Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 51 (2020) 856–863

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)
15-18 June 2021, Athens, Greece.

Flexible low-cost tooling solutions for a one-shot resin infusion of a 3D woven and multi-textile preform

Nikita Budwal[a,b]*, Kent Kasper[b], Jon Goering[b], Carwyn Ward[a]

[a]*Bristol Composites Institute (ACCIS), School of Civil, Aerospace, and Mechanical Engineering, University of Bristol, Bristol, UK*
[b]*Albany Engineered Composites, Inc., Rochester, NH, USA*

* Corresponding author. *E-mail address:* nikita.budwal@bristol.ac.uk

Abstract

3D woven materials are extremely capable for high-performance aerospace applications. Traditionally, components comprised of 3D wovens are manufactured using Resin Transfer Moulding, requiring matched tooling that can result in high costs. Increasingly this is not feasible for mid-to-large structures, therefore flexible tooling strategies are necessary to facilitate low-cost one-shot vacuum mouldings of multi-textile composites. Towards this need, the authors investigated tooling materials and infusion strategies for an as-designed 3D woven pi-section incorporating a Non-Crimp Fabric (NCF) skin. Engaging with stakeholders presented two infusion strategies (flow ‘up’ or ‘down’ pi-NCF geometry) and three inserts (Polyetherimide, Silicone, and Aluminium) for the pi internal channel. Six infusions were completed with manufacturing data recorded followed by X-ray CT analysis to evaluate geometry and infusion quality; and manufacturing costs estimated. In combination, results suggest that coupling flexible tooling materials is most effective in both reducing costs and maximising injection quality, ensuring geometrical performance.

Keywords: 3D woven; Resin Infusion; One-shot; Tooling; Cost

1. Introduction

To reduce the need for bonding and assembly, aircraft manufacturers are looking to employ one-shot resin infusion processes for mid-to-large aerospace structures, including integrated door surrounds, wing skins, ribs and spars with integrated stiffeners. One-shot Liquid Composite Moulding (LCM) methods can reduce weight and improve manufacturing efficiency through labour reduction. The current Airbus “Wing of Tomorrow” program is focused on improving composite manufacturing processes in the single-aisle wing by integrating structures to simplify assembly and reduce fastener usage [1]. Manufacturing processes for integrated composite assemblies, however, can have higher production risks and must be made cost-competitive with low scrap rates. Therefore, smart preform design, complex forming methods, and intelligent infusions strategies require concurrent development with LCM modelling capability.

Historically, efforts to reduce the part count in composite aerostructures were focused on prepreg/autoclave consolidation processes. For example in the 1970s, McDonnell Douglas eliminated approximately 60% of fasteners and reduced overall part count by 62% by co-curing sub-components of the wing and forward fuselage of the AV-8B Strike Fighter [2]. Dasa Airbus also attained a 95% reduction in part count with the introduction of a composite vertical tail fin into the A300 and A310 aircraft, reducing from 2000 parts to 100 [3].

In the last 20 years developments in one-shot LCM co-curing solutions have begun to move manufacturer’s away from energy intensive prepreg/autoclave processes towards Out-of-Autoclave (OoA) process development with the use of dry-fibre preforms. For example, Airbus transitioned from a prepreg/autoclave consolidated Rear Pressure Bulkhead (RPB) in the A340 to a more cost-effective Non-Crimp Fabric (NCF) preform design in the A380, using a Resin Film Infusion (RFI) process. A two-step cure process is followed - firstly the dry-

10.1016/j.promfg.2020.10.120

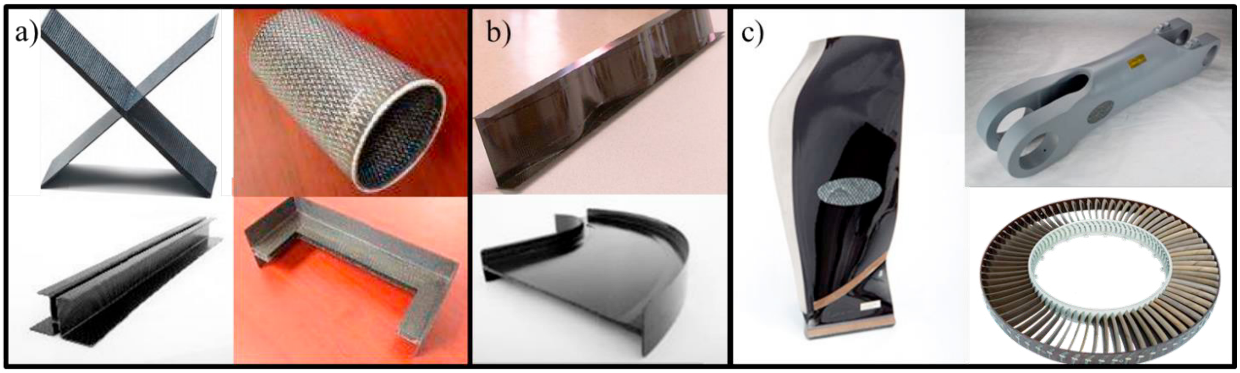

Fig. 1. (a) 3D woven uniform cross sections; (b) Non-uniform substructures with 3D wovens; (c) Aerospace components (LEAP™ fan blade, Boeing 787 landing gear brace, Rolls Royce lift-fan®) with 3D woven reinforcements. [9]

fibre preform is draped over a mould laminated with a resin film and cured in the autoclave; secondly, prepreg stiffeners are added, and the part is post-cured with integrated stiffeners [4]. Ideally this process could be condensed into a one-step cure. Lockheed Martin Space Systems (LMSS) demonstrated the benefit of one-shot Vacuum Assisted Resin Transfer Moulding (VARTM) in producing a Trident II D5 missile. With a one-shot process, up to 75% of costs could be saved due to the consolidation of a 61 part assembly and elimination of 376 fasteners [5]. Mahfuz et. al developed a process using foam mandrels, achieving good consolidation during the infusion and curing stages, which were then dissolved after demoulding [6]. The Japanese Aerospace Exploration Agency (JAXA) investigated a VARTM process using a silicone mandrel and external caul plates for the infusion of skin-stringer panels. Increased tensile strength was found with their process [7]. Many more industrial works on one-shot resin infusion strategies are known of, but most are kept proprietary. Furthermore, the available literature in cost-effective strategies to consolidate textile reinforced materials, like 3D woven materials, is limited.

3D woven composites have demonstrated good energy absorption, damage tolerance, and damage resistance when it comes to load-bearing structural aerospace applications. In a standard 3D woven textile, z-yarns or binder yarns reinforce the warp and weft patterns of the preform. The weave architecture and binder yarn reinforcement can be fabricated into multiple types of preforms, and incorporate features with variable thicknesses, contours, and seams, forming a near-net shape preform. Furthermore, the weave creates a stable preform structure that is less sensitive to handling compared to traditional dry-fibre lay-ups. 3D woven architectures can be fabricated by adapting a traditional weaving machine, although with Jacquard looms complex 3D multilayer weaves can be created and tailored to a specific application (Fig. 1). The versatility and high performance of 3D woven reinforcements make them a logical choice for stiffening elements and replacing mechanical/adhesive joints between parts. For example, Lockheed Martin demonstrated that 36kg of weight and $200,000 could be saved by using 3D woven stiffeners, eliminating 95% fasteners in the Joint Strike Fighter (F-35) inlet duct [8]. The F-35 inlet duct also demonstrates how bespoke dry-fibre structural elements can be incorporated into a "global" multi-textile preform, reducing the need for multiple manufacturing stages.

For complex geometry 3D woven parts, such as the LEAP™ fan blade (see Fig. 1c) [9], Resin Transfer Moulding (RTM) processes are employed. RTM uses dry fibrous reinforcement under injection pressure and/or applied vacuum with a low viscosity resin to wet-out the reinforcement [10]. RTM most commonly uses rigid closed moulds with the preform placed within the mould. The mould is closed, and resin is injected into the mould at pressures between 3-20 bar. To improve the process and remove volatiles, a vacuum can be applied to the sealed mould prior to injection. Using RTM processes, fine surface finishes and controlled geometric tolerances can be obtained at high production volumes. However, with rigid tools design is mostly limited to one geometry, requiring multiple tool sets for different parts and high tooling investment.

Vacuum Infusion (VI), although more labour-intensive, better lends itself to a flexible set-up at lower production volumes. An OoA VI process is less energy intensive than RTM or autoclave manufacturing [2, 11], even though the wetting out of the reinforcement is typically slower than RTM; relying on atmospheric pressure to infuse the preform under vacuum [10, 12]. Generally, a single rigid tool surface is used, with the opposing tool surface being flexible or bagged, to conform the preform to the rigid tool shape. The flexible mould will take the shape of the preform under vacuum, compacting it. Once the resin begins to flow, the resin pressure can result in some reshaping of the flexible surface. A combination of both VI and RTM is known as RTM-Light. In the RTM-Light process, a semi-rigid mould (e.g. Silicone rubber) is used in combination with a rigid tool to apply compaction pressure to the preform, and the resin is injected at a low injection pressure (1-3 bar) [12]. VI and RTM-Light are becoming popular processes for large, more complex, and unique structures that require only one surface to be geometrically controlled.

VI also allows for flexibility through the implementation of process variations on the traditional set-up. Specialised tooling and infusion strategies can be developed in-house and patented by manufacturers to find a cost-effective way to achieve a good quality part. Hindersmann [12] provides an extensive overview and characterisation of some of these modifications to the basic VI process used in industry: VARTM refers to a patented

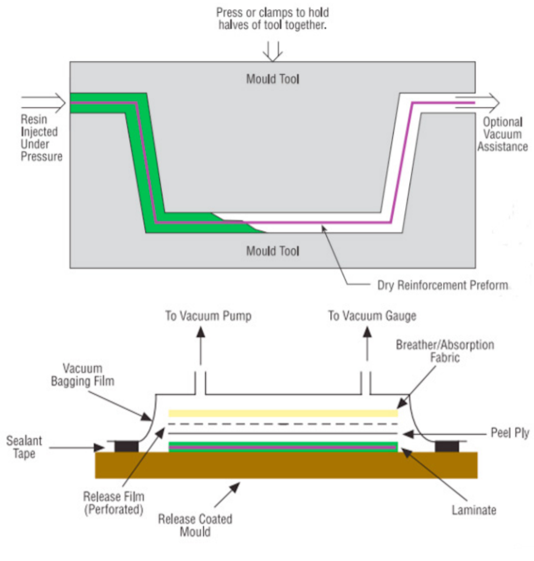

Fig. 2. RTM process (top); VI process (bottom) [13].

process in which the mould cavity is evacuated, and the use of a flexible mould half is used (as per the previous LMSS example [5]); VARI (Vacuum Assisted Resin Injection) is a Lotus Cars Ltd. patented process using two semi-rigid moulding halves; VAP (Vacuum Assisted Processes) is an Airbus patented process using semi-permeable (VAP®) membranes to remove gaseous volatiles from the infusion. Other processes, such as SPRINT, SCRIMP, DBVI, also exist, employing the use of infusion media, multiple inlets and outlets, double bagging methods, and gaseous permeable membranes to aide in decreasing production time while increasing part quality [12, 13]. Whilst almost all these process variations can be readily implemented within a facility, determining a suitable infusion set-up is more dependent on specific preform geometry and complexity.

The downside to high tailorability in the VI processes is the potential for increased variability in the moulding process. Potter [14] outlined sources of variability in moulding (such as tooling preparation and design; temperature fluctuations; vacuum levels; resin flow characteristics, and; demoulding steps) to better understand variability in composite performance. For composite parts, it is critical to limit these variabilities to meet aerospace certification standards [15].

Understanding the compaction and permeability of a preform can drastically improve infusion quality and Fibre Volume Fraction (FVF), through infusion or tooling strategies. When applying additional force to compact a preform, the permeability of the reinforcement will also decrease, and when selecting an infusion strategy this must be considered. For a complex geometry, it can also be difficult to achieve uniform consolidation pressure, fibre distribution, and resin content throughout the part. This will result in defects such as porosity, dry spots, and resin-rich areas. Such defects, and FVF variation, throughout a structure can result in non-uniform load distribution and undesirable structural performance. In VI, reinforcement consolidation and final cured part thickness are often difficult to control, as resin pressure and textile/fibre compressibility varies between dry and wet states. Multi-textile preforms further exacerbate this variation, by incorporating different material architectures and stiffnesses into the one infusion. Current research [16, 17] is focused on characterising & modelling the compaction/permeability of various reinforcement architectures. Modelling tools can also simulate the infusion process of large or complex parts within a designed tooling geometry. However, such tools cannot yet identify the most suitable tooling and infusion strategy without significant involvement of a manufacturing engineer. Additional work in compaction in complex geometries and multi-textile preforms is also required, to develop cost-effective manufacturing processes and reduce risks in unwanted variations.

This paper reviews some tooling strategies for one-shot LCM infusions of multi-textile preforms and conducts a case-study to evaluate the feasibility of combining various tooling approaches to flexibly manufacture high-quality aerostructures whilst reducing costs.

2. Brief Review of Infusion Tooling

In selecting a tooling material there are two classifications: hard or soft material. In literature [18, 19], VI mould materials are further classified as rigid, semi-rigid, and flexible. Hard and rigid tooling are made of durable materials suitable for higher production volumes. Soft tooling is more associated with lower costs and production volumes and is generally classified as a semi-rigid or flexible moulding.

Matched Nickel-Steel tooling (such as Invar™) is a dense highly durable hard material, capable of production volumes of +100,000 cycles. Moreover, the Coefficient of Thermal Expansion (CTE) of Invar™ is well matched to that of carbon-fibre/epoxy composites. However, Invar™ is costly to machine, requiring specialised services, which is exacerbated with increasing size and part complexity. Cost is further elevated when considering additional requirements for handling equipment of large, heavy tool systems.

Aluminium tools are less expensive, lighter, and easier to machine than Invar™ tools; but have a CTE mismatch to the composite, and a lower number of cycles before tool end of life.

Metal tools will generally have a high cost of machining, long lead times in delivery, and limited in-process flexibility. Matched tooling, with designed cavities for a cured part thickness, can require forceful loading of high bulk preforms and therefore risks manufacturing defects such as pinching, shearing, or fibre misalignment (including wrinkling). That said the high quality finishes and controlled geometrical tolerances of metal-moulded components are extremely desirable for aerospace components [20, 21].

Composite tooling is traditionally classified as a soft material and made from epoxy boards, wood & plaster models, foam, or fibreglass. More recently harder versions have been developed, usually consisting of carbon-fibre/epoxy or bismaleimide (BMI) materials, for their improved durability and higher cure temperature tolerance. Northrop have for example started using BMI tooling to match the CTE of their carbon-fibre/epoxy components [22]. Composite tools are said to be 60% lighter than Invar™, with a working life of +700 cure cycles. Further developments have been made in machinable composite materials using CNC routers, such as HexTool™ M61, which is made of randomly oriented BMI unidirectional carbon prepreg strips and can be machined to close tolerances. Solvay offers DURATOOL 450, a carbon-fibre/BMI prepreg capable of 200°C service temperatures [19, 21].

For flexible tooling, Silicone is probably the most often considered material. It provides a conformable internal or external moulding surface as a bag or flexible intensifier. It is commonly used for complex geometries that are difficult to demould such as closed cross-sections or internal forming surfaces. At high temperature the CTE of silicone allows for exploitable expansion characteristics, using thermal expansion of constrained silicone to create additional compaction pressure. In designing silicone tooling, moulds can be undersized to expand to the right dimension at the resin curing temperature. The high CTE of Silicone coupled with its high flexibility is desirable for parts with complex feature consolidation through forming, infusion, and demoulding [7].

Additively manufactured, or 3D printed materials, fall under the classification of soft, semi-rigid tools. Additive materials have been used in lay-up as preforming tools and show increasing potential towards moulding or cure tools. 3D printed designs are said to be advantageous as they will efficiently create net-shape moulds through processes such as Fused Filament Fabrication (FFF). Additive moulds and inserts will be limited to printer-bed size, and capital costs increase relative to the part size. For high temperature processing, ULTEM™ (a polyetherimide designed by Stratysys®) can be used; and includes a CTE between metals and silicone [23]. One significant advantage of composite tooling, and specifically using ULTEM™ and silicone, is the rapidity of prototyping. Table 1 compares the properties of the previously discussed tooling materials [7, 21-24].

Table 1. Comparison Chart of Tooling Materials [7, 21-24].

Material	Raw material cost (£/kg)	Scalability (# cycles)	Max Service Temp. (°C)	CTE (x10^{-6} °C)
Invar	20-30	10^5	900	1.4-5.0
Aluminium	<5	10^4	260	21-23
Silicone	10-20	10-30	290	80-360
ULTEM	200-400	10-30	200	40-50
Composite	30-50	10^2-10^3	200	3.6-9.0

*Sources: stindia.com; indexmundi.com; stratysys.com; easycomposites.co.uk; toolcraft.co.uk;

To address persistent problems with the costs and manufacture of conventional hard tooling; increasing levels of interests in terms of investigating tooling longevity needs, and methods towards more reconfigurable and hybrid strategies, are now being recognised. For longevity needs, methods currently in use include chemical vapour deposition of Nickel onto surfaces to form a shell tool (or Invalite™), and anodising or electroplating of basic metals. For reconfigurable and hybrid strategies, methods currently in use include multi-point moulding of sheet metals, and subtractive pin tooling. These methods can aide the manufacture of large simple geometry structures [22], however the consolidation of complex features within large structures will require further modular tooling designs or alternative moulding strategies to be developed.

Some alternative strategies for complex features include expandable/inflatable moulds, and lost core moulds. Expandable moulds are sheets or forms that increase in size when heated during the infusion or cure process and are made from polymer materials (i.e. silicones or thermoplastics). Similar to the Silicone flexible tooling, this will provide extra consolidation over the cure cycle of the composite, and Boeing have utilised a reusable expandable polymer mandrel for the co-curing of stringer panels [2]. Inflatable moulds, commonly called bladders, are preformed bags made from polymer materials that are filled with a gas or fluid and pressurised to increase consolidation. To demould, the bladder can be deflated and somewhat easily extracted. Bladders are therefore preferable to expandable moulds for changes in cross-sectional geometry. Lost core moulds are made of materials that can be dissolved or melted out of the component after it has been cured. These can be made from dissolving foam cores [6], melting preformed wax or low-melting point metal cores [25], and powders bound with resin [26]. Such moulds may add additional manufacturing steps, but they form a useful strategy for combining a forming and moulding tool.

Recent developments have been made in the use of Shape Memory Polymers (SMP) as moulds. SMPs are rigid at room temperature but when heated (to a pre-designed temperature) they become flexible, enabling their extraction from a preform. The U.S. Air Force Research Lab is reportedly conducting research with these mandrels, to develop a VARTM approach for braided inlet ducts [27].

The focus on tool design guidelines has classically been based on the longevity, cost, or reusability of the mould, and choice of tooling materials is based on these factors plus the thermal cycle of the part. Limited information is available on in-process deformation of the tool over time and its correlation with variability in part performance and manufacture. To address this issue a case study was designed to outline the impact tooling choice and design can have on infusion quality and cost-effectiveness in manufacture.

3. Case-study – Tooling with 3D woven pi-NCF

A complex multi-textile component - a 3D woven pi preform on an NCF skin (Fig. 3a) requiring a modular tool design - was selected for this work, as it is representative of a stiffened aerostructure. Two critical moulding points were identified for the component: (1) compaction of the base of the pi alongside the NCF, and (2) compaction of the upright 3D woven legs (Fig. 3b). The objective was to investigate the change in quality with different infusion and tooling approaches. Emphasis was placed on achieving a high infusion quality (minimal defects) and as-designed geometrical conformation along the part length.

Discussions with various stakeholders, presented options of

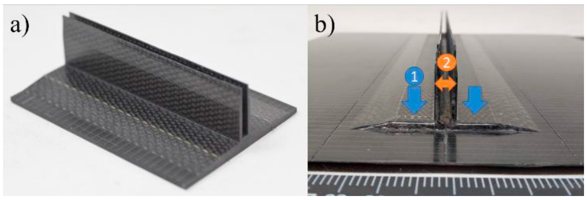

Fig. 3. (a) Trimmed pi-NCF specimen; (b) Critical pi-NCF moulding points.

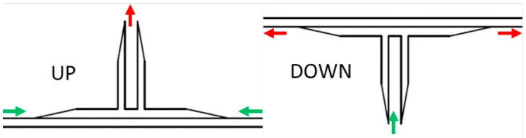

Fig. 4. Infusion set-ups 'Up' (left) and 'Down' (right) with arrows representing direction of resin flow.

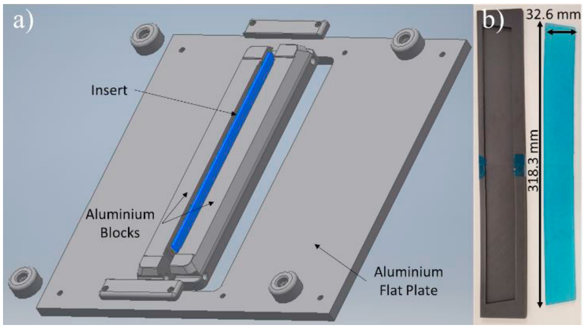

Fig. 5. (a) Modular flat plate infusion tool design; (b) 3D printed mould and silicone insert

two infusion set-ups - labelled as flow 'up' & 'down' configurations (Fig. 4), and the use of three different inserts - Silicone, ULTEM™, and Aluminium, between the pi-legs. In the 'up' configuration, resin was to flow into the preform through two outside edges of the NCF, and out through the pi-legs. In the 'down' configuration the inlet and outlet are reversed, and the set-up flipped over with the legs of the pi now facing downward. Common to both set-ups, resin was injected against gravity, intending to allow the resin to displace entrapped gas in the part during the infusion process.

An infusion tool was designed to allow for both infusion set-ups and the different inserts, by combining an Aluminium flat plate and blocks that would locate preform and compress the pi-preform against the NCF skin (Fig. 5a). The design targeted a FVF of 55% in the 3D woven pi. Each insert was designed to achieve a thickness of 4.52mm ± 0.1mm at the resin cure temperature. Due to the differences in CTE of each material, the room temperature/as-manufactured thicknesses of the Aluminium, Silicone and ULTEM™ inserts were designed to 4.50mm, 4.40mm, and 4.49mm respectively.

3.1. Composite Materials

The 3D woven pi-preforms were manufactured by Albany Engineered Composites, Inc. on an industrial Jacquard loom with Hexcel's IM7™ intermediate modulus carbon fibre. The NCF skin was made up of four plies of Formax™ 750gsm triaxial (-45/0/+45) carbon fibre fabric with 24K tows. The infusion resin was Solvay PRISM™ EP2400 RTM, an aerospace grade one-part epoxy resin system.

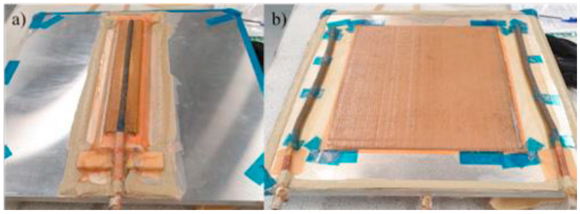

Fig. 6. Example of bagged and infused part (a) Pi-side (b) NCF-side.

3.2. Insert Preparation

The Silicone inserts were made using a two-part addition cure silicone moulding rubber VBS26 from ACC® Silicones, with a 3D printed mould (Fig. 5b). As Silicone is self-releasing, no further preparation was required once the insert was cured. The ULTEM™ 1010 inserts were 3D printed from the CAD design, with a thickness adjustment for two layers of flash tape to be wound onto the insert to enable part release. The Aluminium insert was machined to the correct dimensions and then coated with Frekote 770-NC release agent. Three coats of release were applied to the tooling and the aluminium insert.

3.3. Tool Loading

For each infusion trial, an insert was placed between the pi-legs prior to loading the preform into the tooling. Aluminium blocks were then placed on the outer sides of the pi-legs before loading the assembly into the Aluminium flat plate infusion tool. The triaxial NCF plies were then laid up 0/90/0/90 to the pi and tooling. A balanced asymmetric lay-up was intentionally created to minimize warp in the laminate.

3.4. Infusion

Once the preform and tool was loaded, resin inlets/outlets and flow media were installed depending on the infusion set-up using standard infusion consumables. A vacuum bag was applied to the entire infusion tool edges, to contact the NCF and Aluminium blocks; see Fig 6. A second envelope bag was then installed over the entire assembly, to keep a constant compaction pressure of 1 bar. The now completed infusion set-up was preheated in a Carbolite oven at 120ºC under vacuum while the resin was heated to 90ºC and degassed to remove volatiles. To infuse the multi-textile preform, a CIJECT™

Table 2. Manufacturing parameters and data for pi-NCF infusions.

Name	Insert Material	Infusion Strategy	Inlet	Outlet	Infusion time (min)	Average flowrate (g/min)	Peak flowrate (g/min)	Estimated FVF (%)
ALUP	Aluminium	Up	NCF	Pi	8	70	90	70
ALDO	Aluminium	Down	Pi	NCF	45	20	60	68
SIUP	Silicone	Up	NCF	Pi	8	80	150	69
SIDO	Silicone	Down	Pi	NCF	50	20	90	68
ULUP	ULTEM™	Up	NCF	Pi	20	30	100	67
ULDO	ULTEM™	Down	Pi	NCF	28	20	75	68

injection kit was used. Processing data per part is provided in Table 2. Parts were infused at 120°C and allowed to dwell for two hours before ramping to cure at 180°C for two hours (ramp rate of 2ºC/min). Typically the outlet was closed off once resin was evident in the pipework out of the oven, however for the ULUP trial the outlet was left open for a longer time to try to reduce the presence of dry spots in the initial trials. In Table 2, estimated FVFs of the whole part were calculated based on the initial preform weight, and final part weight.

4. Results and Analysis

Each completed panel was sectioned and imaged using X-ray computed tomography (CT) - scanned using a Nikon XT H-225 system with images reconstructed into a 3D volume using Nikon CT-Pro and post-processing by Volume Graphics VGStudio MAX 2.2.7 software (Fig. 7). The key geometrical configurations of Fig. 8a were then evaluated over the length of the pi-preform in the five locations identified in Fig. 9. The average and standard deviation of those measurements is presented in Fig. 8b-f, with the dashed lines representing the design-intent geometrical target for each measurement (the internal angle and base height difference were intentionally designed to be zero). The infusion quality of each processed infusion was characterised visually, and qualitatively evaluated based on the presence of dry spots on the surface, ease of insert release, and rich resin zones. Localised FVFs in the pi-preform could not be taken from the CT results, but these were used to support the quality assessment by identifying the presence of voids within the pi-preform to give indication of porosity and resin cracks at the pi-NCF interface (Fig. 9).

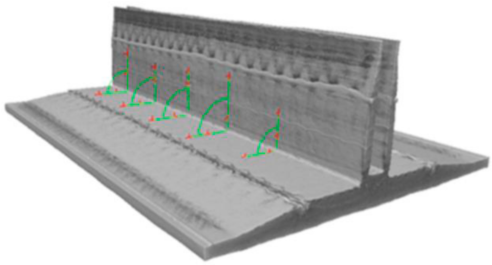

Fig. 7. 3D reconstruction of pi-NCF geometry.

4.1. Infusion Quality

Measurements from the CT images suggests use of the Aluminium insert (ALUP/ALDO) results in higher precision/lower geometry variation over the length of the pi-preform. With Aluminium being the most rigid insert this is not surprising, however it is interesting that SIDO had the best consolidation in the pi-legs (albeit with a very uneven inside leg finish) as Silicone is the most flexible of the inserts used. SIDO & SIUP inserts also resulted in the least difference between the inner/outer base of the pi. The base height difference for each moulding was highly variable. Aluminium and ULTEM™ inserts generally formed a resin channel in the pi inner base caused by variability in tool loading and insert CTE. While Silicone inserts resulted in measurements closer to the design targets (base height difference, internal angle, external angle), but again at the cost of an uneven surface finish. Minimal geometric difference between ULUP & ULDO parts was found, except for internal and external angles, as a result of difficulty with demoulding.

The 'up' infusion strategy generally had a fast infusion rate with roughly a 30% increase in peak flow rate but resulted in poor infusion quality for the Aluminium and Silicone inserts.

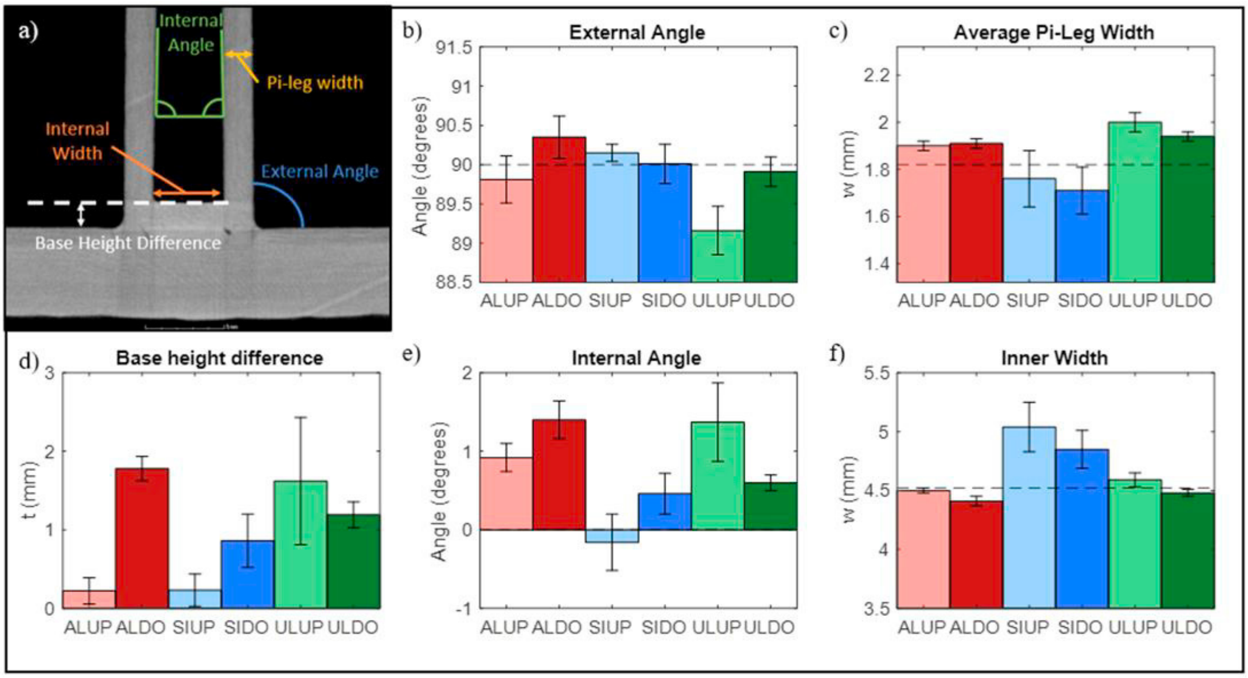

Fig. 8. (a) Measurements taken from CT analysis; (b-f) Results of CT analysis on pi-NCF geometry. Left to right: external angle, average pi-leg width, base height difference, internal angle, inner width.

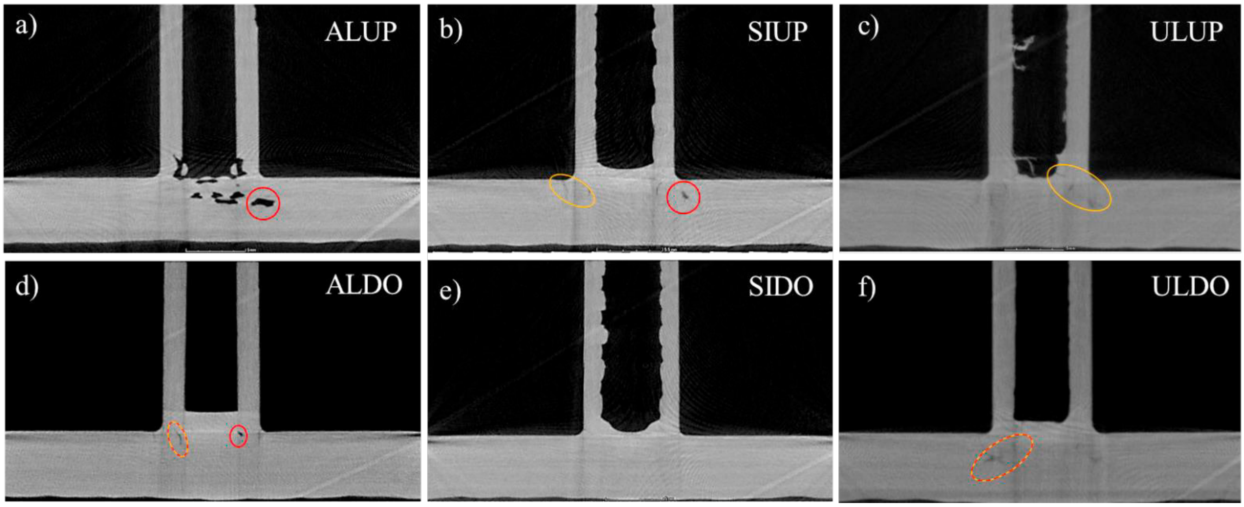

Fig. 9. CT cross sections of pi-NCF parts. Yellow circles indicate some detection of cracking, red circles highlight larger areas of porosity, and combination Red/yellow indicate an area of both. (a) ALUP; (b) SIUP; (c) ULUP; (d) ALDO; (e) SIDO; (f) ULDO.

In both, dry spots were visible on the surface and porosity was detected at the interface of the NCF and pi-preform. Specifically, in the ALUP part a large volume of voids was present in the central fillet of the pi, explaining the comparatively higher estimated FVFs of the part. ULUP in contrast did not have large areas of visible porosity and is likely a result of the variation in processing, leading to a longer infusion time. This somewhat suggests that simply extending the infusion time for the ALUP/SIUP set-ups will contribute to the elimination of the larger void presence.

Although the ULTEM™ inserts generally had a minimal void presence, these parts were observed to have an elevated presence of resin cracking along the pi's internal channel. This suggests that ULTEM™ contributes to the formation of resin rich regions that are prone to cracking. Cracking was also present in the ALDO & SIUP insert parts. In the ALDO part, cracks were found on both the external and internal radii of the pi-legs. For the SIUP case these cracks were mainly found on the external radius of the pi-legs where the preform was in contact with the Aluminium blocks.

4.2. Cost Considerations

To further explore the impact of these insert materials and infusion strategies, their tooling fabrication and in-process manufacturing costs were used to determine the total cost of manufacturing these 3D woven pi-NCF parts. The raw materials, fabrication, and life cycle cost of each insert was factored into tooling cost calculations, estimated from these manufacturing trials and the review presented in Section 2. The effect of the insert on the overall manufacturing process was addressed by focusing on changes in labour time, to ensure it contributed to estimates of in-process costs. Tooling preparation, preform loading into the tooling, and demoulding times were further critical factors considered. Table 3 summarises how these were factored into the cost model.

It was assumed that composite preforming costs would be the same for each part. For simplicity, a burdened labour rate of roughly 30£/hour was used, whilst the cost of raw materials was determined from Table 1. The results of the cost analysis are presented in Table 4 and Fig. 10. Despite the higher fabrication cost of the Silicone insert, the resultant part cost is lower with an expected decrease in processing time. The overall part costs were higher for the ULTEM™ insert due to extra in-process steps required for tool preparation & demould.

Table 3. Factors considered for cost model

Insert Material	Insert Fabrication	Manufacturing Process Impact
Aluminium	Materials: Aluminium Labour: CNC machining of material Lifetime: 1000 cycles	Application of mould release required for each cycle Loading and demoulding tool required additional force
Silicone	Materials: 2-part addition cure silicone rubber, casting mould material Labour: Cast & cure silicone Lifetime: 30 cycles	No insert preparation required Easy loading due to undersized insert Easy demoulding due to flexible insert
ULTEM™	Materials: ULTEM™ 1010 Labour: 3D print insert Lifetime: 10 cycles	Application of Teflon tape Demoulding required extra work to release insert from pi

Table 4. Cost model results.

Material	Insert Estimated Cost (£)	Total Part Manufacturing Time (min)	Total Part Cost (£)
Aluminium	62	388	185
Silicone	95	358	175
ULTEM™	42	424	200

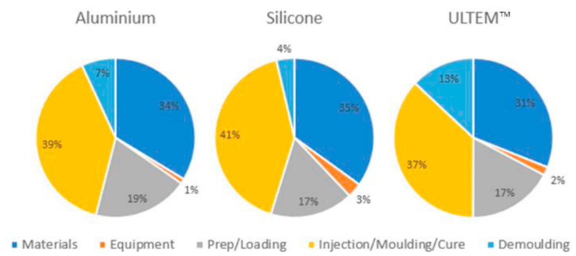

Fig. 10. Cost breakdown for using Aluminium, Silicone, and ULTEM™

The demoulding step appears to have contributed the main area of influence in these costings. With the Silicone insert time was drastically saved in demoulding the part due to its innate self-releasing properties; and so going forward, for the ULTEM™ insert process time must be reduced with the addition of a suitable high temperature sealant to its surface.

5. Conclusions

In this work a review of tooling for composite infusion systems in the open-access literature has revealed a potentially limited understanding in the suitability and capability of available materials for specific applications. For complex geometries further research is required, to fully identify the advantages and disadvantages of placing different tooling materials together to develop modular tool designs. Demonstrating this potential, a case-study whereby the infusion of a 3D-woven pi and NCF preform was performed with three different tooling inserts and two infusion strategies. Generalised observed trends from the case-study are summarised in Table 5, showing that by using flexible insert materials coupled with a rigid outer tool, the consolidation of critical moulding points was markedly improved. The use of a flexible Silicone insert has the potential to better compact complex features with minimal defects versus the traditional Aluminium design, although risks a loss in geometric tolerance. Trials with an additive insert also revealed potential for use with complex composite mouldings. Prior to any further investigation, problems with demoulding these inserts at a lower labour input (and therefore, cost) need to be tackled. The analysis pinpointed the fact that when all factors are considered (cost, part quality, manufacturability) a modular tool design with hybrid use of flexible and rigid materials can efficiently achieve a balance of component quality and geometric precision for complex components.

Table 5. Impact of infusion and tooling parameters on process and quality.

Infusion Type:	Up		Down
Infusion Rate	+		-
Infusion Quality	-		+
Insert Type:	**Aluminium**	**Silicone**	**ULTEM™**
Dimensional Accuracy (value relative to design)	+ -	+ +	- -
Geometric Precision (variation in measurement)	+ +	- -	+ -
Labour Time	+ -	+ +	- -
Tooling Cost	+ -	- -	+ +

Acknowledgements

This research is supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Composites Manufacture (grant: EP/L015102/1) and The Future Composites Manufacturing Hub (grant: EP/P006701/1). The authors gratefully acknowledge Albany Engineered Composites, Inc. (Rochester, NY, USA) and the National Composites Centre (Bristol, UK) for their support of this research. All data necessary to reproduce the results and support the conclusions are included within this paper

References

[1] Gubisch M. Cost reduction central to Airbus future-wing programme. FlightGlobal.com; 2019.
[2] Akin M. Co-cured manufacturing of advanced composite materials using vacuum assisted resin transfer moulding: Middle East Technical University; 2018.
[3] Deo RB, Starnes Jr JH, Holzwarth RC. Low-cost composite materials and structures for aircraft applications. 2003.
[4] Black S. An elegant solution for a big composite part. CompositesWorld: Gardner Business Media, Inc.; 2003.
[5] Tatum S. VARTM cuts costs. Reinforced Plastics. 2001;45:22.
[6] Mahfuz H, Majumdar P, Saha M, Shamery F, Jeelani S. Integral Manufacturing of Composite Skin-Stringer Assembly and Their Stability Analyses. Appl Compos Mater. 2004;11:155-71.
[7] Kuo C-C, Wu M-X. Evaluation of service life of silicone rubber molds using vacuum casting. Int J Adv Manuf Technol. 2017;90:3775-81.
[8] Bannister MK. Development and application of advanced textile composites. Proc Inst Mech Eng Part L: J Mater: Des Appl. 2004;218:253-60.
[9] Albint.com. Composite Aerostructures and Subassemblies. Albany International Corp; 2020.
[10] Ince ME. Performance of composites from 3D orthogonal woven preforms in terms of architecture and sample location during resin infusion. 2013.
[11] Song Y, Youn J, Gutowski T. Life cycle energy analysis of fiber-reinforced composites. Compos Part A: Appl Sci Manuf. 2009;40:1257-65.
[12] Hindersmann A. Confusion about infusion: An overview of infusion processes. Compos Part A: Appl Sci Manuf. 2019;126.
[13] Guide to Composites. Gurit; 2017.
[14] Potter K. Understanding the origins of defects and variability in composites manufacture. In: International conference on composite materials (ICCM)-17, Edinburgh, UK; 2009. p. 18-25.
[15] Gaddikeri KM, Gowda MNN, Sundaram R, Subba Rao M. Innovative tooling concepts for cocured composite structures in aircraft applications. Int J Adv Eng Sci Appl Math. 2014;6:142-7.
[16] Bodaghi M, Lomov SV, Simacek P, Correia NC, Advani SG. On the variability of permeability induced by reinforcement distortions and dual scale flow in liquid composite moulding: A review. Compos Part A: Appl Sci Manuf. 2019;120:188-210.
[17] May D, Aktas A, Advani SG, Berg DC, Endruweit A, Fauster E, et al. In-plane permeability characterization of engineering textiles based on radial flow experiments: A benchmark exercise. Compos Part A: Appl Sci Manuf. 2019;121:100-14.
[18] Equbal A, Sood AK, Shamim M. Rapid tooling: A major shift in tooling practice. J Manuf Ind Eng. 2015;14.
[19] Tooling. CompositesWorld: Gardner Business Media, Inc.; 2016.
[20] Black S. SQRTM enables net-shape parts. CompositesWorld: Gardner Business Media, Inc.; 2010.
[21] Injection Mould Tool Life - What Should You Expect ? : ToolcraftPlastics; 2019.
[22] Stewart R. New mould technologies and tooling materials promise advances for composites. Reinforced Plastics. 2010;54:30-6.
[23] FDM for Composite Tooling 2.0 Design Guide. Stratasys Ltd.; 2017.
[24] Campbell FC. Structural composite materials: ASM international; 2010.
[25] Lehmann U, Michaeli W. Cores lead to an automated production of hollow composite parts in resin transfer moulding. Compos Part A. 1998;29:803-10.
[26] Aquacore. Aero Consultants AG; 2007.
[27] Gardiner G. AFRL evaluates braiding, SMP tooling and VARTM for lower-cost future engine inlet ducts. CompositesWorld: Gardner Business Media, Inc.; 2020