermoplastics which can be softened beyond certain temperatures and removed, offering potential for reuse.[37]

Figure 7.4: Sacrificial mandrels printed in lattice formation with Stratasys ST-130, which can be dissolved out after the part is cured. Image courtesy of Stratasys

[36] E.g. Stratasys ST-130 https://www.stratasys.com/uk/materials/materials-catalog/fdm-materials/st-130/
[37] E.g. 3D systems Accura® Xtreme™ White 200 https://www.3dsystems.com/materials/accura-xtreme-white-200

8. PROCESS CONTROL, SAFETY AND OPERATION

Repeatability is a key part of product quality, and correct temperature and pressure profiles, monitored and managed throughout the production cycle, are critical to successfully creating consistent parts and tools. Knowing the process, and which are the critical control parameters, is important. This is especially true in composite processing where the material is made at the same time as the part. A very basic tool may not have any process control features, but will nevertheless ideally have good labelling, showing part and tool numbers, date of manufacture and last maintenance. It may be RFID tagged or bar coded, so that the operator can scan it at each production stage and so report production process in real time. More complex processes may require any of a range of control and monitoring systems, as described in this chapter.

Controlling temperature and pressure is also important for safety reasons, and this chapter also briefly covers this and other safety and operational factors. Energy efficiency is increasingly an important factor in terms of both economics and sustainability targets. Good understanding and monitoring of temperature and pressure can lead to significant efficiencies, and tools should be chosen and designed with energy efficiency in mind.

8.1 Temperature control and tool heating

Thermoset composites release exothermic heat as they cure from liquid or semi-liquid to solid form, so a well-designed tool and control process will utilise this 'free' chemical heat, while not allowing it to run away and create issues associated with over-heating. But the cure process requires energy to start it, either by raising the materials to an auto-initiation temperature, or by a chemical trigger. Once the chemical cure reaction has started, then the heat released or exotherm must be controlled within safe limits, or the temperature can exceed safe operating temperature for the composite materials themselves, even causing charring or fire, damaging the tool and process equipment, or generating unpleasant or toxic fumes and smoke. The physical properties of the final composite component will also be influenced by the 'cure profile' during the process, and so will other attributes such as shrinkage.

Thermoplastic composite processing is almost the opposite in that the thermoplastics start solid, and need to be heated well past their Tg – glass transition temperature, which is a property of the amorphous portion of a semicrystalline material, where the materials transitions from a glassy to a rubbery state. The melting point is usually quite a bit higher, so they need to be held close to or normally just above their melting point long enough for them to be formed or flow to shape and for pressure consolidation. Then they need to be cooled at the right rate so that the desired physical properties such as crystalline/amorphous chemical structures can form. Rapid cooling will tend to form more amorphous polymers, which are less dense, more flexible and soften at lower temperatures. Controlled cooling, and even annealing, can increase the degree of crystallinity as it allows the polymer chains to reorder themselves into crystalline domains.

There are a number of ways of providing process temperature control, and some of these can be built into the tool rather than relying on ambient conditions, or global heated areas such as ovens and autoclaves. The thermal mass of a tool and its support structure can be quite significant, so the energy and time required to heat and cool a whole tool in a controllable way is one of the reasons that autoclave and oven curing takes a long time.

For single-sided tooling, including tools with thin top tools, bags or flexible membranes, directional heat, for example from hot lamps or heater blankets can be an effective solution to speed up process. Most other alternatives to global heating will be effectively built into the tool, as described below.

8.1.1 Space heating - autoclaves and ovens

The heat supply to both autoclaves and ovens is either by direct or indirect heating of the gas inside the chamber. Indirect heating has the heat source outside the autoclave and transfers this into the working envelope through a heat exchanger. Direct heating systems have their heat source inside to maximise the heat transfer to the gas pressure medium. Heating can be either electric or gas. Choosing which to go for needs evaluation of the whole system and the relative importance of

Figure 8.1: Autoclave interior. Photo courtesy of the National Composites Centre

cleanliness, efficiency, controllability, ease of maintenance and running costs, as well as the potential for decarbonisation of energy sources.

In both cases the objective is to create an even and controlled temperature throughout the space. This is not a simple as it sounds in that the autoclave or oven, tool supports, tool and part materials will all act as heat sinks and heat up at different rates. Control systems are necessary to manage cure cycle temperature strategies, heating gradients, dwell times and cooling gradients, in accordance with the material specified or design criteria.

The heat control systems are reliant on input from multiple temperature sensors within the chamber. Sensors can be at multiple points within the chamber, embedded at critical points in the tool, or even within the part itself. The most common sensors are thermocouples, and these are connected via heat resistant cabling through pressure tight ports through the chamber walls. The hardware associated with the control systems usually involves a PID controller, linked to a computer with control and monitoring software, allowing real time viewing of the process.

Open loop control systems control heating and cooling to a set program and monitor or log the actual temperatures throughout. They will usually have safety features and redundancy allowances to detect a runaway exotherm, and shut down heat or note a detective sensor and carry on with a cure. The aim is always to fail safely in the event of a malfunction or unexpected thermal event.

Closed loop systems take feedback continuously from the sensors, and instead of just logging it, actively use the data to regulate the process as it progresses. This potentially has the advantage that the part cures are more repeatable as it can actively deal with unexpected variations and compensate with minimal lag.

Figure 8.2: Autoclaves are pressurised ovens. They come in varying sizes and temperature ranges. Photo courtesy of Pentaxia

Modern control systems are computer driven with software proprietary to the equipment supplier and sold as part of a service package, or customised to a particular workplace, possibly controlling multiple pieces of equipment. It is now routine to have cure control on a primary computer with a backup control computer available to seamlessly take-over in case the first fails. The monitoring data can also be made available live to other computers on the manufacturers network, where it can be utilised for instance by the maintenance dept or by process or product development teams. Some OEM and software suppliers offer support services and advice on tap in real time, but this means linking the machine performance data to the cloud to be monitored by the supplier.

8.1.2 Microwave heating

Microwaves are an efficient way of inducing heat where it is actually required, rather than heating the whole of a space or tool. There has been a good deal of work to try and use microwaves for curing composites – especially aerospace thermoset CFRP parts – to try and improve on the economics of autoclave cure. The potential exists for considerable savings of production cost and cycle times, but the relatively incomplete understanding of the effect of microwave cure vs thermal cure on the final properties of CFRP materials and allowing for these variables in the manufacture of complex safety critical parts has to date limited its uptake, despite extensive trials.

Microwaves still need to be used inside a shielded chamber, so for composite manufacture are limited as to the size of a component. Microwaves rapidly induce heat in metals and electrically conductive materials, including carbon fibres, so where microwave curing has used standard commercial equipment such as bread ovens, or by adding magnetrons around conventional autoclave pressure vessels, the tooling has needed to be made to be from non-conductive, and therefore microwave transparent, materials such as glass fibre composite or even ceramics.

The purpose-built HEPHAISTOS system patented by Weiss Technik has a hexagonal chamber which gives an even spread of microwave energy throughout the space and allows the careful use of metal tooling by selecting the frequency and pulse rate of the microwave inputs to avoid arcing.[38]

[38] 'VHM Hephaistos Industrial Microwave Chamber For Aerospace Engineering', Weiss Technkik https://www.weiss-technik.com/voetschoven/en/products/detail/vhm-hephaistos-patented-microwave-technology~p10163

8.1.3 Induction Heating

Another method to induce heat where it is needed is via induction using electro-magnetic induction to create heat within electrically conductive materials. This is potentially safer than microwaves, and, because it is carried out at short range, using an induction head or coil, it does not require a closed chamber to contain radiation.

It can heat metal tool surfaces, including on mandrels for continuous processes like braiding, or heat metal mesh embedded in a preform to create tailored local heating, for example for assembly/disassembly jigs. Induction heated tooling is growing in popularity for thermoplastic press processing in small to medium part sizes.

8.1.4 Thermal control through air impingement

The use of air impingement to achieve rapid and localised thermal control of mould tooling has been developed by Surface Generation through their PtFS technology. Whilst the properties of air as a heat transfer fluid compares unfavourably to oil and water, it has the advantage of being clean and comparatively safe to use at high (>300°C) temperatures. Applying this to matched die metallic mould tooling, not only the front face of mould tools are machined, but also a significant amount of metal is removed from the back side of mould tools. In this way the thermal, or "heated", mass of tooling can be optimised for the heat transfer properties of air. The machining on the back side of the tool forms pockets and care is taken to ensure that the mechanical design of the tooling meets the process requirements.

The key to PtFS technology is the delivery of separate currents of air at controlled temperature into each of the back face pockets. This heated air impinges on the back face of the tool and heat transfer occurs through impinged convection. Impinging air temperature up to 700°C is possible and this can result in heat up rates of up to 50°C/min for steel tool skins approximately 3mm thick. Tool face temperatures up to 420°C are possible. Figure 8.3: below illustrates the typical layered construction of a PtFS matched die tool. It is notable that for an overall tool assembly mass of 3.5 t, the heated mass of the tool faces are only 150 kg in total.

The ability to deliver rapid changes of temperature with localised control has found most interest with producers of fibre-reinforced thermoplastic parts in the aerospace, oil and gas and consumer electronics sectors.

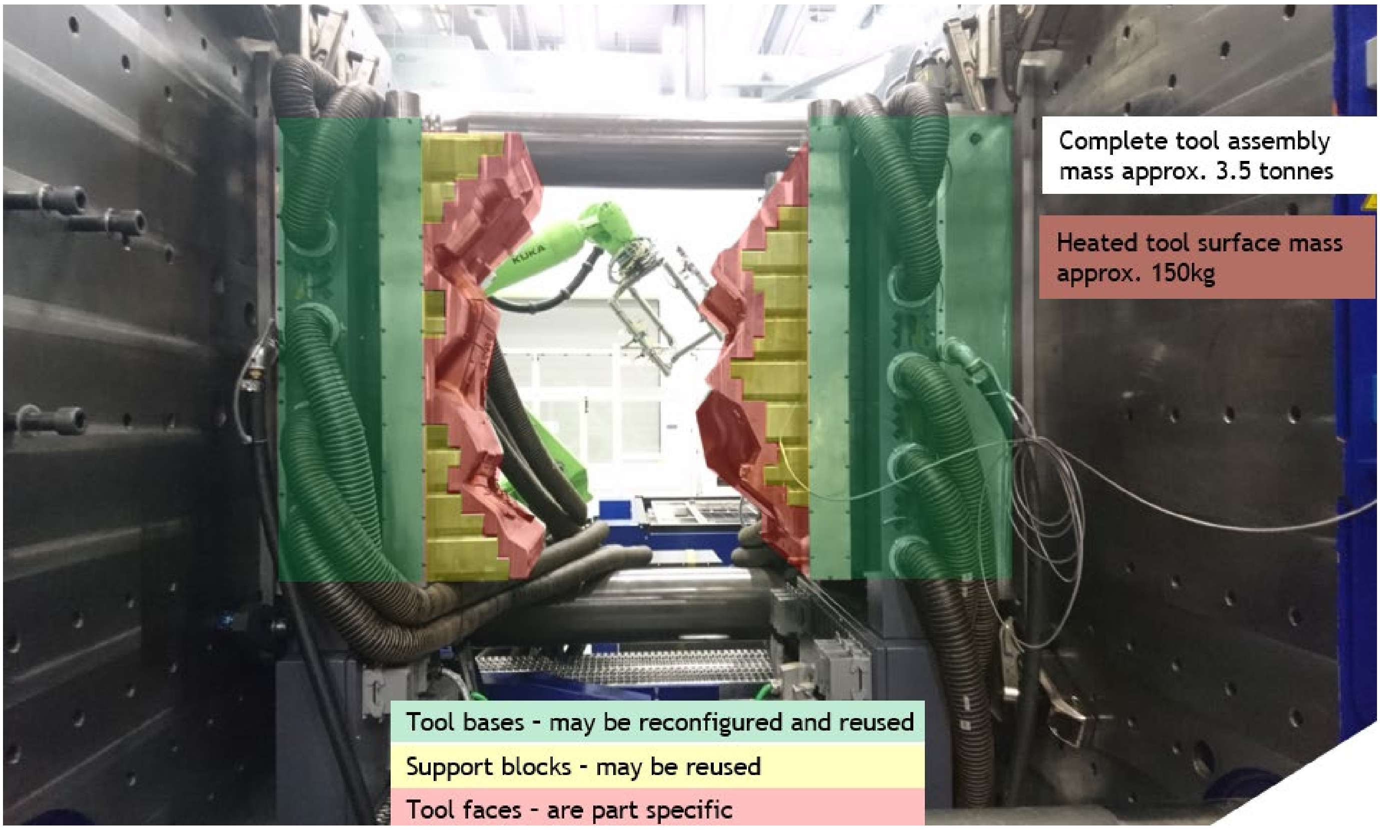


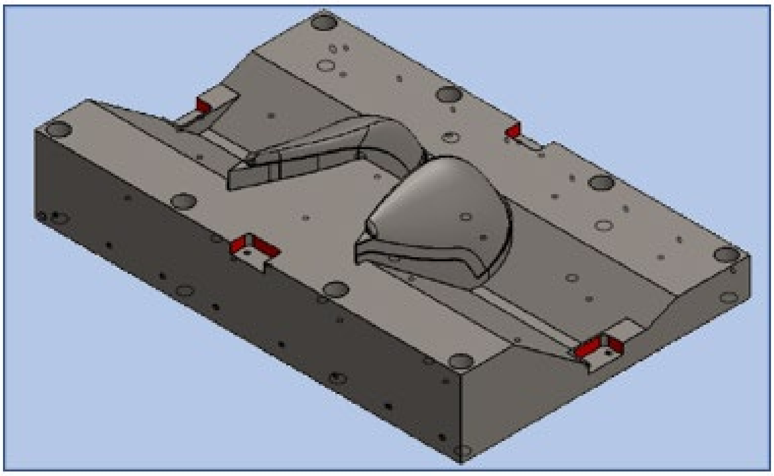
Figure 8.3: Illustration of a PtFS injection overmoulding tool. Image courtesy of Surface Generation

Case Study: Long discontinuous fibre-reinforced thermoplastic composites

Alasdair Ryder, Special Projects Engineer, Surface Generation

Surface Generation offers turnkey tooling solutions incorporating its PtFS technology. PtFS uses air impingement technology as the primary heat transfer mechanism to deliver rapid and localised thermal control. This superior level of thermal control can be exploited with both unfilled and fibre-reinforced plastics, thermosets and thermoplastics, open and closed tooling, metallic and composite tooling structures.

PtFS has been shown to deliver competitive advantage with a particular class of material; long discontinuous fibre-reinforced thermoplastic composites. These chopped prepreg materials offer designers a means of achieving superior specific properties for components with high levels of geometrical complexity that aren't suitable for continuous fibre deposition.

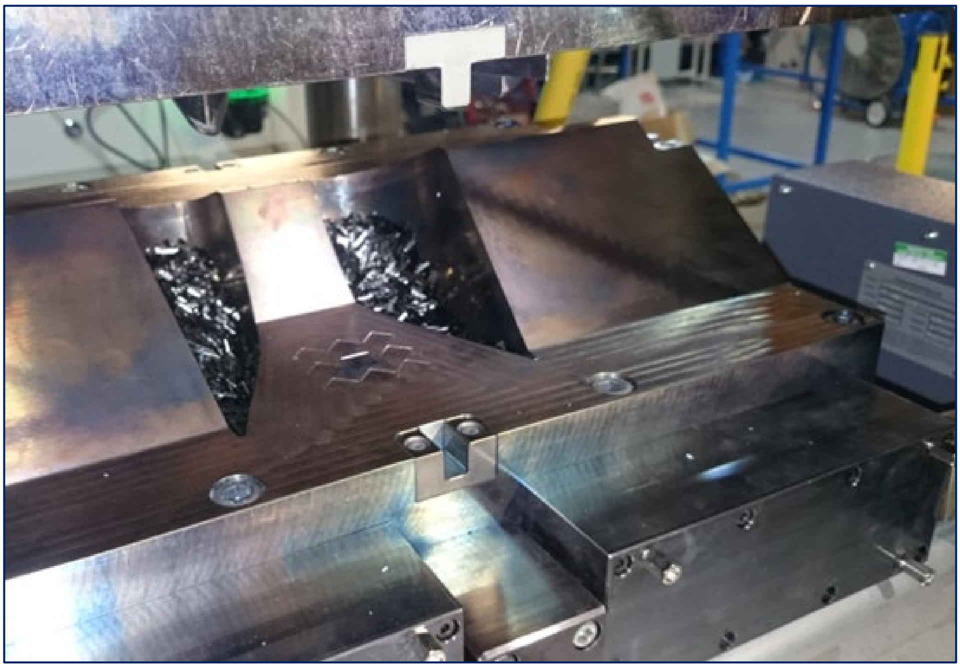


CAD representation of core tool

Cycle time and labour costs, compared to manual deposition, are reduced. Moulded parts are net shape with light de-flashing required and lower downstream process costs. Part quality and repeatability is improved. However, two processing features of this material class are worthy of note and are supported through the use of PtFS technology.

Firstly, to fill a matched die cavity both phases of the material must remain together. Too high a viscosity and filling won't occur. Too low a viscosity and the fibre may separate from the matrix.

Secondly, the thermal conductivity of the charge varies from poor conductivity at the start of the cycle when it is loosely packed with comparatively high amounts of air entrapment and a frozen matrix, to good conductivity towards the middle of the cycle when the matrix is molten, the charge compacted and most of the air has been vented. The co-ordination of tool displacement, pressure application and temperature is critical to realising a good part.



PtFS enables this co-ordination with its localised and rapid thermal control techniques. An illustration of an example part is shown here. In this case, a thin wall (2.3 mm to 0.8 mm) deflector guard for a motorsport application, was moulded at a maximum tool temperature of 380°C with a cavity pressure of 40 bar, a demould temperature of 200°C and an overall cycle time of 40 minutes.

Material loaded in cavity tool

8.1.5 Embedded heating and cooling coils

A more conventional heating method for medium temperature and isostatic tools is to embed a network of tubes beneath the tool surface and use a heat transfer fluid to convey heat to and from the tool.

The fluid can be water or, for higher temperature, a suitable mineral oil. The tube network and heating control can be relatively simple, a single coil with regular spacing between each loop, linked to a heating element and inlet and outlet temperature controls, or more complex, multiple loops serving different heated zones linked to various sensors controlling the heat for each zone.

For solid metal tooling these channels are sometimes drilled or machined into the tool and connected externally via threaded inlet and outlet ports at the tool edges. In FRP tooling this kind of tooling is often achieved by embedding copper pipe cooling coil using resin casting, often with metal powder filler to improve heat conductivity. 3D printed tooling can potentially create complex channelling close to tool surfaces for highly responsive heat control, sometimes using hot or cold air as the heat transfer method for speed of response.

Alternatively heating elements built into the tool may allow for direct electrical heating, but this cannot incorporate cooling.

Figure 8.4: Composite VRTM Tooling – heating pipes being applied to partially complete tool. Photo courtesy of Composite Integration

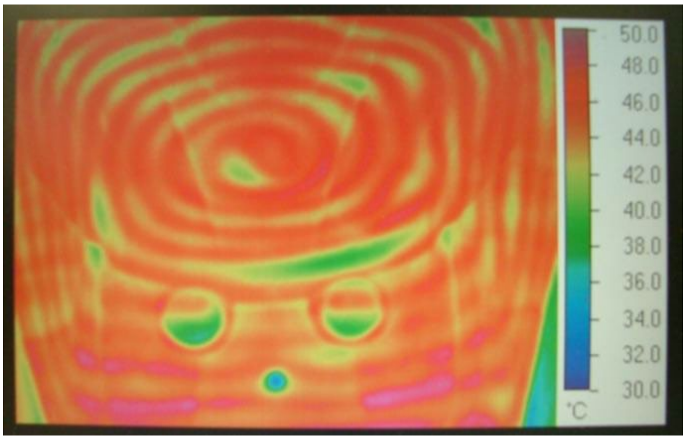


Figure 8.5: Thermal image of tooling in Figure 8.4 when heated. Image courtesy of Composite Integration

8.1.6 Insulation and energy efficiency

Composite manufacturing always involves some form of heat. Even 'room temperature' processes will need to manage the heat of exotherm generated by the resin chemistry to achieve a cured part. Knowing that the tooling is within a manageable temperature range is therefore important across the whole spectrum of composite processes.

Metal tools have fairly high thermal mass but also good heat conductivity. Once heated, a metal tool surface will retain heat well so long as it is insulated from contact with obvious heat sinks, but because of thermal mass a metal tool machined from billet can take a fair amount of energy to get to temperature and keep hot, and even more to repeatedly ramp up to temperature and cool. Where mould tools operate at high temperatures accidental contact with hot surfaces must be provided against, it is common for hot tool sides to be shielded by insulation boards or a rockwool or thermal barrier blanket. Effective thermal protection and insulation may also be needed for electrical contacts and control system cabling to and from the tool.

Carbon tools tend to be significantly lighter and have very low thermal mass, but also low thermal conductivity. This means they need less energy to heat up and change temperature, but also that any variation in heat profile across the surface can be exaggerated. This is the main reason for slow ramp-up during a typical autoclave cure. Metal fixings, fixtures and support structures can all act as heat sinks, keeping adjacent areas of a carbon tool cooler until temperature is fully equalised over time, meaning some areas of a tool may lag behind during a temperature ramp, causing uneven cure or residual thermal stresses in the part. Thermally insulating a carbon shell tool from a metal support structure is good practice, this can be done by extra thickness at contact points on the rear of the shell, or even by tabbing the tool to the structure with a rubber pad shielding contact with the metal, or using rubber washers and hole inserts in bolt holes.

Increasingly tooling prepreg materials are looking at incorporating graphene additives tailored for enhanced thermal conductivity that help even out heat, especially close to the tool surface. It is now theoretically possible to model the thermal conductivity of the tool surface to modify heat transfer rates across different parts of the tool.

GFRP tooling materials are of themselves fairly good thermal insulators, but thermal conductivity of a GFRP tool can also be tailored to suit the process. It is normal practice to use metal fillers in resin systems when casting around heat exchange piping, to reduce hot spots and allow more generous pipe spacing. Insulation layers behind electric heat elements keep heat in the tool and directed towards the tool surface, reducing overall energy consumption.

Variation in insulation can also be used to manage cure and shrink for cast resin systems. A good example is onyx cultured marble cold casting of round tabletops on glass tools. With no long fibre in the composite the filled onyx system has limited strength in the green state and can tear around the perimeter as the centre peaks and shrinks before the outside, which is otherwise cooler and cures more slowly. By providing thick foam insulation beneath the glass perimeter and reducing the thickness of insulation towards the centre the heat evolved as the resin cures can be evened out so that the whole casting cures, and shrinks, at the same rate, preventing tears.

8.2 Pressure / vacuum

Composites rely for optimum strength properties on the correct, consistent fibre to resin ratio, or fibre volume fraction (FVF). Optimum mechanical performance in the part is achieved by the highest possible FVF consistent with good fibre wetting. Pressure is important to drive out excess resin and minimise porosity. The higher the viscosity of the matrix material, the more pressure will be required for consolidation.

In hand lamination this pressure is provided manually using consolidation rollers, LRTM and vacuum bagging techniques provide an even consolidation by using atmospheric pressure, and very simple control features will include witness ports, to check that the resin charge has reached key parts of the mould cavity. In an autoclave, pressure can be ramped up still further. In more sophisticated tooling the same information about the progress of the resin front through the tool is collected by pressure sensors (see section 8.3.3 below). Presses are used to provide that consolidation directly in SMC and BMC, wet press and stamp forming, and for thermoplastics and resin systems with high melt points both pressure and heat are required.

Tools often therefore need to be 'airtight' and be equipped with seals, to maintain vacuum integrity on open tooling, to resist or contain pressures, and prevent leakage, which at high pressures can be extremely dangerous. Tools also need to have ports and connections to vacuum lines or air lines. Hydraulic pressure can also be used to assist tool handling and closure, and positive pressure used to aid part removal, especially on large tools with deep draw.

8.3 Sensors and measurement

Good temperature control is often the key to faster, more reliable production. While experience may tell an operator when the cure has peaked and the part will soon be ready to demould, it is good practice for time and temperatures to be specified at process control points, perhaps monitoring peak exotherm with an infrared heat gun. Thermal cameras can also give insight as to where the hot and cold spots are. Temperature control is a key enabler for automation processes, and it is often better to embed multiple thermocouple points within a tool. These can give a lot of information about how the part cure progresses, and when linked back to a control system can provide the basis for automation. The progress of mould fill and cure can also be detected using dielectric sensors, which can sense the change in electro-chemical state as the resin system hardens.

Case study: A tool for wet compression moulding

John Halfpenny, Technical Lead, Composites, AMRC

The aim was to design a mould tool to produce battery box covers at rate via a wet compression moulding method using a dry fibre preform and liquid resin added using a robotic dispensing system.

The customer desired the process to be isothermal and monitored in real time, and the tool to include an ejection system.

To achieve complete impregnation of the component the tool was sealed and was evacuated while the resin infused the preform. This required the mould to seal before it was fully closed, as is the case with gap resin transfer moulding.

The tool was heated using hot oil. Simple gun drilled holes were put though the top and bottom cavity blocks, connected with braided hoses. To allow deeper channels/pockets to be heated, loose inserts were manufactured, and the oil was channelled into these inserts using blanking plugs sealed with O rings. The tool was fitted with insulation boards, covering all exposed areas, to reduce the amount of energy needed to keep the tool at a constant temperature.

Since the mould tool needed to pull vacuum before it was fully closed a customised lip seal was designed to allow the mould to seal yet still move. A high temperature O-ring was used for the full vacuum seal. Both seals could be replaced without removing the mould from the press.

Cure was monitored using pressure and dielectric sensors. These were located on the bottom face and side walls of the tool. They were fitted into loose inserts and sealed with O-rings.

The integrated ejection system was operated by the press controller. Ejection ports were sealed off during injection, then activated once the mould tool was opened. The system was hydraulically operated, and linked to a return manifold, this controlled the pressure to all of the ejectors, enabling them all to open at the same time and speed. Each ejector had a proximity switch, to guarantee they were fully closed before the press closed to avoid a clash. The tool was also designed & built with dummy ejector ports in case the original positions were found to be ineffective or too few in number.

The battery box mould (lower side) showing the lip seal (white) main seal (red), ejector pins and sensors. Photo courtesy of AMRC

8.3.1 Contact temperature sensors

Temperature control in composite moulding is typically regulated by thermocouples placed at or close to moulding surfaces. They can be embedded in tooling or even within a laminate. Thermocouples work by generating a voltage at a bimetallic junction, with K type thermocouples most commonplace due to their wide temperature range and robustness. They are both cost effective and sufficiently accurate across the process temperature range, are typically supplied with thermally shielded cabling, and pattern into a wide range of control and monitoring electronics and data loggers.

Resistance temperature detectors (RTDs) work on the principle that a pure metals electrical resistance changes with temperature. Platinum RTDs can be more accurate than thermocouples, and are less prone to drift in calibration over time, but are more costly.

Thermistors rely on resistance changes across dissimilar semiconductor materials and usually form part of electrical control devices as safety cut outs and compensation circuitry.

Fibre based strain sensors can also be used to monitor temperature. These can be fibre optic devices based on fibre Bragg gratings (FBG) or based directly on resistivity of carbon fibres. Such devices are sometimes embedded within the fibre architecture of a part or tool to monitor in service stresses and strains, but they also serve as temperature monitors in a steady strain state, such as when the part is being moulded and not yet cured. Information from such sensor fibres can be useful in monitoring cure and temperature profile during production as well as strain once the cured part is in service.

8.3.2 Non-contact thermal measurement

Infra-red thermometers and pyrometers can be a useful tool during processing, or process set-up, but because they give indicative temperatures based on the infra-red radiation from the surface, and so are also affected by reflected radiation they have limited use in permanent tooling and control systems. The emissivity of the material being measured needs to be known and set on the instrument.

Thermal imaging using infra-red cameras can be a great way to spot hot spots or uneven heating on a tool, and to monitor and record processes creating a video record of thermal changes for future reference. These are now low cost, and some work with a smartphone app, however it is important to ensure they are correctly calibrated.

Trials have been conducted to use thermal imaging within particularly hot processing chambers and for microwave cure with the objective of using spot temperatures from the digital images to control processes, but this is not yet a widespread practice and unlikely to be cost effective for most processing.

8.3.3 Pressure sensors

For optimum strength properties composites rely on the correct, consistent fibre to resin ratio, or fibre volume fraction (FVF). Optimum mechanical performance in the part is achieved by the highest possible FVF consistent with good fibre wetting. Pressure is important to drive out excess resin and minimise porosity but care should be taken under vacuum that porosity is not generated by use of excessive vacuum and this is why pressure measurement is key. The higher the viscosity of the matrix material, the more pressure will be required for consolidation.

Pressure is a key control parameter in a number of composite manufacturing processes. Changes in pressure in a mould cavity occur at key stages of the process and can be used to accurately detect and record vacuum build and integrity, resin front arrival, gelation and cure, and so can be a useful tool in automation of the process. Pressure sensors are typically temperature compensated to ensure accuracy and so can also provide temperature information.

Wired sensors are typically mounted to be flush with the tool surface, often on the B face, or in a part area where witness marks from the sensor are not aesthetically critical. Sensors come in various ranges of pressure sensitivity and temperature tolerance and chosen to fit the process.

A new generation of magnetic microwire sensors offers the potential for wireless pressure/temperature monitoring via RFID interrogation of sensors embedded within composite tooling. This gives the potential for monitoring process across many data points on the tool without any surface witnessing or the necessity to make wired connections to sensors.

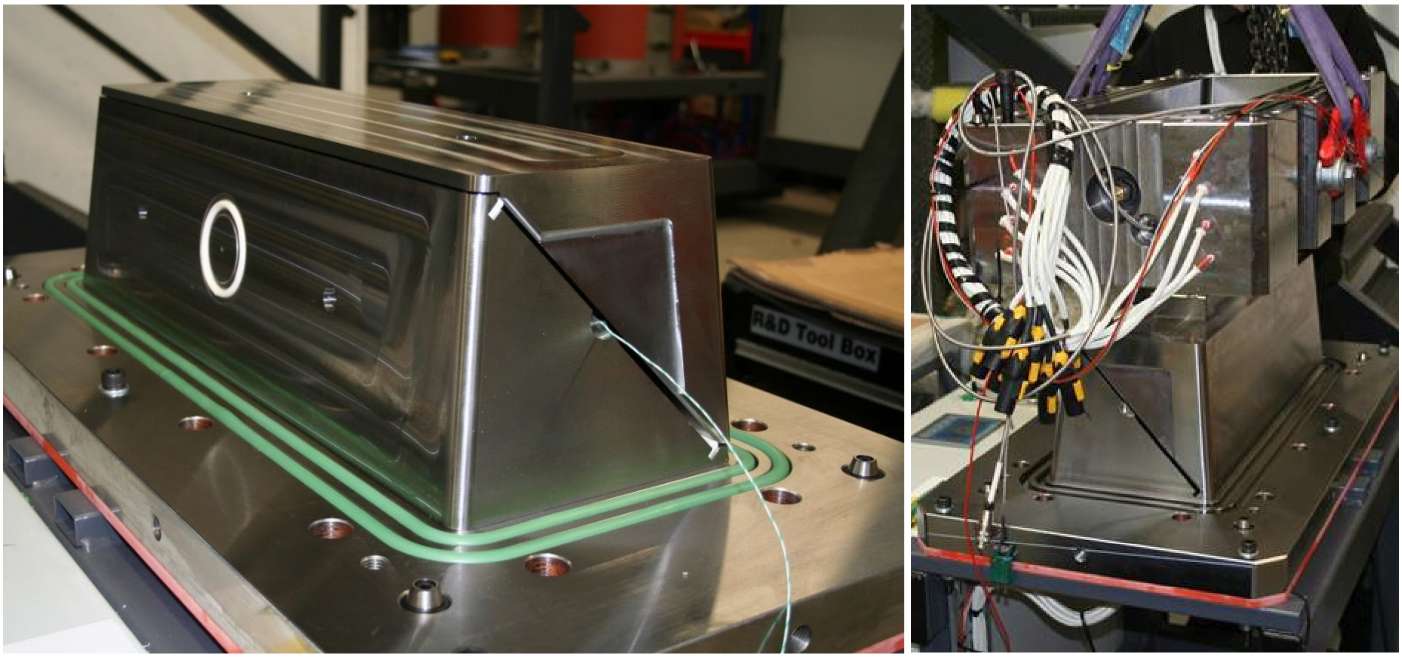


Figure 8.6: Multi part P20 steel high pressure RTM tooling with electrical heating to 200 °C for manufacture of complex shape aerospace components. The tool has multiple pressure and temperature sensors along with a multi zone PID temperature control system and full data acquisition. Tooling design approach enables part shape changes within the tool envelope, reducing costs and increasing flexibility. Photos courtesy of Composite Integration

8.3.4 Dielectric cure sensors

The dielectric properties of resins, that is their resistivity within an induced electric field, changes with cure state. The mobility of electrically charged ions and polar elements of molecules first increases as the liquid resin heats up, then decreases as the concentration of monomers and volatile organics reduces during the chemical change to crosslinked polymer and the viscosity rapidly increases from liquid to solid, and finally levels off trending towards a steady state when cure approaches completion.

The measurement of dielectric properties during process can therefore describe accurately the relationship between temperature, viscosity and cure state in real time, once a resin has been characterised using rheometry.

Coupled with accurate thermometry (usually Pt RTDs), dielectric sensors can be used within tools and parts to 'see' the progress of resin infusion and part cure as it happens, within a closed tool or autoclave chamber, even giving a real time indication of the actual Tg of the resin, and to within a tight tolerance when compared to offline differential scanning calorimetry (DSC) measurements.

Coupled with pressure sensors, dielectric sensors placed at input and near part edges can also detect resin arrival for injection or infusion processes, indicating the moment that the preform is fully filled and wet out, or when flow is fully mobilised within a prepreg or press moulding layup stack.

Large scale projects in both aerospace and automotive sectors, across RTM, autoclave and press moulding processes have demonstrated that outputs from these sensor types and placements can be linked to the control system, and used to fully automate as well as monitor the process, and are starting to be used routinely in wind turbine blade manufacture.

In one project the demonstrated closed loop control system was designed to trigger the heating ramp-up to start immediately the tool was filled, monitor cure progress, and trigger cooling or ramp down as soon as a certain Tg had been reached. By accurately knowing when the part is fully wet, and when the cure cycle is complete enough for the part to be demoulded, significant reductions can be made in process times – up to 30% in case studies – compared with fixed production cycle set ups calculated using flow and cure simulation software. It is believed that implementation of these process optimisation projects within mainstream aerospace project partner companies is now underway.

8.4 Safety and operational factors

Health and safety should always be the first priority in any production set-up and tooling is no exception. Hazards to be aware of include moving parts such as presses, pinch points on mould closure with clamps, hot surfaces, dangers from high pressure fluid leaks and chemicals, and exposure to potentially harmful volatiles from cure processes.

Other operational factors such as lifting and energy efficiency should be dealt with according to general good practice and are covered briefly here.

8.4.1 Temperature, pressure and leak overrides

Safety features are a must have for process control, and should always be designed to fail safely. This can mean planning for runaway exotherm, by setting a temperature cut out, planning for a pressure leak, by setting an alarm and shutting off resin injection, and designing tooling such that excess resin and venting gasses will always be diverted to safely positioned resin traps and exhaust vents. In vacuum infusion under bagging films it is a normal part of the process to check for vacuum leaks, either by ensuring steady state vacuum is maintained with a pressure sensor, or by listening for leaks, locating them using a leak finder, and mending or patching the leak before proceeding.

8.4.2 Safe closures and clearances

All moving equipment in a workshop needs to be treated with caution in respect of physical entrapment to avoid injury to operators. Most closed tooling has a 'nip' or pinch points or areas where fingers could potentially be trapped at the point of closure. Normal safety feature is to have at least a hand's width of flat flange around all edges of a tool so that operators are not tempted to keep fingers in the tool during closure, perhaps to hold down or poke in place a bit of fabric. This can be a safety risk even when the top tool is relatively light, or lowered into place using a hoist, but is much more of a concern when the tool is heavy, in a press, or when higher clamping forces are involved.

8.4.3 Guards and emergency stop buttons

Hoists can be fitted with features that prevent single handed operation. Presses should have both a safety guard that prevents hand access during closure, or closure unless the guard is in place, and an emergency stop button. For automated and shuttling presses these guards may be infrared beams rather than physical barriers. Smart tools, with pressure or contact/proximity sensors, can effectively tell the control system that they are closed properly.

8.4.4 Location features and guides/tie bars

Location features are physical guides built into tooling that allow consistent placement of reinforcements, and accurate placing of inserts, cores etc. They can ensure correct, or prevent incorrect tool closure, provide features on the part, or on cut-outs or unused parts of the part, that assist post processing accuracy. These can vary from a shallow, scribed trim line to crosshair features for camera assisted robotic handling systems.

A guide or tie bar is a particular feature that assists accurate closing of two mould halves, they can be edge features that guide bosses on one tool half into a secure clamping point, or raised features on flanges, such as tapered cone and cup, that allow the top tool to accurately settle into the right place as it is lowered. These can include 'hard stops' that prevent the tools from being closed too tight and ensure correct part thickness even under high pressure clamping.

8.4.5 Lifting and handling

All tools, even lightweight temporary ones, need sufficient structural integrity to withstand handling and process forces. Many tools will need at some point to be moved and anchored securely to prevent movement. Lifting and lowering of the top tools in closed moulding will require anchor points or attachment points that spread the weight of the top tool evenly through the support structure, which has in turn to be stiff enough to lift without deforming excessively. Flexible membrane top tools may need a number of hoist points with a local load spreader bar, or even a shaped lifting frame.

Press tools will normally need the fixing points to be a specific bolt size and pattern to work with the press platen, or have a tailor-made spreader plate to transfer the press forces evenly across the tool.

Very large two-part tools, such as for wind turbine blades, will likely have hydraulic or electrically assisted clam shell closure. Often such handling and closure systems are most cost effectively fabricated from steel, but this has both weight and CTE penalties, and fixing points may need to be thermally insulated if the tooling itself is composite.

Some large frames, jigs and fixings are now being partly fabricated in carbon fibre for its stiffness and weight reduction characteristics. On large tools this can allow for savings due to reduced size of cranes or actuators, improved handling speeds and better safety, as well as giving improving dimensional accuracy through reduced CTE.

8.4.6 Ancillaries, reusable membranes and disposal routes

One of the major changes in recent years has been the changes in ancillary products / consumables to make them easier to use, with reduced cost. These include for example multi-layer films that include for example peel ply, flow media and gas permeable release film, pre-made plastic profiles to accurately locate seal rebates etc.

A key technology that is growing fast is the reusable membrane. Flexible silicone membranes are now versatile and resilient enough to replace vacuum bagging films in many cases, both on prepreg tooling and in resin transfer and vacuum infusion. Fears of 'free silicone' residues causing pre-release, poor surface adhesion or potential kissing-bond interlaminar failures have been proven unfounded, and flexible top-tooling offers many opportunities to reduce consumables and cost. The degree of flexibility can be tailored, the membranes can incorporate stiffeners, textures, and be bonded to tough reinforcing fabrics to allow robust handling. The technology can be extended to other areas such as tailored seals for split moulds etc, that also significantly reduce refinish times. See sections 4.5.6 and 7.6.

Where disposable ancillaries are unavoidable, it is good practice to follow the "reduce – reuse – recycle – recover" waste hierarchy. Consumables with recycled content are available in some cases, including recycled / cleaned silicone release paper, which has the added advantage of more consistent prices and lead times compared to virgin.[39] See also section 6.6 Disposal routes.

[39] See Techlan https://www.techlanltd.co.uk/index.htm

9. TOOLING DURABILITY AND SERVICE LIFE

There are several factors that influence tool life, related to both the production and maintenance cycles, the components of both the composite part material and the tooling materials, and the care and good practice of production staff. Quality control of parts produced depends on keeping the tool in good condition, as well as process control and monitoring.

9.1 Causes of tool failure

A well-made tool which is well looked after can last the lifetime of the product, and still be good enough to archive against the need for future spares. Conversely, pushing a tool too hard in pursuit of faster tool turn-around times can be counterproductive. Is it better to invest in more expensive and robust tooling at the outset? Or plan for multiple production cells on cheaper soft tools. Finding out half-way through a product lifecycle can incur painful unanticipated costs and delays. Common causes of early tool failure in service are described below.

9.1.1 Poor part or tool design

This is where design for manufacture becomes a key factor and having a critical look at the details of a proposed design can pay dividends. Is a 1mm radius really needed there, or will 3mm look better AND produce a lower scrap rate? Is it wise to make this as a single mould tool, or would production actually be much easier with a split tool. Poor materials selection and/or application during tool manufacture is also a very common cause of premature tool failure.

9.1.2 Rough handling during release

Rough handling is the most common cause of tool failure leading to tool damage that shortens its life or creates the misery of regular downtime for repair. A common issue is repeated damage in a tight corner that is difficult to release. It can also be due to over-enthusiastic use of metal tools, rather than gentler plastic wedges, to demould, scrape off overspray, or lever apart a reluctant top-tool or split line. Repairs themselves often become the weak-point, or the witness mark on every part that needs extra refinish, which increases the per part costs and scrap rate.

Getting the release system right, allowing for more generous radii and draft angles where possible, adding ejection pins or air points to push up a deep part of the tool local to verticals can all help avoid rough handling. Sometimes just making sure there are always two operators available to lift a top tool or part out squarely, or providing well-spaced and braced lifting points and an air-hoist will make all the difference.

9.1.3 Cycle times and exotherm

Regular expansion and contractions due to heat cycling can cause thermal fatigue. This can cause failure through brittleness of a support structure, or accelerated collapse of a tool surface feature, often a corner or boss. Certain features may need extra reinforcement to compensate, especially where thick cross-sections are near to thinner sections. In areas of the tool that get very hot, next to thick sections of parts, faster surface degradation or heat cracking will occur if the Tg of the tooling materials is exceeded. Thermal cycling will tend to exacerbate interfacial bonding issues between dissimilar materials. For example, if the tooling material has a very low CTE, but perhaps an aluminium or mild steel backing structure, it will be necessary to either insulate or allow some flexibility at the fixing points, or both, to avoid stressing the tool.

9.1.4 Wear and abrasion

Many reinforcement materials are abrasive, carbon, glass and basalt can all scratch a tool surface. Tool damage from abrasion can be due to scraping of dry fabrics over raised features next to deeper draw areas when the tool is closed. Consider changing the ply layup or kitting order, providing specific tools or wedges to nest the preform accurately, and consider tape or spray to tack down areas that cause problems during closure.

Tooling materials can be chosen to mitigate wear. A steel tool could have a chrome or nickel coating, aluminium can be hard anodised, or on a FRP tool an abrasion resistant tooling gelcoat could be specified. In specific areas of metal tooling a ceramic insert might be appropriate.

9.2 Tool maintenance and repair

Maintaining tools is key to quality trouble free production. The biggest challenge to keeping tools trouble free is physical abuse when a part fails to release easily. A full clean-down and re-release between cycles, or even between shifts may not be economic so efforts to find the right release system and making sure the fibre loading, tool handling and demould processes are easy, encouraging a light touch from operators, will pay dividends. FRP moulds really do not like metal tools being used to pry them apart or to dig a tight corner out. Ensuring that mallets are rubber and wedges are of soft plastic can be an important tool saver.

Identify 'problem' tools early and consider alterations that aid processing *before* the tool becomes damaged. Damage to FRP tools can be successfully repaired, using similar tooling materials and repair putties, but a repaired surface will always be different from the original surface, and will tend to witness on the parts after some cycles, or to be a regular weak spot requiring re-repair.

Metal tools wear better if looked after and usually cope better with hot processes and rapid thermal cycling. The cost of metal tooling often comes down to machining time. A complex tool might be cheaper in aluminium than steel, but aluminium often has a softer, more easily scratched surface. Metal tools can usually be resurfaced, and for some shapes even completely re-machined, but this is too expensive to do often.

9.3 Inspection and testing

There are multiple methods for general tool testing which are readily available, including the following:

- Co-ordinate measuring machine (CMM) reports can be used to assess final geometric accuracy.
- Hand-held surface roughness and gloss meters determine final surface quality.
- Thermal imaging cameras, which are now cost effective enough to be used for mapping heating performance.
- A standard vacuum drop test can be used to ensure tools are vacuum tight, with helium leak detection helpful in finding any leak locations.
- Further NDT methods are available for more specialised testing if required.
- A tap test carried out by an experienced operator will give a good indication of the tooling laminate quality.

Figure 9.1: Inspection of patterns and mould tools against CAD is required to ensure conformity with customer requirements. This is typically carried out in two ways for tooling: inspection arm with a probe, and laser scanning. Photo courtesy of Pentaxia

10. NO TOOL AND SPECIALIST TOOLING

There are many processes for making composites, and some do not require any special tooling. This includes 3D printing which is gaining traction for increasingly large structures. Continuous composite manufacturing processes such as pultrusion and continuous sheet forming produce constant cross-section parts and use very different tooling.

10.1 Do I need one? - 'No tool' options for FRP components

'No tool' techniques for composites tend to be used for one-off designs or simple shapes. For manufacture of multiple components, it generally pays to spend time and money on tooling to achieve part consistency.

'No tool' methods are traditionally used for items such as surfboards, where the FRP is wrapped onto the shaped core, which remains in place. In this situation the exterior finish will always be faired and painted. Effectively the shaped core becomes both the tool and part of the finished product. Other examples include situations where the composite is used to stiffen or protect an existing shape. Examples include hot-tubs and baths, where the surface aesthetic has already been formed from thermoplastic, or modular building lining where composite is used as a waterproof and chemically resistant lining or reinforcement of existing concrete or wooden structures.

'No Tool' methods still tend to be for niche products and for vast majority of composite parts a tool will be required.

10.1.1 Flat tooling

Flat plate tools can be used to make a block or sheet of material by stacking multiple layers, allowing to cure and then using this as a 'tailored' billet from which to machine the final component. The plate is still a 'tool' but is not part specific and can be reused for many different components. This approach is useful where there will be a significant amount of accurate machining required, for example when the detail itself on a part is too fine or complex to be moulded. This approach is used where flat carbon fibre plates or blanks are made to be subsequently machined into flat components like gears, plates and connectors.

Glass plates, or even a piece of high-pressure laminate board can be used to make thin flexible FRP sheets that can be trimmed to a set of 2D shapes that can be assembled into a 'Space Framed' 3D shape. The individual pieces are held or 'tabbed' onto a temporary framework or jig, bonded at the edges, and when the shape is stable, the thicker structural elements are added behind the shell surface. The jig or framework can be removed once the shell shape is fully cured and stable, or it may remain in place as part of the substructure. This approach has been used for boats, domes, and bespoke structures and enclosures, has the advantage that a good surface finish, and high level of flatness on each facet can be achieved, but with the downside that each facet edge is essentially a split line and will need more re-finish work.

10.1.2 Flexible or drape tooling

A membrane or fabric can be used as the 'tool surface'. FRP materials can be applied to the film or fabric and consolidated on a flat supporting surface then cured while in a draped or tensioned shape. It can be draped or stretched over a frame or tensioned like a sail. An industrial scale version of this is continuous roof sheet manufacture, where a film is stretched over profiling boards and glass and resin laid onto it and passed through a curing oven, the film being stripped at the end of the process. The film or fabric can be stripped after cure or left in place to provide a UV protective layer. The composite finish will mirror that of the fabric or film, so this can be utilised for aesthetic effect too.

10.1.3 3D printed composite components

3D printing techniques using multiple materials have advanced very rapidly and 'composite' materials are now routinely deposited using a variety of techniques. Materials range from tough unreinforced thermoplastics, short fibre (<2mm) reinforced thermoplastics, long fibre or even fabric patch techniques, right through to powder deposition techniques with metal powders, wires and even high-performance ceramics. Short or discontinuous fibre 3D printable materials will not be as strong, stiff or high temperature capable as a fully design optimised, long fibre, composite component, but there are many applications where this is less of an issue, and the speed, labour reduction, repeatability of automated production, and design flexibility of 3D techniques will be commercially attractive.

The limitations for such techniques are machine bed size and the inherent stepped or ridged finish and porosity resulting from some deposition techniques. As increasingly large machines become available bed size limitations are shrinking, and there are ways to effectively join multipart 3D printed pieces together. Capital outlay for large format machines, the know-how to adapt a design for 3D manufacture, and the software to drive the machines, are all expensive, but specialised companies offer full design to print tooling service.

Because mould tooling is a stiffness rather than strength dominated application the use of 3D printing to rapidly make tools, rather than components, for composite manufacture is gaining momentum. This is a form of direct tooling, in that the required 3D shape is created or built layer by layer from a flat bed and from CAD/CAM data and software. Because tooling will often be further machined and resurfaced the drawbacks of 3D print methods such as porosity and stepping can be mitigated during post processing. 3D printed tooling is covered in more depth later in the guide.

There is clearly a technology cross-over happening between 3D printing, traditionally small scale and with thermoplastics, metals and ceramics, and the automated fibre deposition techniques being used for large scale aerospace components. An increasing number of both composite tools and components made this way can be expected.

10.2 Tooling for continuous and linear processes

10.2.1 Pultrusion and pull-winding

In pultrusion, continuous fibres from bobbins, and in some cases also fabrics, are simultaneously guided and pulled together before being saturated with resin. The fibres are then pulled through a heated die, which cures the composite before the profiles are cut to the desired length at the end of the line.

Pull-winding is very similar to pultrusion with the exception that fibres are wound around a profile before it enters the heated die. This allows for fibre alignment in both the crosswise and longitudinal directions which enable stronger / thinner tubing.[40]

A pultrusion die, and the pre-die guides that feed materials continuously to the die, are designed to taper down to the final shape, compensate for heat and shrinkage from resins that are highly reactive, and resist wear from abrasive reinforcement materials constantly moving through the hot tool at the fastest economic line speeds.

10.2.2 Continuous sheet forming

Continuous sheet forming (CSF) is the process used to make GFRP corrugated rooflights and flat roofing sheet. A benefit of CSF is the simple, low-cost tooling required, involving a series of wooden formers cut to the cross-sectional profile of the corrugated sheet required.

CSF is a continuous process which involves producing a laminate by spreading resin onto a polymer carrier film, chopping glass fibre or laying a fabric from a roll onto the resin layer, then applying another carrier, or UV absorbing, film. Where a profiled sheet is required, the film is pulled over the wooden formers to produce the shape as the laminate is passed through an oven to cure.

Figure 10.1: Continuous sheet process showing wooden formers which shape the profile as the sheet goes through the oven. Photo courtesy of Filon Products

[40] See 'The push and pull of composite manufacturing', Exel Composites https://exelcomposites.com/the-push-and-pull-of-composite-manufacturing/ and associated YouTube video https://youtu.be/DJUIRhBxejc

11. NEXT STEPS AND FUTURE DEVELOPMENTS

Future tooling for composites processes must meet multiple challenges. Reduced material usage, reduced waste, reduced energy use in both manufacture and operation, reduced time from design to production, improved tool life, improved thermal resistance, use of sustainable materials, end of life recyclability, manufacturing skills availability etc. The list is extensive.

The composites sector also has a relatively unique tooling challenge in terms of both production volumes and part size. Tooling must be design and manufactured to make production runs from 1 part to >100,000 per annum, and manufacture part sizes with moulded surface areas from just a few cm^2 to more than 500 m^2.

As is normally the case with composites manufacture, no one solution will meet all these criteria, but a combination of technologies will combine to address the challenges varying their theme to meet the specific process requirements.

It would appear that 3D printing or additive manufacturing offers solutions to many of these challenges going forwards. The technology and market penetration for 3D printed toolmaking is still in its infancy, but as with the change from traditional pattern making to CNC patterns, rapid growth of both materials and manufacturing capability is expected. There are several case studies of use, as demonstrated in section 7.5 with BAE Systems, and others such as TPI Composites working with Oak Ridge National Laboratory (ORNL) [41], and new materials developed specifically for tooling such as the Dahltram® systems by Airtech with low CTE and high temperature capabilities.

Figure 11.1: ORNL, in a consortium with TPI and others, built the first set of utility-scale wind turbine blade moulds using 3D printing. This eliminates the need for the plug, and incorporates hot air ducts for curing, removing the need for wiring. Photo courtesy of ORNL

Dutch LFAM machinery manufacturer CEAD has been working with GKN Aerospace on a new approach, Automated Tape Layering Additive Manufacturing (ATLAM) which combines 3D printing and automatic tape laying for aerospace tooling with lower CTE compared to tools printed using only short fibre reinforcement.[42]

In addition, we can consider metal additive printing for high performance tooling. The National Centre for Additive Manufacture at MTC Derby has several case studies of the use of these techniques.

The potential benefit of additive manufacturing for tooling are manifold. The need for a pattern(s) is removed, reducing material and energy requirements from the toolmaking process and the opportunity for recycling of materials used in toolmaking becomes significantly larger. Lead times are a key challenge for tooling. The removal of the pattern stage, and the rapid printing and machining capabilities of current systems (up to 230 kg/hour) should enable vastly faster 'design to production' timescales. In the 3D printing world, 'design complexity is free' as the saying goes. Whilst this may not be 100% accurate, complex design features such as insert holders, magnets, clamping fixtures, heating channels can all be either

[41] 'Additive manufacturing of wind blade molds targets time, cost savings', Oak Ridge National Laboratory, 24/5/17 https://www.ornl.gov/blog/additive-manufacturing-wind-blade-molds-targets-time-cost-savings

[42] Ginger Gardiner 'ATLAM combines composite tape laying, large-scale thermoplastic 3D printing in one printhead', Composites World 21/4/23 https://www.compositesworld.com/news/atlam-combines-composite-tape-laying-large-scale-thermoplastic-3d-printing-in-one-printhead

embedded or incorporated into the tool design in ways not accessible to traditional tool manufacturing methods. There is still much thought to be given to the best ways to explore and exploit this opportunity.

There are other areas to be considered with additive tooling. Vacuum integrity of the completed tool is often a critical requirement. This can vary from system to system and application method. Where precision geometrical tolerancing, low roughness or high gloss surfaces are required, it would be expected to print slightly oversize, then machine back to required dimension, potentially followed by a surface coating system for final finish and/or to seal tool porosity. Consideration must also be given to the CTE of tooling materials used, and their compatibility with the moulded component. Finally, weight and thermal mass of additive manufactured tooling can be a considerable issue, leading to static tools with integral heating being perhaps more practical.

With regard to energy efficiency, with much consideration being given by the aerospace sector in recent years to both the Capex and Opex costs associated with autoclaves, work remains to be done to evaluate the effectiveness of static tooling with in-mould heating. For liquid resin processing, where a preform may be placed into a tool without direct hand contact, there are benefits to well insulated tooling operating at constant elevated temperatures, improving productivity and reducing heat/cool time/energy costs. For prepreg, the case is less clear, especially as the additional pressure brought by an autoclave is a key process parameter, but it is worthy of consideration. The use of static tooling can also significantly aid factory layout and logistics, removing the need for constant tool movement.

Figure 11.2: Lower wing skin tool from the Airbus 'Wing of Tomorrow' project. The tool uses an integrated heating located close to the mould surface to provide rapid and precise temperature control and features a semi-flexible membrane and heated tool lid. Photo courtesy of Spirit AeroSystems

Multiple heating methods must also be evaluated for future tooling as well as the temperatures needed to process materials. If this can be reduced, energy usage can also be reduced. This guide has demonstrated some traditional methods including oil/water pipes or pathways, electrical cartridge heating etc. Other technologies such as utilising the resistive nature of carbon fibre in composite tools is used, but not commonly due to high current loads and temperature consistency on larger structures.

> 'Alternative methods of heating exist. In automotive, inductive heating is in use and giving cycle time reductions of 50% from inert systems, up to 90% CO_2 reduction and 95% energy savings. Also in the pipeline is resistive heating, being studied on Wing of Tomorrow and said to offer 99% energy savings. Xenon flashlamp heating has been used on Clean Sky 2 aiming to achieve TRL6 by 2023.'
>
> *Norman Green – ATI.*

Figure 11.3: Typical power monitoring device fitted to heated tooling

In an environment where energy costs are a significant factor, it is becoming ever more important to accurately monitor, compare and improve energy usage of all tooling and equipment involved in the manufacturing process. Fitting energy usage measurement devices to each item to provide high quality data will quickly become the norm rather than the exception. A perfect way to evaluate the results of improving tool insulation for example.

Considering material efficiency in tooling presents further opportunities. This falls into four broad categories – recycling, use of recycled/renewable materials, tool life, and reconfigurable/adaptive tooling.

A huge body of work has been carried out to date on composites recycling, well beyond the scope of this chapter. It should be noted however, that non-metallic tooling has additional recycling challenges often due to its multi-material nature. As well as FRP layers, tools can contain core materials, metal frames, adhesives, aluminium/sand particles etc, all bonded into a single final structure. Additive manufactured/3D printed tooling appears to represent the simplest route to both material efficiency and direct recycling opportunity. This may well prove to be the case as the technology develops, but care must be taken with tools which may have absorbed resins through porosity, or required surface coating for final surface finish.

For metal tooling, the recycling pathway is well defined, feeding recycled materials back into the supply chain. For composite tooling, whilst we acknowledge some of the limitations of recycled (e.g., rCF) and renewable materials, it is prudent to consider and test these for each particular application. Composite tooling structures overall, are often quasi-isotropic, which can support a wider range of material use.

It is evident that the longer a tool can last, the better the financial and environmental return.

Over recent years, much work has been done by materials manufacturers to improve the performance of tooling materials, with particular focus on HDT, elongation, toughness and usability. It is now possible to make high quality tooling from room temperature (RT) prepreg for example, reducing energy costs significantly, with tool life improved via the use of additives such as graphene (see Haydale Composite Solutions case study in section 7.3.1). Epoxy tooling gelcoats have improved hugely in their usability and temperature resistance, providing a repairable/polishable surface for high temperature CFRP tooling. There is no one technology leading the way, but many small improvements, and the knowledge of how to use these new materials with their inherent tool life improvements will benefit all.

Reconfigurable or adaptive tooling has existed for many years. Examples of the current art include Adapa adaptive curved surface moulds, Cikoni Dynapixel systems and companies such as Surface Generation incorporating intelligent heating and cooling into adaptable tool sub-structures. Though not suitable for every type of product, development is certain to continue in this direction and the prospect of combining adaptive mechanical and thermal capabilities with additive manufacturing may prove an interesting combination.

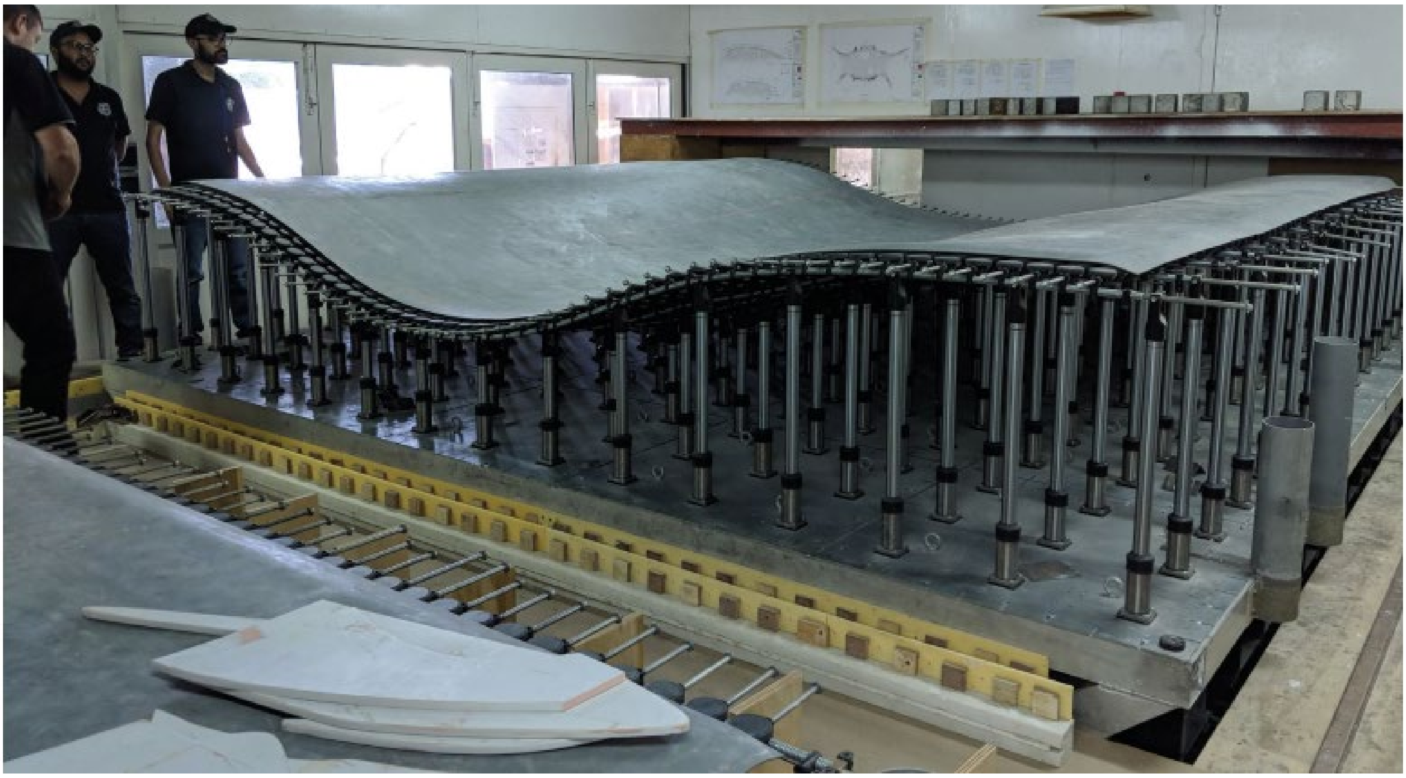


Figure 11.4: Adaptive mould technology. Photo courtesy of Adapa

At a simpler level, silicone tooling, if carefully designed, can be used to accommodate a range of shapes within a given envelope. Reusable silicone membranes can also offer waste, labour and cost benefits when used to replace traditional vacuum bags/films for either prepreg/dry fibre debulking, or liquid resin processing. Improvements in chemical resistance should see membrane life improve beyond its current state, and work is ongoing to improve processing methods to further reduce waste and improve resin flow. The potential to replace single use consumables in production is significant.

Looking further to the future, design, instrumentation, and intelligent control of tooling are all areas in which there will be significant technical progress. The use of AI design tools will enable us to routinely capture and evolve existing design principles, analyse draft angles and tool splits, develop seal paths etc whilst minimising material waste and cost. Finite element analysis (FEA) systems must improve their ease of use and accessibility for both flow and thermal modelling to match that of mechanical analysis. Open-source comprehensive materials databases would support this greatly.

Mould instrumentation already covers thermal, pressure and dielectric sensors, and camera vision systems for flow front monitoring are being incorporated into resin infusion processes, but true through thickness thermal, pressure and flow front monitoring at much closer geometric spacing than currently available is needed. The data acquired from improved tool and process measurement should be used to inform and improve digital twins, and ultimately lead to intelligent real time decision making for automated process improvement and optimisation 'on-the-fly'. Some of this is being developed at research stage, but for the composites sector to continue to grow, it must become a common tool.

One of the greatest challenges facing the future of tooling is the skills and knowledge required in design and manufacture. It is becoming increasingly difficult to recruit employees with these capabilities for both metal and composite tooling. Competitive advantage often inhibits sharing of direct knowledge between organisations, but it is clear that education in tooling design and manufacture is required across the sector to close the skills gap. This guide is a step forward in providing support in developing these skills.

APPENDIX 1: GLOSSARY & TERMINOLOGY

a) Acronyms / abbreviations

Abbreviation	Definition
AFP	Automatic fibre placement
AM	Additive manufacturing
ATL	Automatic tape-laying
BMC	Bulk moulding compound
CAD	Computer aided design
CAM	Computer aided manufacturing
CFRP	Carbon fibre-reinforced polymer
CMM	Co-ordinate measuring machine
CSF	Continuous sheet forming
CTE or CLTE	Coefficient of (linear) thermal expansion
DMSL	Direct metal laser sintering
EOL	End of life (n.) or end-of-life (adj.)
EuCIA	European Composites Industry Association
FDM	Fused deposition modelling
FRP	Fibre-reinforced polymer
FVF	Fibre volume fraction
GFRP or GRP	Glass fibre-reinforced polymer
HDT	Heat distortion / deflection temperature
HP-RTM	High pressure resin transfer moulding
ISO	International Organization for Standardization
LCA	Life cycle assessment
LPPM	Low pressure press moulding
LRTM	Light resin transfer moulding
MDF	Medium-density fibreboard

Abbreviation	Definition
MIG	Metal inert gas (welding)
OOA	Out-of-autoclave
PVA	Poly vinyl alcohol (mould release agent)
QA	Quality assurance
rCF	Recycled carbon fibre
RFI	Resin film infusion
RFID	Radio-frequency identification
RT	Room temperature (may be used in reference to RT prepreg, RT cure resins, etc)
RTM	Resin transfer moulding
RVB	Reuseable vacuum bag
SLS	Selective laser sintering
SMC	Sheet moulding compound
Tg	Glass transition temperature
UV	Ultraviolet
VARI	Vacuum assisted resin infusion
VRTM	Vacuum resin transfer moulding
VOC	Volatile organic compounds
WAAM	Wire arc additive manufacturing

b) Terminology

For descriptions of composite materials and processes referred to in this guide, see the Composites UK ‘Composite Materials’ pages.

Term	Definition
Caul plate	A stiff plate of material, usually used behind a bag or flexible membrane to intensify pressure and consolidation contact, ensure better flatness and/or closer thickness tolerance, and limit bag movement.
Draft angle	The angle between the tool surface and the direction in which the part is pulled or withdrawn, also referred to as release angle
Glass transition temperature, Tg	The temperature at which a resin matrix material starts to soften or depart from linear elastic behaviour.
Heat distortion temperature (HDT)	Heat distortion temperature is a more direct physical method of determining the maximum service temperature of a composite material. The HDT is obtained by heating a defined sample under load at a defined ramp rate until it is deflected by a fixed amount related to the geometry of the sample. In composite samples the HDT can be influenced by filler loading and reinforcement and not necessarily mirror theoretical deflections based only on Tg of the matrix. Also known as heat deflection temperature or deflection temperature under load (DTUL).
Invar	A nickel–iron alloy notable for its uniquely low coefficient of thermal expansion (CTE). It is known generically as FeNi36 (64FeNi in the US) as it typically contains 36% nickel and 64% iron, though there are other variations.
Kissing bond defect	An adhesion or delamination defect between two layers of a composite component where there is no detectable void between the un-bonded layers. Causes include contamination by release agent type materials during lay up and are the reason for traditional strict elimination of silicone containing materials from layup and clean-room prepreg manufacturing facilities.
Matrix or resin	The resin or binding medium that wets out surrounds and embeds the reinforcement.
Pattern (or plug or model)	A form taking the shape of the required final product, which also incorporates any flanges or locating features needed, from which the mould tool can be created
Preform	A shaped, pre-assembled or stabilised reinforcement pack ready to put into the mould tool.
Print through barrier	Layer of material behind the surface coat on a tool or part intended to reduce print through. This is often a nonwoven fabric, veil or tissue, or can be a highly filled secondary coating containing glass microbeads.
Print-through	Visible or cosmetic waviness in a part or tool surface caused by witnessing of fibre patterns in the bulk fabric following matrix shrinkage.

Term	Definition
Reinforcement	The fibre(s) or fabric(s) within a composite component
Splash tool	A tool created using the original part as a pattern
Stick-up	When the part does not release from the mould

APPENDIX 2: GENERAL REFERENCES

While references are given in footnotes to the text, the following more general references provide further information on this subject.

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iii. Materials & Processes: Tooling for composites', Composites World, 5/7/22 https://www.compositesworld.com/articles/tooling

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v. 'FDM for Composite Tooling 2.0: Design guide', Stratasys https://www.stratasys.com/en/resources/resource-guides/fdm-composite-tooling/

vi. 'Sacrificial Tooling and Mandrels for Composite Part Fabrication: Design guide', Stratasys https://www.stratasys.com/uk/resources/resource-guides/sacrificial-tooling/