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Resin Infusion under Flexible Tooling (RIFT): a review

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Increasing legislation to limit styrene emissions (mainly from polyester resin systems) into the work place has been the key factor in promoting new technology in the manufacture of fibre reinforced plastics composites. Styrene emissions can be reduced by the development of: resin systems with low styrene emission; improved ventilation and air filtering systems; closed moulding techniques. It is the final area on which this paper concentrates.

RIFT is a variant of vacuum-driven RTM in which one of the solid tool faces is replaced by a flexible polymeric film. The process is known by several acronyms—in this paper it is referred to as RIFT (Resin Infusion under Flexible Tooling). Potentially a very clean and economical composites manufacturing method, the process draws resin into a dry reinforcement on an evacuated vacuum bagged tool using only the partial vacuum to drive the resin. It reduces worker contact with liquid resin whilst increasing component mechanical properties and fibre content by reducing voidage compared to hand lay-up.

For higher performance composites, RIFT offers the potential for reduced tooling costs where matched tooling (RTM or compression moulding) is currently used.

This paper reviews the progress of RIFT from its first development as the Marco method in 1950 to the Seemann Composites Resin Infusion Manufacture Process (SCRIMP) today. Development of the process has been slow (compared to RTM) and generally lacking in scientific rigour. Current research is reviewed and the potential for scientific development is discussed. Copyright © 1996 Elsevier Science Limited.

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INTRODUCTION

The choice of modern composite manufacturing methods are, as with all engineering decisions, driven by cost, quality, health and safety and fitness for purpose. Development for the manufacture of medium to large area structures of high fibre volume fraction ($V_f \geq 45\%$) has centred on resin transfer moulding techniques, compression moulding and autoclave vacuum bag methods.

Resin Transfer Moulding (RTM) is considered in the context of this paper to describe the injection method of composite production. Tooling is considered solid and resin is injected under positive or negative pressures. This has enabled the manufacture of high V_f (volume fraction of fibre) composite components with good dimensional tolerance in matched moulds. For large area structures, tooling costs become very large for RTM due to the structure required to resist moulding pressures. Tooling for vacuum bagging is of much lower cost since only a single mould face is used. A high structural stiffness is not required, as even in the autoclave, the tooling is subjected to hydrostatic, rather than differential pressures.

With vacuum bag and hand lay-up methods, the operator is exposed to uncured liquid resin systems and to any volatile components they may emit into the work place atmosphere. This is a particular problem for resins cured by addition crosslinking, notably when using unsaturated polyester or vinyl ester resins which emit styrene vapour. Styrene vapour has been reported to cause detrimental effects in workers: depression and fatigue with a slowing of reaction times[1] and in severe cases detrimental psychiatric symptoms[2]. These obviously pose a safety threat. A new voluntary limit of 50 ppm on air borne styrene in the work place has been adopted in the UK[3] with the prospect of the limit becoming law by 1996.

Installing extraction is costly and time consuming. For low volume production a shift to alternative resins, e.g. ambient cure epoxy or low styrene content polyester, may be a cost effective short-term solution. In the long term the process must be re-designed to take advantage

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of cheaper resin systems and reduce health and safety risks. A requirement thus exists for a closed mould technique with much lower tooling costs than RTM. Such a technique is particularly suitable for medium to large area structures.

This paper reviews the development of vacuum bag injection methods or Resin Infusion under Flexible Tooling (RIFT) for the production of structural composites.

HISTORICAL DEVELOPMENT

Despite the recent interest in the RIFT process, it was being considered as a clean alternative to hand lay-up as long ago as 1950. The Marco method[4] was designed in the USA for the manufacture of boat hulls with reduced voidage and tooling costs when compared to RTM. It was not widely adopted because resin and reinforcement development favoured open mould lay-up or spray deposition (for boat manufacture) in what was until recently an under-regulated industry. The Marco tooling design can be seen in *Figure 1*; dry reinforcement was laid up onto the solid male tool and a semi-flexible/splash female tool was used for consolidation and to provide a seal for the application of vacuum.

In 1972, Group Lotus Car Ltd[5] patented a vacuum moulding method for the production of FRP components. The process consists of a closed GRP mould into which is placed dry fibre. Before tool closure a measured amount of resin is poured onto the fibre. On closing of the tool halves the tool cavity is evacuated, drawing the tool faces together, diffusing the resin into the fibre stack.

In 1978, Gotch[6] detailed the use of vacuum impregnation using one solid tool face and a silicone rubber diaphragm bag. Liquid resin is poured onto preplaced dry fibre before being enclosed by the bag. The work was a response to the introduction of the Health and Safety at Work Act (1974) to reduce styrene emissions into the work environment. Moulding quality was higher than that achieved using hand lay-up. Gotch also reported that "the method removes the operator dependence of quality when compared to hand lay-up". Vacuum pressure only was used to draw resin into the tool. The elastomeric bag design was changed to solid tooling for complex shapes due to problems with the variability of fibre content and flow control. These problems were attributed to the high viscosity resins used at the time rather than to the method of manufacture itself.

In 1980, Gotch[7] and later in 1985[8] again highlighted the need for manufacturing to recognize the lower levels for styrene vapour being imposed in EEC countries. He again considered the silicone vacuum bagging method detailed in ref. 6, but now with resin drawn into the sealed vacuum bagged tool using vacuum pressure. Gotch suggests the ideal resin viscosity for a vacuum injection system is 1–200 mPa s. Commercially developed resin systems with such viscosities have been developed, stimulating further process development.

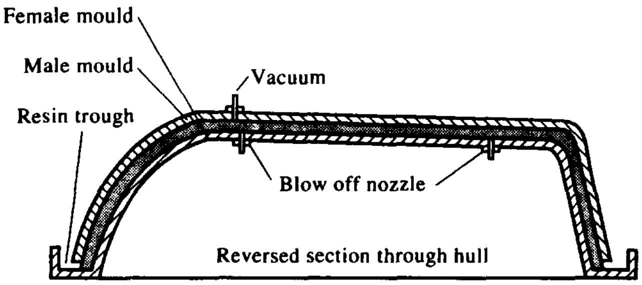


Figure 1 The Marco method of RIFT (circa 1950)

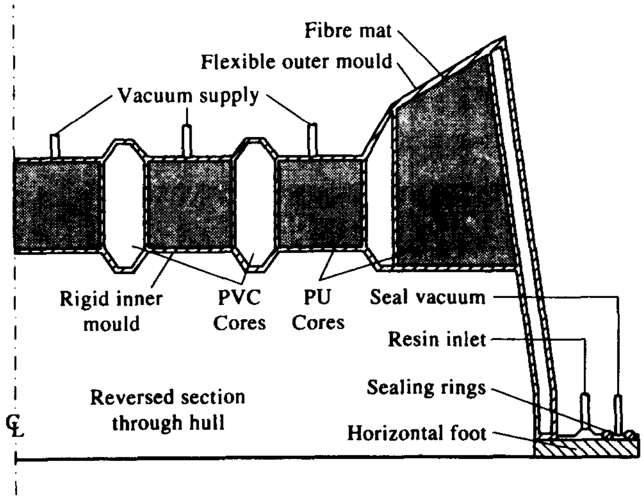


Figure 2 Section through the tooling used by Le Comte

The flexural strengths of laminates of identical constituents manufactured by hand lay-up, cold press moulding and the vacuum bag infusion process were compared. Gotch noted that values obtained from the hand lay-up process were scattered and very operator dependent whereas the values for press moulding and vacuum infusion were more consistent. He found that the production rates for railway coach panels of medium complexity were typically three times greater for the vacuum infusion method than those for hand lay-up.

In 1982, Allen *et al.*[9] considered the use of vacuum infusion to manufacture high fibre content composites. Closed aluminium tooling was used with consolidation via a platen press. Fibre volume fractions achieved ranged from 43 to 60% using 0°/90° plain woven E-glass reinforcement and vinyl-ester resins. Although the work did not consider flexible tooling it demonstrated that infusion of high V_f components can be achieved at resin pressures as low as 1 bar.

In the same year Le Comte[10] patented his 'Method and apparatus for producing a thin walled article of synthetic resin, in particular a large-sized article'. The patent describes a design similar to the Marco method, i.e. reinforcement fabric compresses under vacuum between a solid and flexible tool face. The method can be used for the production of glass reinforced plastic boat hulls with cores and stiffeners in place, *Figure 2*.

Tooling materials are glass reinforced plastics[11]. The resin is raised 4–5 m above the injection point to provide some positive pressure. Le Comte has produced 50 m surface effect ship hulls using this method. Infusion takes approximately 10 h before resin gelation occurs at workshop temperatures of 18 to 20°C.

In 1985, Tengler[12] reported on a vacuum injection process to produce high strength carbon fibre reinforced composites. He used closed aluminium tooling with a vacuum being drawn inside the cavity to facilitate consolidation and to draw resin into the tool. Double edge seals were also used to reduce air leaks. Components of 35% fibre volume fraction could be successfully manufactured but problems with the high viscosity of the epoxy resin and short gel times were encountered for mouldings of higher fibre content. This led to incompletely filled mouldings.

Adams and Roberts[13,14] used the solid nickel coated metal tooling Vacuum Assisted Resin Injection (VARI) method to produce solid and cored laminates. This process was developed from their work in the 1970s[5]. Once the tool cavity had been evacuated consolidation was due only to atmospheric pressure. No mould clamping was used. This method was used to manufacture structural components such as car side-impact panels for Lotus. Cost savings were suggested when compared to RTM owing to the reduced moulding forces. They also stated that vacuum infusion saved production time when compared to pre-preg manufacture as debulking operations were not required: the process being a one-shot manufacture method.

Ciba-Geigy published details of their vacuum infusion process for the manufacture of glider ailerons[15]. Tooling consisted of a solid composite female and nylon bag male. Resin is drawn into the tool on evacuation of the tool cavity. The process, as shown in *Figure 3*, was developed as a manufacturing method to replace conventional hand lay-up of large parts, reducing health and safety risks and increasing production efficiency with repeatable quality. Vacuum infusion was chosen using female composite tooling with internal oil heating/cooling and silicone or PVC bagging material. Sealing of the bag was via a circumferential seal compressed by an aluminium box section and toggle clamps. Resin entered the tool via a peripheral resin channel and impregnated circumferentially toward the central vacuum ports. The use of Injectex fabrics[16,17] and low viscosity epoxy resins helped resin flow. Good quality components were produced. No mechanical properties of the components have been published.

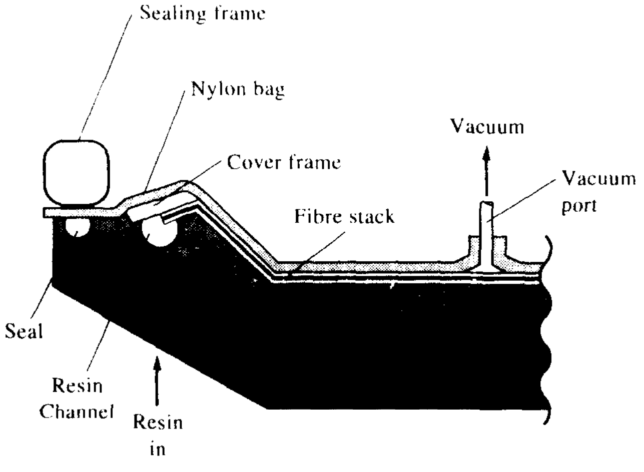


Figure 3 A schematic of the Ciba-Geigy RIFT method

Bagging materials

Bag material choice is a key process parameter for any vacuum forming process, including RIFT. Bag integrity is a key factor. Thin nylon bags can be prone to perforation giving rise to voids in the part.

At DSM, Brittles[18] has developed a highly flexible, styrene impermeable film and a low viscosity resin (Synolite 6637-W-1) with a low peak exotherm of 75°C in a laminate thickness of 4 mm. Exotherm is of course component geometry dependent for the vacuum injection process. DSM have also introduced a method using a double vacuum bag. Low vacuum (0.1 bar) is initially applied to the inner bag to lightly compress the reinforcement. At this stage the fabric is manually pressed into corners of the mould. Vacuum is then raised to 0.5 bar after which the outer bag is put in place. An even distribution of vacuum has to be achieved between the films: a breather layer (synthetic tissue is used so the resin front can be seen) is laid between each film. Vacuum between the films is increased to 0.96 bar (gauge pressure). The increase in vacuum pressure between the films removes the danger of air ingress into the tool through the bag. During laminate filling the inner vacuum is switched off, with resin inlets/outlets plugged. The outer bag vacuum is maintained in order to consolidate the laminate until the resin has cured. This method was first suggested by Letterman[19] and also Höhfeld[20].

Marcus[21] described new developments in vacuum bag forming. He indicated the benefits of silicone bag materials as its tear resistance, re-usability and large percentage elongation (i.e. good conformity). Shepherd[22] patented an embossed vacuum bag design. This eliminates the need for a breather layer to ensure even vacuum over the component surface. Removal of the breather reduces consumables and allows the observation of resin flow through the vacuum bag. Kohama *et al.*[23] have investigated the behaviour of various bagging films when forming components with sharp radii. Although the authors were studying vacuum bag forming, their findings are of relevance to RIFT. They used positive air pressure to force a bag into a female mould containing pre-preg. The tooling used had both convex and concave corners included. Four bagging films of varying stiffness, nylon, silicone rubber, polypropylene (PP) and low density polyethylene (LDPE), were used to examine the effect of bag material properties on component thickness variation.

Nylon and silicone rubber have low Young's modulus and elongation for vacuum forming. However, the properties of nylon film are extremely sensitive to moisture, while silicone rubber was found to have poor solvent resistance and high cost. Other bagging materials have higher Young's modulus (e.g., LDPE) than nylon and silicone. They required higher vacuum or pressure to form complex shapes and produced components of irregular thickness. PP and LDPE were both found to have heat resistance below that required for the exothermic reaction peaks of the epoxy resins used.

In 1989 Boey[24] described a vacuum bag technique for autoclave pre-preg material using formable and re-usable silicone bagging materials. Although not a process involving long-range resin flow, novel techniques for bag sealing, clamping and breaching without losing vacuum are suggested (*Figure 4*). Such techniques and ancillaries may benefit the development and applicability of the RIFT process.

Process conditions

In 1989 and 1990, Hayward and Harris[25,26] studied the effect of injection using vacuum in addition to pressure for RTM and found marked improvements in laminate appearance, flexural and short beam shear strength. Quality improved for all laminates regardless of the resin/fibre combinations used and even for modest levels of applied vacuum. The benefits of vacuum were primarily due to the reduction in voids. The authors also recommended turning off the vacuum when the mould is filled to prevent excess styrene being boiled off. This may result in cured-in voids. In practice this may be hard to achieve because small vacuum bag or seal leaks will inevitably reduce consolidation pressure if the applied vacuum is removed.

Lundström *et al.*[27] suggest that the 'boiling off' of styrene under vacuum is unlikely. At vacuum levels typical of the process, the boiling point of styrene is not reached. This is confirmed by *Figure 5*, the boiling pressure of pure styrene is 0.01 MPa (90% vacuum) at 40°C. The boiling temperature increases for decreases in vacuum level to a point where the temperature required to boil styrene at 10% vacuum is in excess of 100°C. At this temperature rapid cure of the polyester resin will take place causing an increase in viscosity and a further resistance to the formation of bubbles. Lundström suggests that poor laminate quality for polyester/vinyl ester systems, normally attributed to styrene, is more likely to be air due to mould leakage. He suggests that double seals should be used in mould design with a greater vacuum applied between the seals than in the component area.

Boey[28] in 1990 and Boey and Liu[29] in 1991 used vacuum bag infusion techniques to study how the process can reduce laminate void content. Boey[28] describes a vacuum infusion method utilizing one solid and one bagging film tool face, resin is drawn into the tool by evacuating the tool cavity. He reports that consistently low void content (about 1.3%) and correspondingly high and consistent flexural strengths were achieved. Voidage was also reduced when two as opposed to one vacuum port was used on the 600 mm by 300 mm flat plate mouldings. In the later paper, the process was taken further by manufacturing a model smoke tunnel (*Figure 6*). A big advantage of the vacuum process over the traditional hand lay-up method was that the dry reinforcement could be carefully positioned before resin entered the tooling, allowing accurate placement of fibre layers. For high production runs the vacuum bag could be replaced by a flexible splash tool or re-usable bag.

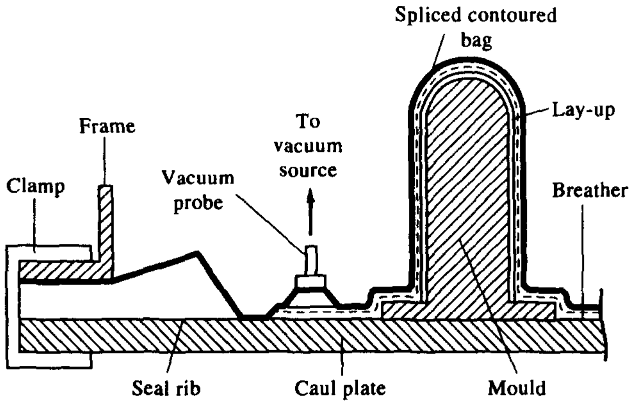


Figure 4 Novel bag sealing and clamping techniques used by Boey[24]

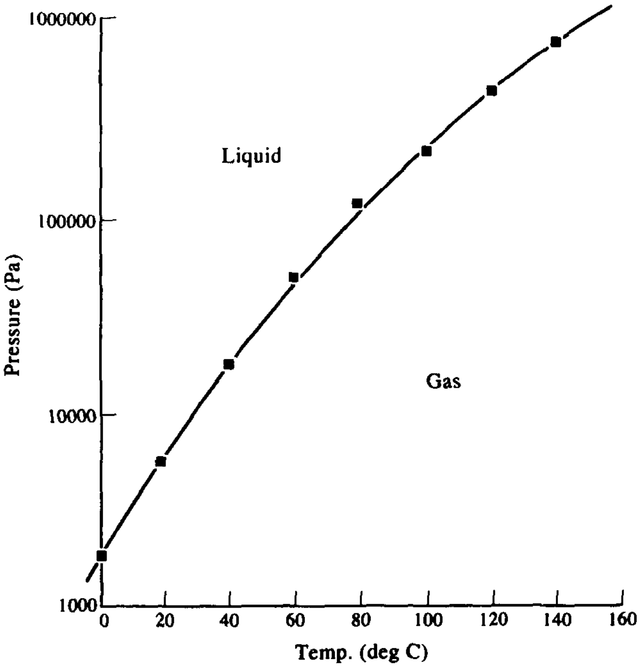


Figure 5 Pressure against temperature response for styrene. The transition point between liquid and gas is clearly shown

In 1991, Seemann made UK and European patent applications[30,31] for a variation of the US patented[32] Seemann Composites Resin Infusion Moulding Process (SCRIMP). Both were rejected due to prior art. The process is simple and resembles other vacuum infusion techniques in that the laminate is contained under a nylon bag (so preventing styrene entering the workshop).

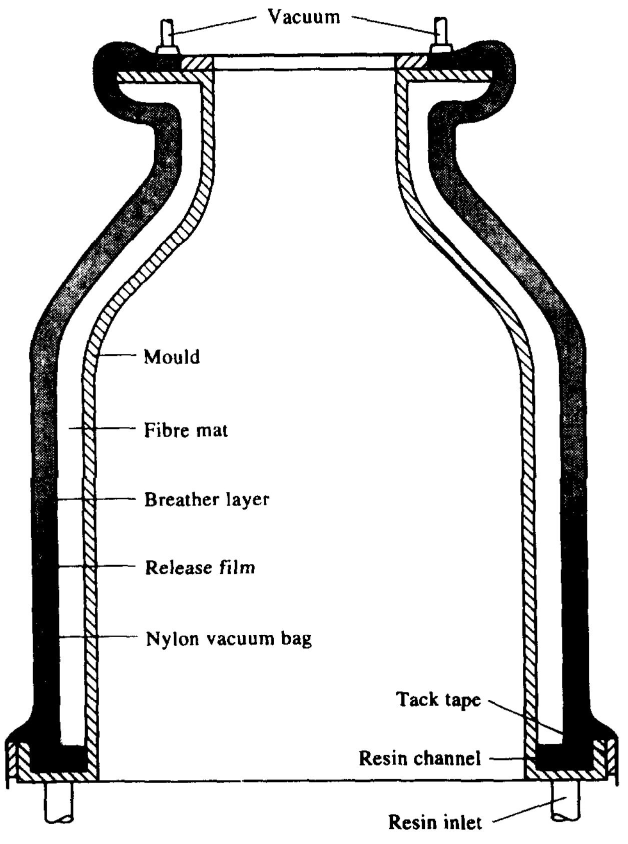
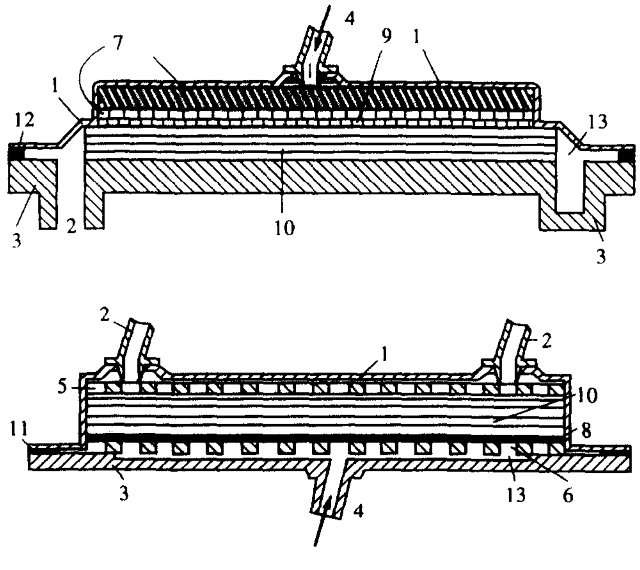


Figure 6 Schematic of the RIFT type tooling used to manufacture model smoke tunnels



1	Vacuum bag	8,9	Porous peel ply
2	Vacuum connection	10	Fabric
3	Rigid tool	11,12	Tape
4	Resin inlet	13	Mould space
5,6,7	Resin distribution media	14	Helical spring

Figure 7 Schematic of the SCRIMP process. US patent version above, European patent application below

Resin is drawn in under vacuum. The novel aspect of SCRIMP is the use of a mesh to distribute resin within the tool; eliminating the need for a breather cloth. The differences between the US patent and the European application is that the distribution medium is placed on one side of the moulding in the former and on both in the latter. The differentiating features can be seen in *Figure 7*. This process has been used to manufacture 15 m boat hulls, with foam cores, in a single shot. Seemann[32] has claimed weight fractions 26% resin for test samples manufactured using the SCRIMP process. The test material consisted of vinyl ester resin reinforced with five layers of approximately 800 g m^{-2} plain weave glass fabric. The achievable fibre content figures are confirmed by Brian Barer, a senior engineer with TPI, who currently uses the technology in the production of marine craft[33]. The application of the technology in the manufacture of boat hulls uses a staggered resin entry system enabling large parts to be produced by sequential changes to the porting arrangement.

The surface finish achievable with SCRIMP may be affected at high vacuum levels by mesh print-through[34]. Poor cosmetic finish (in SCRIMP) owing to print-through of cores into the gel coat has been solved by US boat manufacturer Hinkley[35]. They used sufficient skin coat on one side of the gel coat and polyurethane paint on the other which provides a thick layer to resist print-through.

Lazarus[35] highlighted the need for improved resin systems. Increased gel times and reduced viscosity are required to enable larger, thicker components to be manufactured more easily at ambient temperature. The ideal viscosity for an injection resin is suggested to be 2–300 mPa s.

Ancillary consumable costs for the SCRIMP system are high. Most of the hoses, all of the peel-ply, resin distribution membrane and bagging film are thrown away after each infusion, resulting in additional cost over hand lay-up and eroding the benefits of reduced process time. However, Pfund[33] reports that users of the technology (e.g., TPI in the USA) have found that labour costs per part have dropped compared to hand lay. The labour being relatively unskilled compared to that of hand laminators.

Seemann[36,37] has attempted to reduce consumable costs by designing and patenting a re-usable elastomeric vacuum bag for use in SCRIMP. The bag incorporates a built in long-distance resin distribution membrane and resin inlet tube although it is suggested that porous peel plies may be needed between the bagging system and resin to aid release. This adds an extra consumable but may improve production efficiency for repeated mouldings.

In 1993, Senibi *et al.*[38] supported the findings of Hayward and Harris. They found that the application of vacuum during the RTM process reduces microvoids in epoxy matrix, graphite fabric laminates up to a fibre volume fraction of 53%. They also concluded that the use of vacuum allows an increase in flow rate without an increase in microvoids.

In 1993, Barnes and co-worker[39–41] developed a hybrid SCRIMP-like system for the repair and reinforcement of steel structures including offshore oil platforms and surface vessels. The method involved infusing high V_f carbon fibre patches directly on to the prepared structure with epoxy resin. Flow lengths may exceed 1500 mm. The steel substrate effectively acts as the solid tool surface. A good adhesive bond is required at the interface.

Lazarus[42] recently described the history of resin infusion in the boat building industry. He confirms Seemanns'[30] claims that large boat hulls (13–18 m) can be infused in 1 h. They also comment that it takes two men ten days to prepare the lay-up. The lengthy preparation time is taken up by the need to ensure accurate placement of all reinforcement layers before injecting the resin. The core used in SCRIMP is usually a foam which has to be scored with a grid pattern to provide channels so that the resin can spread over the laminate area and infuse the fabric. The fabric layers are tacked together using aerosol contact adhesive so they stay in position before they are stabilized by the vacuum bag. Lazarus[42] reported on three existing resin infusion methods currently being used by industry.

1) Sandy Martin[43] uses the 'paddle lite process' to construct canoes up to 5 m in length using combinations of materials including carbon fibre, Kevlar, PVC foam cores and epoxy and vinyl ester resins. Fibre skins and core materials are laid up dry onto a gel coat, then a peel ply layer is placed with a bleeder tube running along the mould flange. The lay-up is then vacuum bagged and catalysed resin drawn in. The method requires the operators to coax the resin around the part to speed up the infusion and evenly spread the resin to areas of complex geometry. The process is slower than SCRIMP but is simple and has evolved through experience rather than scientific investigation.
2) 'Quick draw VARTM' (Vacuum Assisted Resin Transfer Moulding)[44] is currently being considered in competition with SCRIMP for US Navy contracts. Pfund[33] confirms that the US Navy is using the method to manufacture half-scale midship sections of Corvette class military vessels. This is part of the Navy's prototype ship building programme. Shepherd Manufacturing Group have also developed a textured thermoplastic polyester high temperature vacuum bagging film which has an embossed pattern, avoiding the need for a resin distribution membrane and other ancillaries such as bleeder and breather plies. This in turn allows resin to be cured using UV light. During UV cure areas can be covered and hence cure retarded in regions where secondary bonding is required. Infusion is slow and the use of UV light can be expensive and difficult to control. Shadowing leading to differential cure is a major problem. The process is limited to transparent laminates and core materials.
3) Resin Injection Recycling Method (RIRM)[45], developed by Structural Composites under funding from the US Navy, is a vacuum system which utilizes a conventional FRP female mould with a thin FRP splash male. This gives good cosmetic surfaces to both faces of the part. It is claimed by Lazarus that the process can be adapted to any existing hand lay-up mould. However, many contact moulds are porous and may not have adequate areas for sealing.

An historical critique on the RIFT process has been presented. The process has been developed to some extent industrially but the academic community, whilst investigating work relevant to RIFT, has concentrated on the more traditional vacuum RTM and autoclave closed vacuum bag infusion applications. There are, however, several areas in need of scientific investigation to provide basic process data for the successful use of the RIFT process in industry.

KEY AREAS FOR DEVELOPMENT

Development of the RIFT process has been component specific. Most examples manufactured using the process have been of low fibre content and so the limits of the technology have not been identified. For the technology to progress, parameters such as maximum achievable fibre content, flow rates (linked to fabric permeability and resin viscosity) must be understood and their relationship with vacuum levels, reinforcement/resin combinations and laminate quality defined.

Fibre content

Two modes of fabric compression exist with RIFT which ultimately determine the component V_f. These are i) the initial compression of the dry reinforcement and ii) a further compaction which becomes possible once the reinforcement has become lubricated by the flowing resin. Much work has been carried out in both areas of fabric compression but most consider only the compression either between metal platens (RTM and pultrusion)[46,47] or vacuum bagging using preplaced resin or pre-preg[48,49]. No data for the dry or wet compression of a fibre stack between a smooth rigid tool face and a flexible vacuum bag has been identified.

Fabric relaxation, characterized by Kim *et al.*[50] and Pearce and Summerscales[51], might be a method by which higher V_f could be achieved for lower consolidation pressures.

In RTM with completely rigid mould the fibre content is defined by the tool cavity. In most commercial tooling, fibre lubrication may be observed as a relaxation of the reaction force on the mould. In RIFT, one tool face is flexible so a further compaction may again occur upon lubrication such that a 'wet' fibre volume fraction may exist which is higher than the 'dry' value.

Porosity/permeability

Much work has been conducted in this area with respect to the RTM process and the behaviour of fluids in permeable media is well documented[52,53]. Resin flow rate through a reinforcement fabric is proportional to the pressure gradient and inversely proportional to the resin viscosity (Darcy's equation). The constant of proportionality is known as the permeability. Permeability is a complex function of the reinforcement architecture (Kozeny–Carman equation) and the wetted surface presented to the fluid (Blake hydraulic radius). Permeability typically decreases with increasing fibre content (reduced porosity) and is predicted to increase with increasing clustering of the fibres[54]. The permeability of a particular lay-up and resin distribution method will partly determine process times and void content. Preliminary studies of the process–property–microstructure relationship have been reported by Griffin and coworkers[54–57]. If higher fibre volume fractions are to be achieved, the mechanism for resin infiltration into the fibre stack must be understood and optimized to reduce dry areas and voidage.

Void formation and component quality

It has been shown that the use of vacuum has led to reduced void content in laminates with a resultant benefit in laminate shear strengths[58]. The voidage and composite quality in RIFT processed laminates will be dependent on the resin distribution method and can be determined by quantitative microscopy[59] and mechanical testing[60].

SUMMARY

An historical critique on the RIFT process has been presented. The process has been developed to some extent industrially but the academic community, whilst investigating work relevant to RIFT, has concentrated on the more traditional vacuum RTM and autoclave closed vacuum bag infusion applications. Areas in need of scientific investigation to provide basic process data for the successful use of the RIFT process in industry have been highlighted.

A large user of the RIFT technology could be the boat building industry. Traditionally a large user of unsaturated polyester resins, it will need to consider alternatives to reduce styrene emissions from the hand lay-up process in order to comply with ever tightening air quality regulations. Marine applications are usually of a low to medium V_f (≈ 30–40%) with high performance craft requiring structures with $V_f \geq 50\%$. For high V_f applications (i.e. $\geq 50\%$) a process such as RIFT could result in considerable cost savings. Although probably only viable for medium to large area structures, RIFT could cut tooling costs compared to solid tooling methods which require expensive tool backing to resist moulding pressures.

The University of Plymouth is currently the only known British academic institution developing a RIFT type technology[61,62].

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