Low-pressure (vacuum infusion) techniques for moulding large composite structures

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Abstract: Resin transfer moulding (RTM) involves the long-range flow of resin into a dry fibre pack that is preloaded into a defined mould cavity. Resin infusion under flexible tooling (RIFT) can be considered as a variant on RTM in which one tool face is replaced by a flexible film or a light splash tool. The flow of resin results only from the vacuum drawn under the film and any gravity effects. In RTM the dimensions of the component are defined by the separation of the mould faces, whilst in RIFT processes the thickness of the part is a function of the pressure history during the process. This paper reviews current developments in resin infusion processes.

Keywords: composites manufacturing, flexible tooling, resin infusion, RIFT, SCRIMP, vacuum infusion, VARTM

1 INTRODUCTION

The techniques for the manufacture of continuous-fibre reinforced polymer–matrix composites have been reviewed elsewhere [**1–4**]. Certain processes have been considered in greater detail:

- vacuum bagging, including autoclave cure [**5–8**];
- liquid moulding technologies (LMT) or liquid composite moulding (LCM), including resin transfer moulding (RTM) [**9–15**];
- resin infusion under flexible tooling (RIFT) [**16–18**];
- filament winding [**19**];
- pultrusion [**20**, **21**].

The resin infusion process has been known for almost 60 years, being patented by Marco Chemicals Inc. [**22**]. In the original Muskat patent,

> The method of the present invention contemplates the handling of the fibrous base to be impregnated. . . . preferably in a substantially dry state, and the subsequent impregnation of the base in a mold with a liquid or liquefied resinous material by an applied force which serves to drive the resin into the base to impregnate it and at the same time drive from the base all air entrapped therein. The applied force is obtained by applying an outside pressure differential between the inside and outside of the mold.

Further,

> impregnation of the fibrous base . . . may be obtained by providing tubes in each of the complementary molds or in only one of the molds, one tube being connected to a source of resin and the other to a vacuum pump, and sucking the resin up through the tube and into the mold until it is filled.

The patent implies that the ‘complementary moulds’ are solid rather than bag materials, but the two mould halves appear to be free to move together under the applied vacuum. The process was introduced to the UK by Scott Bader in 1946 [**23**] when moulders had to use closed moulds in order for the resin to cure properly because of chronic air inhibition.

2 RESIN INFUSION UNDER FLEXIBLE TOOLING

It is appropriate to consider these processes under several headings:

- in-plane flow parallel to the layers of reinforcement;
- through-plane flow from a flow medium or scored core;

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- resin film infusion (RFI);
- partially pre-impregnated materials (semi-preg).

The fifth stage would then be fully pre-impregnated materials: this is a process where infusion is undertaken by the materials supplier and the component is manufactured by conventional vacuum-bagging (and autoclave consolidation). This final process is not considered in this paper.

2.1 RIFT 1: in-plane flow parallel to the layers of reinforcement

In the most basic format, resin infusion can be considered to be similar to resin transfer moulding except that the second mould face is replaced by a flexible skin (bagging film or a splash tool). The dry fabric is positioned on/in the mould tool and enclosed in a vacuum bag. One set of pipework delivers the resin, whilst a second set of pipework allows a vacuum to be drawn in the cavity. The negative pressure removes air from the dry laminate stack (hence minimizing trapped air) and then the resin inlet is opened to permit resin to percolate through the laminate from a container (usually at atmospheric pressure) into the reinforcement pack. The flow front in the reinforcement also pushes any residual air towards the vacuum port. Flow is usually stopped when there is no evidence of air being flushed from the reinforcement into the outlet pipes. This process typically requires short flow distances and/or high permeability fabrics. Where bagging film is used as the second face, it is necessary to work with only vacuum for the pressure gradient to avoid ballooning of the cavity.

The Scott Bader 'VacFlo' process [**24**] involves a lightweight, matched two-part mould. The lower half may be an existing mould with a widened flange area. The upper half is usually a lightweight 3–6 mm thick GRP laminate. A double seal arrangement allows the first vacuum source to close and clamp the mould halves while the second vacuum source is used to pull the resin from a peripheral inlet channel to a central outlet port.

The Plastech VM (vacuum moulding)/RTM Light [**25**, **26**] process uses a similar configuration with the addition of an injection machine to control the introduction of resin. Two different levels of vacuum are employed for VM. The clamping vacuum, used to close the mould and seal around the mould flange, is usually between 50 and 100 mbar absolute. The mould cavity is usually maintained around 500 mbar absolute. Resin delivery pressures must be accurately controlled to prevent overpowering the external atmospheric clamping pressure.

2.1.1 Resins

In resin infusion, the resin flows long distances in comparison to most other processing techniques. Rudd *et al.* [**11**] suggest that the most significant practical limitation on the suitability of a resin system is imposed by viscosity. Resins with extremely low viscosity may be unsuitable for LCM processes as they may result in high porosity or gross voidage. Becker [**27**] quotes an upper limit for viscosity in RTM of 800 mPa s (1 mPa s = 1 centipoise). The non-injection point (NIP) is defined as a viscosity of 1000 mPa s [**28**]. The flow front is effectively stationary at this viscosity and the low pressures used in infusion processes.

For comparison, Stringer [**29**] suggested that there was a dwell time 'window' for each resin system within which high-quality laminates could be consistently produced by wet lay-up with vacuum bagging. Carbon fibre–epoxy composites were produced with fibre volume fractions up to 58 per cent and less than 2 per cent voids. The range of viscosities for this window was 7500–16500 mPa s.

Most resins formulated for hand lay-up can be used for this process, but resins of lower viscosity specifically formulated for liquid composite moulding processes are more suitable for RIFT techniques (e.g. Table 1).

A potential problem in RIFT processes is often described as 'boiling' of the volatile components. Lundström [**30**] states that styrene is only evolved in this way when the pressure is down to 0.01 bar at 40 °C. Poor laminate quality, normally attributed to the volatile components, was suggested to be an indication of air permeability of the mould.

2.1.2 Reinforcements

The depth of the tool cavity is a function of the local pressure in the mould and thus fibre volume fraction (and hence permeability) change with the progress of the flow front. The application of vacuum to the bagged laminate stack results in fabric compaction which, in turn, increases the fibre volume fraction

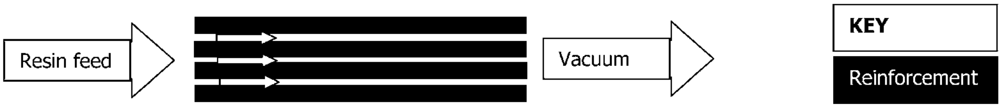

Fig. 1 Schematic representation of the resin infusion in-plane flow process [the bagging film (above) and mould tool (below) are omitted for clarity]

Table 1 Comparison of hand-lay and LCM resins [**18**]

Property	Units	Resin SP AMPREG 20/slow Hand lamination	 SP PRIME 20/slow Infusion
Mix viscosity (at 25 °C)	mPa s	447	188
Glass transition temperature (after 50 °C post-cure)	°C	85	86
Tensile strength of casting (after 50 °C post-cure)	MPa	83	74

and reduces the porespace and hence the permeability. This in turn results in slow in-plane flow rates in the fabric. High vacuum results in significant compaction of the laminate with only limited recovery on the release of the vacuum. The thickness of the reinforcement stack changes with the local pressure during the resin infusion process.

Williams *et al.* [**31**] have presented results of a preliminary experimental study of the effects of changing pressure consequent upon the flow during the process (Fig. 2). The compaction of the reinforcement is complex. The application of vacuum causes an initial reduction in thickness. The arrival of the resin front appears to have a lubricating effect and may result in further compaction. As the flow front progresses beyond the monitored position, the net pressure on the laminate is reduced and the fabric relaxes. To produce a laminate of uniform thickness it may be necessary to seal off the bagged wetted laminate and allow the pressure within the bag to equilibrate.

In order to overcome the low permeability of highly compressed reinforcement fabrics, different strategies have been adopted. Commercial fabrics are available where the architecture of the reinforcement is designed to cluster the fibres to give higher permeabilities than conventional fabrics. Whilst this fabric improves processing times, there is evidence that such clustering (at constant fibre volume fraction) is detrimental to the mechanical performance of the resulting composite [**32**, **33**]. Pearce *et al.* [**34**] studied twill weave fabrics woven by Carr Reinforcements Limited with both 3K and 6K carbon fibre tows. The new fabrics had improved permeability due to the introduction of the smaller tow to provide flow enhancement whilst reductions in mechanical properties were in-line with the change in fibre volume fraction.

Andersson *et al.* [**35**] used up to three layers of Vetrotex Unifilo U813-300 random glass fibre mat as flow-enhancing layers for eight plies of Devold DBT-800-E06 stitch-bonded non-crimp reinforcement infused with polyester resin. The experiment was conducted with point injection and radial flow. They observed that the lead flow front in the high permeability mat was farther ahead of the lag flow front in the fabric close to the inlet. Existing analytical models agreed with the experiments when ‘effective permeability data’ was used.

2.1.3 *Typical process window*

The preparation of the bagged laminate is normally conducted at ambient temperatures and pressures in the interests of the comfort of the workforce. Flow may be undertaken at elevated temperatures to reduce the resin viscosity and hence fill-time.

2.1.4 *Process equipment and manufacturing set-up*

The capital equipment required for RIFT process is simply the mould tool and a vacuum pump. The mould tool may be that used for contact moulding (spray or hand lay), although the extension of the

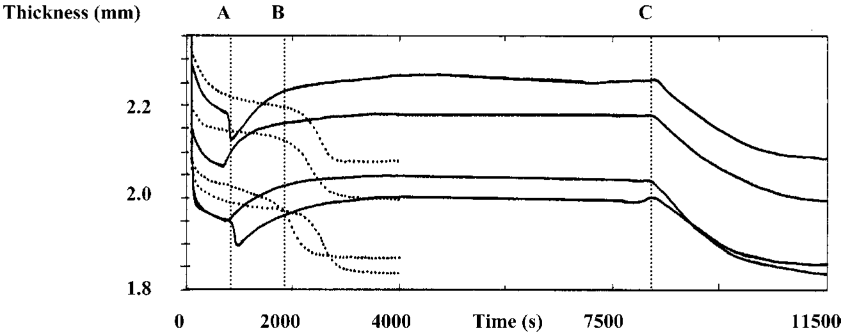

Fig. 2 Thickness variation with time during the RIFT process for four separate mouldings. Solid lines are for a transducer at 30 mm from the inlet, dotted lines are for a transducer at 180 mm from the inlet. A is resin arrival at first transducer, B is resin arrival at the second transducer, C is the time at which inlet and outlet pipes are clamped (after Williams *et al.* [**31**])

mould tool to permit attachment of the bag may be needed. The tool should also be vacuum-tight as any route for the ingress of air will result in tell-tale void trails in the laminate. There is increasing interest in the use of integrally heated mould tools for the processing and cure of infused laminates [**36**].

The consumables applicable to RIFT processes are similar to the peel ply, bagging film, and pipework required for vacuum bagging. The pipes are often perforated within the bag or a lightweight steel coil or plastic cable-wrap channel is incorporated to promote ‘race-tracking’. These form inlet and outlet galleries that minimize the distances the resin flow front has to travel in the laminate stack.

Equipment developed for RTM may find applications in RIFT. Plastech [**37, 38**] have developed the Autosprue®, an automated injection sprue, and MPG™, a mould pressure guard for their VM vacuum moulding system. They also offer both catalyst flow monitoring and an AGC (arrival, gel, and cure) sensor. The latter provides a signal indicating arrival of the resin flow front, subsequent electrolytic activity, and temperature.

The position of the flow front may be monitored visually through the bag or using fibre-optic sensors [**39**]. The state-of-cure of the component within the mould may be monitored using dielectric methods [**40, 41**] or chemical spectroscopy via embedded optical fibres [**42**]. The technologies available for monitoring the progress of composite manufacturing processes and for advanced process control and optimization have been recently reviewed [**43**].

2.1.5 Resin infusion for autoclave consolidation

The use of resin infusion techniques to prepare laminates for autoclave consolidation may result in considerably less expense in the acquisition of raw materials. This advantage must be set against the potential increase in both labour and quality costs for the fabricator due to the extra stages of production in-house.

2.1.6 Possibilities and limitations

The potential advantages are:

- it can be used for most resin systems (polyester, vinylester, and epoxy);
- it can be used with most conventional woven, stitched, knitted, braided, or random fabrics;
- large structural components can be fabricated;
- materials acquisition costs are lower than for prepreg and vacuum bagging;
- tooling costs are relatively low for high-performance components;
- it is more consistent than wet-laid components with minimal modification of the tooling;
- heavy fabrics are more easily wetted than by hand lamination;
- higher fibre volume fraction leads to improved mechanical performance;
- microstructure is more uniform and void content is minimal relative to hand lamination (Fig. 3);
- cored structures can be produced in a single flow process.

The disadvantages include:

- the process is relatively complex and requires different skills to hand-lamination;
- greater emphasis is placed on pre-moulding preparation than on the actual moulding process;
- the process is sensitive to leaks (air paths) in the mould tool and the bag;
- unlike prepregs, the quality control of the resin mixing is ‘in-house’;
- the requirement for very low resin viscosity may compromise thermal and mechanical properties, especially for polyester and vinylester matrix composites;
- uneven flow may result in unimpregnated areas and thus very expensive scrap parts;
- it cannot easily be implemented for honeycomb core laminates;
- only one side of the component has a moulded finish (cf. resin transfer moulding);
- thinner components have lower structural moduli.

Further, patenting of aspects of the process in the USA, and associated licensing costs, have caused potential users to be wary of adopting the process for fear of legal action.

2.2 RIFT 2: through-plane flow from a flow medium or scored core

This form of the process is known by a number of names with the most common being VARTM

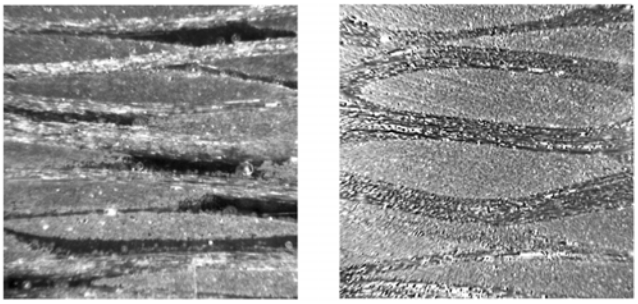

Fig. 3 Typical microstructures for hand laminated (left) and resin infused (right) composites showing the improved fibre distribution and reduced void content for RIFT; the composites are nine layers of 764 gsm plain woven E-glass in epoxy resin [**44**]

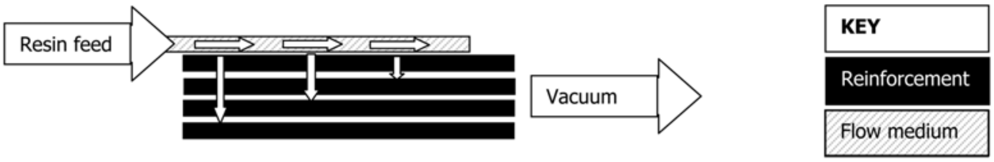

Fig. 4 Schematic representation of the resin infusion flow medium and through-plane flow process [the bagging film (above) and mould tool (below) are omitted for clarity]

(vacuum-assisted resin transfer moulding) or SCRIMP^{TM} (Seemann Composites Resin Infusion Molding Process). In this variant of the processes, the dry fabric is positioned on/in the mould tool, a peel ply/release film and flow medium are placed and these materials are enclosed in a vacuum bag. The flow medium/resin carrier layer is usually a knitted non-structural open weave fabric. The vacuum removes air from the dry laminate stack (hence minimising trapped air) and then draws resin from a container (usually at atmospheric pressure) into the reinforcement pack and into the carrier layer. This floods one surface of the component and impregnation then proceeds by through-thickness flow more or less simultaneously across the whole component. The flow front in the reinforcement also pushes any residual air towards the vacuum port. Flow is usually stopped when there is no evidence of air being flushed from the reinforcement into the outlet pipes.

SCRIMP^{TM} [**12**, **45**, **46**] is a patented process involving a vacuum bag with a resin distribution medium. It is believed that the SCRIMP patents are not valid in Europe due to prior art. The carrier layer may be interleaved with the fabric layers [**1**]. Resin is quickly distributed across a large part of the component surface, then saturates through the preform thickness. UVRTM (ultraviolet cure RTM) [**12**] is a SCRIMP-like process with ultraviolet cure through a UV-transparent vacuum bag.

The flow media can be applied either outside the laminate (any feeder material separated from the laminate by peel ply) or within the laminate (e.g. balsa, Rovicore or Multimat [**47**] or Soric [**48**]). Hetron Resins, in combination with SCRIMP, have developed a resin capable of producing class A finish in this vacuum infusion process [**49**].

2.3 RIFT 3: resin film infusion (RFI)

The B-stage resin used in pre-pregs typically has a viscosity in the range 2000–10 000 mPa s and thus will not flow the long distances associated with resin infusion in the plane of the fabric. These resins are now available as unreinforced films which can be laid up at the surfaces or interleaved with dry fabric reinforcements. The flow distance is thus limited to the thickness of the component or in the latter case may be as little as half the ply thickness.

Kruckenberg *et al.* [**50**] manufactured T-beams by placing epoxy resin film on the base of the mould with carbon-fibre preform above supported by L-shaped mould sections. Flow was through-thickness in the flange then in-plane in the stiffener. Flow height was calculated using one-dimensional Darcy's law (with two regions of different permeability) and the dynamic viscosity curve and gave predictions close to the experimental data. Demonstrator aerospace components (aileron skin, swaged wing rib, and the three-bay box) have been manufactured.

Uchida *et al.* [**51**] used a similar configuration to infuse Cytec 5250-4RTM bismaleimide resin (100 mPa s at 100 °C) into an 880 × 780 mm woven five-axis three-dimensional fabric preform. A fuselage skin panel for the Boeing 767 aircraft was moulded as a demonstrator with integral stiffeners. Full size automotive 'front nose' and 'rear fender' components were also manufactured.

Resin film infusion was selected [**52**] as an appropriate technology for fuselage panels in the TANGO (Technology Application to the Near-term business Goals and Objectives of the aerospace industry) programme. The skins will be non-crimp fabric preforms whereas the integrated stringers will be triaxial braids with unidirectional fibres incorporated.

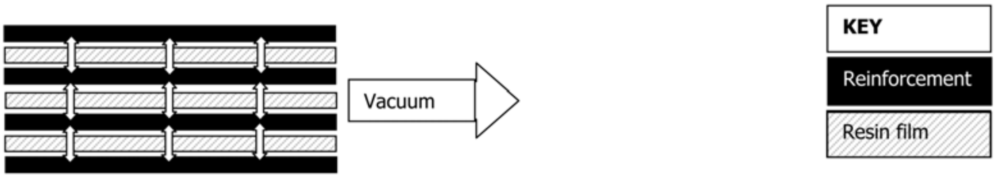

Fig. 5 Schematic representation of the resin film infusion process [the bagging film (above) and mould tool (below) are omitted for clarity]

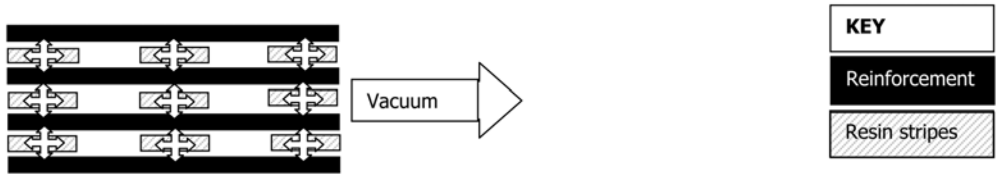

Fig. 6 Schematic representation of the 'semi-preg' infusion process [the bagging film (above) and mould tool (below) are omitted for clarity]

2.4 RIFT 4: partially pre-impregnated materials

In this form of resin infusion the reinforcement is supplied partially pre-impregnated with resin, often referred to as 'semi-preg'. Commercial systems are available.

Advanced Composites Group ZPREG [**53**, **54**] is available as heavy bulk (backing) plies and as medium-weight surfacing fabric laminated to a light-weight fabric. Resin stripes are applied to one surface to provide a light tack for ease of lay-up and to provide the matrix for the laminate after cure.

The Cytec Carboform system [**55**] consists of two reinforcement layers (e.g. 280 gsm 4×4 twill weave 3K HS-carbon fibre fabrics) each with a resin layer on the tool side with a non-woven polyester random mat impregnated with resin (e.g. 600 gsm Cycom® 754) between the fabrics.

SP Systems SPRINT® (SP Resin Infusion New Technology) materials [**56**] consist of a layer of fibre reinforcement either side of a precast pre-catalysed resin film with a light tack on one face. As the fibres remain dry and unimpregnated before the curing process they have good breathability and can produce 'autoclave quality laminates from vacuum bag processing'.

Frost *et al.* [**57**] compared the three systems to demonstrate that lightweight automotive body panels can be manufactured without the use of capital intensive equipment (e.g. autoclave). Panels were lighter, surface finish was better, and overall cost was lower than for pre-preg components. However, the impact resistance was lower than for the pre-preg panels.

2.5 General comments on resin infusion processes

In practice, the boundaries between these four classifications are not clear. Many variants incorporate aspects of more than one approach. The many variants of the process are known by a wide variety of names, which may not always be used for a specific procedure, including:

- CIRTM – co-injection RTM [**12**, **58**]:
  - ○ injection of more than one resin into soft-sided tooling and vacuum bag mould;
  - ○ separation of flow between multiple resins through the thickness of the part;
  - ○ elimination of the need for secondary bonding.
- Crystic VI – vacuum infusion from Scott Bader [**23**].
- DRDF – double RIFT diaphragm forming [**59**]:
  - ○ dry fabric is placed between two elastomeric membranes;
  - ○ resin is infused into the fabric;
  - ○ the 'sandwich' is vacuum-formed over the mould shape.
- LRI – liquid resin infusion.
- Quickstep [**60**, **61**]:
  - ○ a curing procedure appropriate to resin infusion;
  - ○ the tool and uncured component in a vacuum bag are placed in a low-pressure liquid filled chamber;
  - ○ liquids are held at low temperature, dwell temperature, and the curing temperature and are delivered by a computer controlled system;
  - ○ the mould is surrounded by a liquid at hydrostatic pressure so no significant loads are imposed on the tool structure.
- RFI – resin film infusion (see Section 2.3).
- RIFT – resin infusion under flexible tooling [**16**]:
  - ○ generic term for all vacuum-driven resin infusion processes under soft tooling.
- RIRM – resin injection recirculation moulding [**12**]:
  - ○ combination of vacuum and pressure infusion;
  - ○ resin recirculated until satisfactory wet out achieved.
- VAIM – vacuum-assisted injection moulding.
- VARI – vacuum assisted resin injection system originally from Lotus cars:
  - ○ vacuum (typically 0.34–0.95 bar) used to pull resin into the preform;
  - ○ process *may* use pressure to push resin at the same time.
- VARIM – vacuum-assisted resin injection moulding.
- V(A)RTM – vacuum (-assisted) resin transfer moulding:
  - ○ American acronym for through-plane flow from a flow medium or scored core.
- VIARTM – vibration-assisted resin transfer moulding [**62–64**].
- VIM – vacuum infusion moulding.

- VIMP – vacuum infusion moulding process [**12**]:
  - resin fed by vacuum or gravity, and may also use positive pressure;
  - resin transfer occurs from preform *interior* within the mould.
- VM/RTM Light – a hybrid RIFT/RTM vacuum moulding system from Plastech [**25**, **26**].
- VIP – (vacuum infusion process) [**12**], see VARI:
  - proposed as a generic term for 'resin introduce at lower than atmospheric pressure' by Bob Lacovara of CFA (USA).

2.5.1 Practical limitations

In some circumstances, easy flow paths can result in some areas of the component being starved of resin. Barnes and Galbraith [**65**] proposed the following options for practical situations:

- block the flow of resin over the reinforcement to force resin to flow through the reinforcement before reaching the vacuum pump;
- incorporate 5–10 per cent high permeability layers within the laminate to achieve wet-out of thicker laminates;
- use a flexible former (intensifier) between the bag and the laminate to maintain consolidation pressure during the process especially on large vertical or overhead surfaces.

For large products, it is often beneficial to employ a 'grid-like' injection strategy of one major channel with several branches [**47**]. The quality of the tooling is critical with maintenance of vacuum integrity becoming increasingly problematic as component size increases.

There is some concern, particularly from the boat-building industry, that the RIFT processes produce laminates with a surface that echoes the topology of the reinforcement fabric. This is due to the resin shrinkage in the resin-rich region in between the points at which tows cross. It is mainly a problem with polyester and vinylester resins formulated with high styrene contents to achieve a viscosity appropriate to the infusion process. Finer fabrics adjacent to the surface can help to minimize this effect, but further research is needed to optimize materials and processes to eliminate the effect. Avoiding 'print-through' is of commercial importance for all components where good surface finish is required and especially for producers of boat hulls.

The use of vacuum to drive the RIFT process causes fabric compression and results in reduced resin content in the laminate. The laminate produced is therefore thinner than for a comparable number of layers of reinforcement made by hand-lamination (in our experience the RIFT panel is <75 per cent of the thickness of the hand laminated panel). Some of the classification societies for boat-building have scantlings (standard dimensions for parts of a structure) in which the thickness assumes manufacture by hand lamination. To meet these requirements with RIFT manufacture would require additional layers of fabric. The use of RIFT processes produces thinner parts with a higher elastic modulus. However, loss of thickness may compromise the structural modulus due to the effect on second moment of area, so panel stiffness may be reduced.

2.5.2 Health and safety and the environment

It would be impractical to fully review safe practice for handling the materials used in composite manufacturing processes in the context of this paper. The following short section draws attention to some key points. It is written from the viewpoint of UK users. Legislation, and voluntary codes, can differ quite markedly between countries. Users should consult the suppliers for safety information and the national regulatory bodies for the latest standards.

In the UK, the principal legislation is the Control of Substances Hazardous to Health (COSHH) Regulations [**66**]. This is not a bureaucratic exercise, but a route to reduce pain and suffering caused by ill health. Before committing to any manufacturing process, the manufacturer should satisfy themselves (in the order given) that:

- they cannot substitute a safer material;
- they are using appropriate engineering solutions to minimize exposure;
- that appropriate personal protection equipment is provided.

The chemical components of resin systems are potentially hazardous to the health of composite fabricators, but need not be problematic if treated with due respect. Appropriate precautions should be taken to prevent undue exposure. Appropriate action would be to change to a less problematic resin system, to treat the vapours within the working environment or to adopt a closed mould process in line with the COSHH requirements. The resin infusion technique offers a cost-effective route to an improved working environment.

Even where styrene levels are controlled to within the Occupational Exposure Limits (OEL), there are other environmental restrictions which may apply, such as the Pollution Prevention and Control Act 1999 [**67**]. In particular, styrene has an odour threshold of 0.63 mg/m^3 [**68**] or 0.034 ppm [**69**]. For composites processing plants, if these levels are exceeded at the site boundary, then there may be increasing pressure from neighbours for further controls or prosecution for nuisance.

3 APPLICATIONS AND INDUSTRIAL UTILIZATION

Early commercial applications of RIFT/RTM processes included Lotus car bodies [**70**, **71**], British Rail rolling stock [**72–74**], ferries on inland waterways [**75**], and Dowty aircraft propellers [**76**, **77**]. Preliminary experiments on high fibre volume fraction composites were conducted in the early 1980s [**78–80**]. In the following sections, it may be assumed that the manufacturing process is RIFT2 (through-plane flow from a flow medium or scored core, a.k.a. SCRIMP^{TM} or VARTM), except where an alternative technique is specified.

3.1 Marine applications

Le Comte bV [**75**, **81**, **82**] produced a series of simple versatile reinforced plastic landing craft up to 22 m long using vacuum-assisted injection moulding (VAIM) and proposed that the 5 ton hulls of 34 m surface effect ships would be produced using this technique.

Vosper Thornycroft has progressively increased the extent to which components manufactured by the SCRIMP^{TM} technique are incorporated in the *Sandown*-class single-role minehunter for the Royal Navy [**83–87**]. The 55.2 m 470 tonne displacement craft is ~30 per cent reinforced plastic, largely moulded by VI. The benefits of SCRIMP^{TM} are:

- resin infusion into the tows is independent of fabric weight;
- reduced costs and greater efficiency in production – fewer layers of a heavier (6000 g/m^2) fabric are needed compared to the 35 separate plies of 800 g/m^2 woven roving glass used in hand lamination;
- reduced component weight (up to 72 per cent fibre by weight);
- void content reduced from 5 per cent by hand lamination to <1 per cent by SCRIMP^{TM};
- increased laminate strength (due to the higher fibre fraction and reduced void content);
- cleanliness (reduced styrene emissions and waste resin).

SCRIMP^{TM} is now used for the entire superstructure and some internal structures. Laminates up to 100 m^2 in area and up to 20 m long have been made. The superstructure is moulded on two 10 × 50 m vacuum tables with two vacuum ring mains and resin delivery systems capable of delivering 50 kg/min. The use of epoxy resins specially formulated for infusion processes (e.g. SP PRIME 20) has been found to reduce fill times by 10 per cent compared with equivalent polyester or vinylester resins.

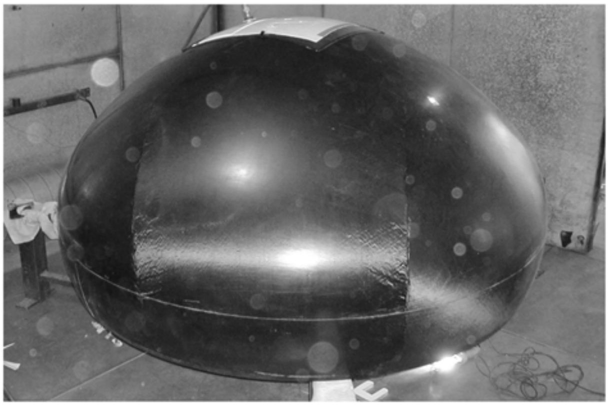

Fig. 7 The 2 m diameter carbon epoxy composite sonar dome

Hoebergen [**47**, **88**] has described the use of vacuum injection techniques for the production of the hull (16.4 m long × 4.5 m wide × 2.5 m high) of the Contest 55 sailing yacht (Conyplex shipyard, The Netherlands) in a female mould. The injection strategy chosen for the glass fibre skin balsa core moulding was a main channel running from the stern via the keel to the bow with branches from the main channel running up to the deck flange. The balsa core was used as the flow medium. A second injection was used to fabricate monolithic stiffeners for attachment of the keel. A two-stage sequential injection strategy has been implemented [**47**] for the deck in order to overcome fill problems around the wheelbox. Injection was simulated using π-7 software (developed by TNO during BRITE/EurAM II grant BE5477) and subsequently RTMworx (POLYworx, NL).

Leenders *et al.* [**89**] conducted a study to improve repeatability and quality of large load-bearing secondary ship structures such as removable bulkheads and hatch covers. They concluded that higher absolute pressures and an increased pressure difference (from 650 to 860 mbar) solved the problems of voids appearing in large structures. Leenders [**90**] further reported the use of VIM for the production of an 11.1 × 8.5 m removable grain bulkhead for a small cargo vessel.

Lindblom [**91**] reported that the resin infusion technique was used to manufacture carbon fibre skin–PVC foam core sandwich panels up to 60 m^2 for the Royal Swedish Navy *Visby*-class stealth corvette.

The Advanced Composites Manufacturing Centre [**92**] has worked with Thales Underwater Systems to develop a 2 m diameter sonar dome component (Fig. 7). The non-crimp carbon fibre fabric monolithic composite varied between 9 and 50 mm in thickness. The component was vacuum-infused on a split female tool with especial care needed to ensure vacuum tightness. Fibre volume fractions over 60 per cent were achieved with minimal void content.

Other vessels constructed using SCRIMP^{TM} techniques include:

- Projection Yachts Sundeer 64 [**93**] and the 8 m (25 foot) 762 [**94**];
- J/Boats including the larger 12.2 m (40 foot) J/120 [**95**, **96**], 13 m (43 foot) J/133 [**97**, **98**], 15 m (48 foot) J/145 [**99**, **100**], 16 m (53 foot) J/160 [**101**, **102**]; and
- the 27.4 m (90 foot) North End Composites deep-vee power boat hull [**103**].

3.2 Land transport applications

A successful example of the application of RIFT processes is 21 m railroad freight cars for the transportation of refrigerated goods. The units use glass-fibre reinforced vinylester resin skins over a polyurethane foam core. Payload is increased to 135 per cent of that for conventional steel freight cars, whilst the insulation is so good that the cargo can be loaded cold and transported for week-long journeys with no refrigeration unit required. The cars are assembled from two sections: the roof and an integrated floor and walls [**104**, **105**].

Vosper Thornycroft have used SCRIMP^{TM} to produce the Strasbourg tram bumpers (fenders). The process can meet the high impact and low weight requirements which are not possible with hand lay-up, yet is less expensive than RTM [**83**].

Weinhold and Wozniak [**106**] have described the use of SCRIMP^{TM} for the fabrication of compressed natural gas integrated storage system (ISS) for light duty vehicles. The two mating shells, when assembled, contain three high-pressure filament wound cylinders. Labour for lay-up was significantly less than for pre-preg fabrication methods, although labour for vacuum bagging was about the same.

3.3 Armour applications

French [**107**] has reported that the hull mouldings for an Advanced Composite Armoured Vehicle Platform (ACAVP) demonstrator have been manufactured by ‘VARTM also known as SCRIMP’. The reinforcement is E-glass as a quasi-isotropic non-crimp fabric. The bare hull weight is around 6000 kg. These mouldings will probably be the thickest components made by an RTM-like process. The following advantages were identified for the process:

- similar materials costs to hand lamination or compression moulding;
- more consistent higher quality product than produced by hand lamination;
- superior dimensional and quality control relative to hand lamination;
- thicker fabrics can be processed than is possible with hand lamination;
- manufacturing costs below those associated with pre-preg manufacture;
- the materials do not have the limited storage/shelf life problems associated with pre-preg;
- greater flexibility and lower process equipment costs than compression moulding.

Kelkar and Vaidya [**108**] have described the use of vacuum-assisted resin injection moulding (VARIM, ‘flow of resin in plane as well as in the transverse directions to the preform’) for the manufacture of the thick load-bearing laminate in integral armour for the upper hull of the Composite Armoured Vehicle – Advanced Technology Demonstrator (CAV-ATD) for the US Army. Thirty-eight layers of S2-glass twill weave fabric were infused with vinylester resin to produce a laminate of 25.4 mm thickness with full wetting achieved within 20 min fill time. The properties (tensile strength, modulus, and fatigue) were comparable for VARIM and similar RTM panels.

Fig. 8 The 40 m radius AL40 carbon–wood epoxy wind turbine blade

3.4 Renewable energy

TNO-CLC in the Netherlands [**89**] have used vacuum injection techniques for the manufacture of demonstrator wind turbine blades. The Danish company, LM Glasfiber developed a resin infusion process for their 54 m (176 foot) glass fibre Future Blade model [**109**]. The blades were produced as two half shells joined by a spar beam.

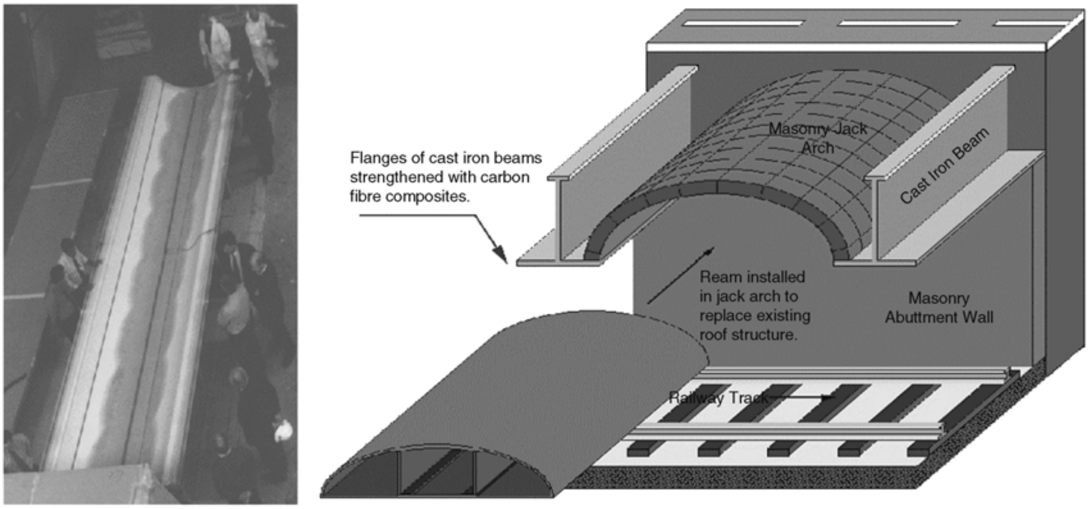

Fig. 9 Structural beam for strengthening of London Underground tunnels (courtesy of Devonport Management Limited, Plymouth, UK)

NEG Micon has traditionally produced wood wind turbine blades. Since 2001 they have introduced some carbon fibre–epoxy components for specific load-bearing elements to permit larger designs. They have developed a proprietary production method based on vacuum infusion of dry fibre reinforcements [**109**]. The new blades are claimed to be 30 per cent lighter than equivalent GRP blades.

The Advanced Composites Manufacturing Centre has undertaken an on-going development programme with NEG Micon Rotors, Isle of Wight since 2000. The process was formerly wet lamination of birch plywood sheets followed by vacuum bag consolidation. Laboratory tests were undertaken on 5 and 7 m-long sections at the root end of a 31 m half-blade tool using five resin inlet lines across the width of the tool [**92**]. A novel resin infusion technique has been developed and optimized which should lead to considerable reductions in production time for very large (40–60 m) blades (Fig. 8) [**110**].

The Canadian manufacturer Polymarin-Bolwell Composites Inc. has adopted VARTM for the production of 24.5 m (80 foot) blades for the North American market [**109**]. The Mexican blade manufacturer Vien Tek LLC (a joint venture between Mitsubishi Power Systems and TPI Composites) is to build 30 m (97 foot) blades for 1 MW machines using the SCRIMP^{TM} process [**109**].

3.5 Offshore applications

Devonport Management Limited (DML, Plymouth, UK) have developed RIFT techniques for the reinforcement of existing structures with carbon fibre composites manufactured *in situ*. These have been applied to fire and blast protection systems for offshore oil and gas production platforms [**65**, **111**]. The substrate to be strengthened is used as the mould. The requirement for adhesion between the composite and the substrate eliminates the need for release agent on the ‘mould’. The system has been used for blast strengthening of the Mobil Beryl B and BP Cleeton platforms and for strategic strengthening of the Chevron Alba North platform. Between 5 and 10 per cent of the laminate was layers with low resistance to flow evenly dispersed between the primary unidirectional reinforcements.

3.6 Civil engineering infrastructure applications

Fibrelite injects resin through gaps and channels in the sandwich core to produce composite manhole covers for service station forecourts. Their process is known as ‘network injection moulding’ [**112**].

DML have also applied RIFT techniques to the rehabilitation of the London Underground Limited (LUL) railway system infrastructure [**113**, **114**]. This has included temporary strengthening of the District/Circle Line tunnel at Sloane Square station (Fig. 9). Permanent strengthening solutions have since been implemented for LUL.

Hardcore Composites (Delaware US) [**115**] designed and constructed a one-piece bridge deck using the SCRIMP^{TM} technique. The deck, supported on six steel girders, is 11.9 m long, 5.2 m wide, and 254 mm at the deepest section. It achieved the American Association of Highway and Transportation Officials (AASHTO) H25 load rating, confirmed by loading with a 30-tonne truck.

4 PROCESS SIMULATION

The models appropriate for process simulation of resin transfer moulding techniques should be applicable to resin infusion under flexible tooling. However, these models will not normally take account of the thickness variation during the process due to the compression characteristics of the fabric.

Hammami and Gebart [**116**] have presented a one-dimensional model for the 'vacuum infusion moulding process'. The rough first formulation showed fairly good agreement with experimental results. The experimental investigation clearly showed that the process was governed by complex relationships.

> The fibre volume fraction and permeability of the laminate stack depend upon the vacuum level achieved. The problem is further complicated by the flexible top surface. In addition, the lubrication effect introduced by the resin impregnating the fibres adds to the complexity of the problem [**116**].

Their good agreement between the model and experimental results indicates that Darcy's law is still valid if an additional equation for the vertical equilibrium of the cavity height is added.

Sun *et al.* [**117**] used a three-dimensional (3-D) control volume/finite element method (CV/FEM) to solve the flow governing equations for the relative flow in the flow medium, peel ply, and a stitched fibre mat reinforcement. The flow front lead-lag (flow medium leads reinforcement lags) was 'not very large and remained nearly constant through the entire mould filling process'. A simplified 2-D CV/FEM model was proposed using two assumptions:

- the permeability of the fibre preform is much less than that of the flow medium;
- the length along the flow direction is much greater than the thickness of the composite part.

In consequence, there is only flow through the thickness direction in the peel ply and the fibre preform. The models appear to assume constant cavity height. Ni and the previous authors [**118**] have also presented similar results for SCRIMP with grooves acting as flow channels.

Han *et al.* [**119**] have developed a flow model to simulate resin infusion processes for composites manufacturing. A hybrid 2.5-D and 3-D modelling technique is introduced with some assumptions to simplify the complex problem of fluid flow through compressible porous media. The model was used to simulate different injection strategies for a quarter-scale model of a 5 m (16 foot) boat hull. The simulation results for flow pattern and filling time agreed well with the experimental SCRIMP infusion.

5 SUMMARY

This paper has reviewed the four major variants of the Resin Infusion under Flexible Tooling processes. It has further considered the application of these techniques to the manufacture of large composite structures and has briefly introduced some of the process simulations which have been presented in the open literature.

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