Composites Part A **29A** (1998) 111-114
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1359-835X/98/$19.00

PII: S1359-835X(97)00038-9

The compression response of fibre-reinforced plastic plates during manufacture by the resin infusion under flexible tooling method

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(Received 20 September 1996; revised 1 February 1997; accepted 10 March 1997)

Resin infusion under flexible tooling (RIFT) is a variant of vacuum-driven resin transfer moulding in which one of the solid mould faces is replaced by a polymeric film. One variant of the process is known commercially as SCRIMP. In comparison with traditional hand lay-up, the process has obvious health and safety advantages, through reductions in worker contact with liquid resin and in reduced emissions to the environment. Additionally, laminate mechanical properties are improved by higher fibre contents and lower voidage. In comparison with conventional (matched mould) resin transfer moulding, the process can offer a substantial reduction in tooling costs, especially for large parts.

As one of the tool faces is flexible, the moulded laminate thickness depends in part on the compressibility of the reinforcement and on its interaction with the flowing resin. This paper describes a preliminary experimental study of the measurement of fabric compression and the effects of the interaction between reinforcement and resin flow on the final component thickness. © 1997 Elsevier Science Limited.

(Keywords: resin transfer moulding; vacuum injection; reinforcement compression)

INTRODUCTION

Resin transfer moulding offers many advantages over other processes for the manufacture of fibre-reinforced thermosetting polymer composites. These include better component thickness tolerances and surface finish, and reduced emissions of volatiles. However, tooling costs can be prohibitively large for parts of more than a few metres in dimension, particularly for one-off or small production runs.

In resin infusion under flexible tooling (RIFT), dry reinforcement is placed onto a rigid tool, then enclosed and sealed by a flexible polymeric bag. The bag is then evacuated, and catalysed resin drawn into the reinforcement. The 'Marco method', an early version of RIFT, using a flexible female splash tool was described in 1950 (US patent 2,495,640) and employed in boat hull production. The use of a rubber bag as the flexible tool was investigated during the 1980s [1] and several patents were filed [2,3].

The process has been rediscovered during the 1990s [4,5], and has found applications particularly in the marine industry [6]. A version of RIFT is used to strengthen offshore structures with carbon fibre [7]. A review of the process, its applications and the potential for scientific development has recently been published [8].

In principle, RIFT retains many of the environmental advantages of RTM, but at a much lower tooling cost, since half of the conventional rigid closed mould is replaced by a bag. It may also prove feasible to adapt existing contact moulds for the RIFT process.

Compaction of the reinforcement

Unlike rigid mould RTM, there is no direct control over the thickness or fibre content of the final composite laminate in the RIFT process: these parameters depend on the compressibility and relaxation of the reinforcement under pressure, and interactions with bagging film, breather and other ancillary materials.

The compressibility of dry fabrics has been reviewed by Pearce and Summerscales [9], who also reported experimental work. They noted that the response of a dry preform was dynamic. Time dependent compression and relaxation were observed, and higher compaction at a given pressure was achieved by repeatedly loading and unloading the reinforcement.

Saunders *et al.* [10] have conducted an experimental study

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of compression of both dry and static uncured polyester resin impregnated plain weave glass fabric. Dry cloths were found to have a power law relationship, $P = cV_f^n$, between the pressure P and the fibre volume fraction V_f. The power law index n was reported as 10 or 11, respectively, in the text and in the summary of the reference. For wet fabrics, the viscous resin pressure component was dominant at high compression rates ($1\ \mathrm{mm\ min^{-1}}$). At low compression speeds ($0.05\ \mathrm{mm\ min^{-1}}$), the curve was more like that for dry cloth.

The compression of the reinforcement during RIFT is further complicated by the arrival of the flowing resin. This provides lubrication for the fibres and may hence affect the deformation of the laminate under the vacuum bag. Also, the effective compressive force acting on the reinforcement is not constant during the process. Before the arrival of the resin at a given point, the dry laminate is subject to (approximately) atmospheric pressure. As the resin flows further past this point, the pressure in the resin rises, so the net compression on the reinforcement reduces. A theoretical and practical understanding of these compaction mechanisms is required in order to assess whether moulded laminates can be produced with a consistent, reproducible and predictable fibre content and quality. There is also a need to quantify any interaction between the laminate and the ancillary materials during the process.

EXPERIMENTAL PROCEDURE

Figure 1 shows a schematic diagram of the experiment. The tool plate is machined 20 mm thick MIC-6 grade aluminium (Aalco, Plymouth), providing a flat rectangular moulding area 660 mm by 360 mm. Nine layers of $290\ \mathrm{g\ m^{-2}}$ plain weave E-glass fabric (SP Systems Limited) were laid up beneath a non-porous PTFE-coated glass fabric peel ply. The nylon vacuum bag (Capran 650) was sealed with tape at the edges and clamped parallel to the tool surface above the vacuum tapping. LVDT1 and LVDT2 are 30 mm and 180 mm, respectively, from the resin inlet channel.

At the edge of the reinforcement, a layer of $450\ \mathrm{g\ m^{-2}}$ Unifilo continuous random swirl glass filament mat (Vetrotex UK Limited) was placed over the resin inlet channel. This provided a resin-rich reservoir across the full width of the mould tool, and ensured that the progression of the flow front was linear.

The pressure within the mould was measured by 3 piezoresistive differential 0–1.034 bar (0–15 psi) pressure transducers (RS Components 286–692) located at tappings in the tool plate 30 mm, 180 mm and 330 mm from the inlet. Each sensor was calibrated *in situ,* after attachment to the tool, using an Edwards EPS10 total pressure gauge (Severn Science Limited) as a secondary standard. This avoided any spurious effects which may be caused by the tool fitting.

The compression of the reinforcement was measured by three miniature DC energised ± 5 mm stroke DFg5 LVDTs (RS Components 646–476) which were located in a purpose-built holding frame and brought into contact with the vacuum bag lay up. These sensors were calibrated before use with slip gauges, and zeroed before each experiment. The LVDTs were positioned at the same locations as the pressure transducers with respect to the resin inlet, with spreader plates to reduce the pressure at the tip. The outputs from all sensors were monitored by Labtech Notebook version 8.01 software on a PC.

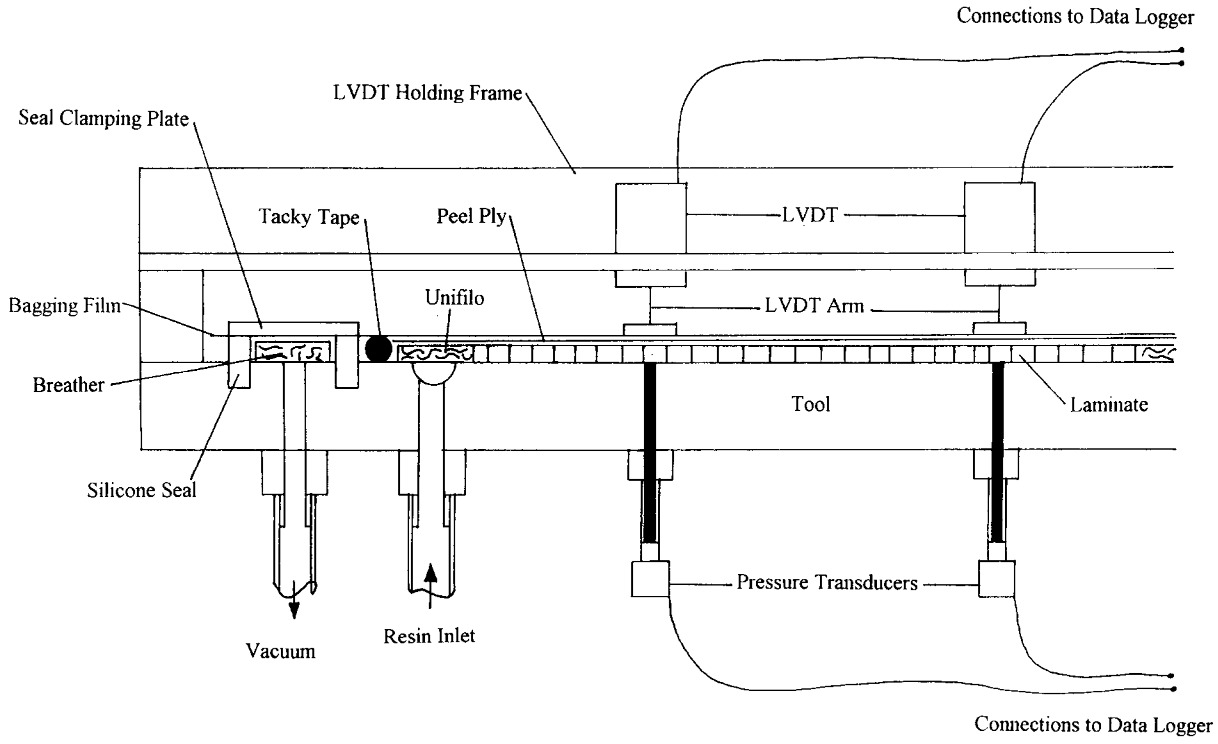

Figure 1 Schematic diagram of the experiment.

The matrix resin system was Jotun Polymer 42-10 unsaturated polyester catalysed with Scott Bader standard catalyst (methyl ethyl ketone peroxide at 33% in phthalate plasticiser) which had been previously degassed for 2 h. After application of vacuum to the bag, the change in thickness was monitored for 10 min. The resin inlet valve was then opened, and resin was allowed to flow through the reinforcement. The progression of the resin was recorded visually by tracing the position of the flow front on the top of the bag at suitable time intervals. Resin flow rate was measured by monitoring the change in weight of the storage vessel.

RESULTS AND DISCUSSION

All experiments were conducted with the mould evacuated to − 1000 ± 20 mbar relative to atmosphere (notionally zero pressure within the resolution of the gauge). The degassed resin at the inlet was at atmospheric pressure.

Figures 2 and *3* show the thickness–time record at LVDT1 and LVDT2 (30 mm and 180 mm from the inlet, respectively) for the first 4000 s of the experiment. The four traces were obtained from four nominally identical runs. The thickness scale is not absolute. Each laminate has a different initial recorded value of thickness which may be due either to differences in the nesting of the layers or to the transducer zeroing procedure. It will be observed that the changes in thickness are consistent for the four experiments.

Figures 2 and *3* both show an initial, almost instantaneous, compaction of the laminate as pressure is applied. Reduction in thickness continues at a slower rate after the initial change: this is consistent with the time-dependence observed by Pearce and Summerscales [9]. At LVDT1, the laminate is still undergoing compaction when the resin front arrives about 700–800 s into the experiment.

Two of the experiments (INF18 and INF19) recorded a rapid decrease in thickness at the resin front, followed by a steady increase after the front had passed. This may be explained by the initial lubricating effect of the fluid, followed by a steady increase in pressure under the bag as the front moves further away: it is assumed that the pressure in the resin decreases linearly from atmosphere at the inlet to vacuum at the flow front.

However, in two of the experiments (INF20 and INF21) the lubricating effect is not apparent. This may be explained by the fact that the resin mass flow appears to be faster in these two experiments, and thus resin pressure at the monitoring point may then rise too fast for lubrication to have an effect. A second possible explanation for the absence of the lubrication effect would be that the packing of the fabric layers was more closely nested at the start of the experiment, thus limiting the ability to settle further.

The resin reaches LVDT2 after about 2000 s (c. 35 min). The thickness change at this position is considerably smoother. The resin flow rate is much slower and pressure

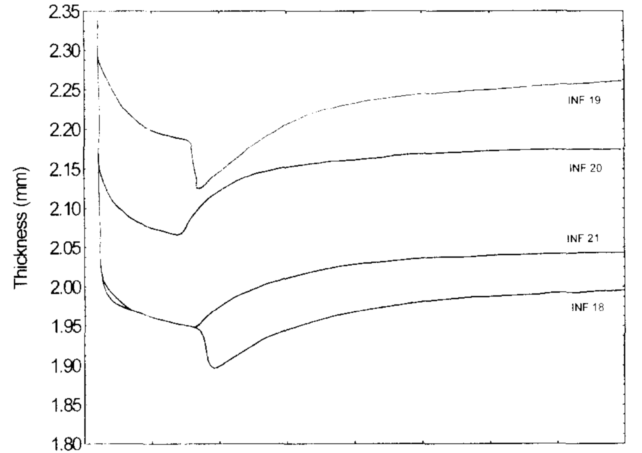

Figure 2 Thickness–time record at LVDT1 for the first 4000 s (30 mm from the inlet, respectively).

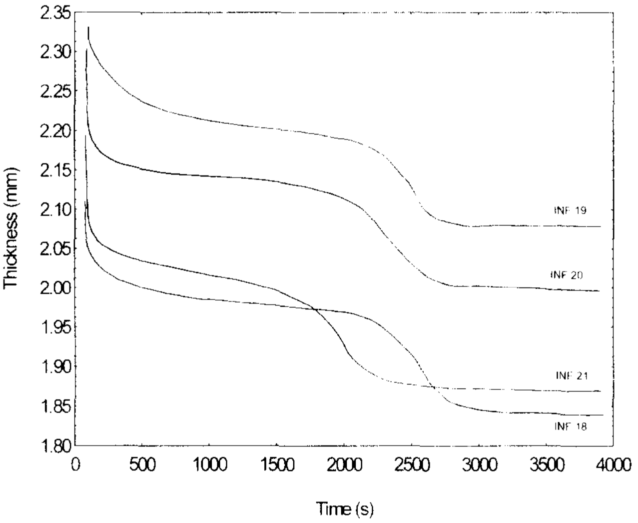

Figure 3 Thickness–time record at LVDT2 for the first 4000 s (180 mm from the inlet, respectively).

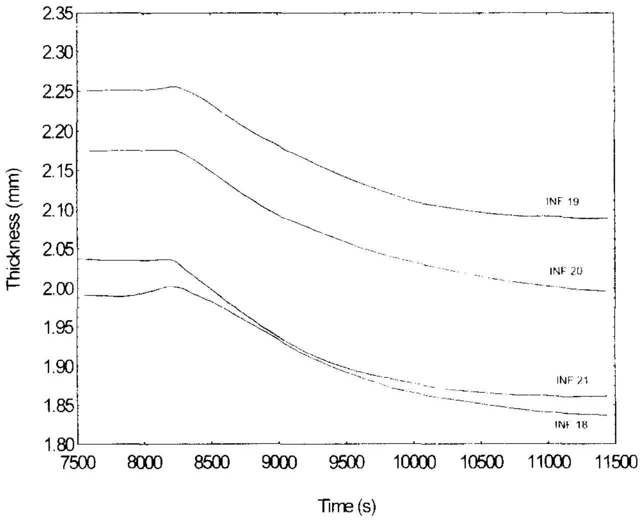

Figure 4 Compaction of the laminate at LVDT1 for 7500-11500 s.

rises much more slowly. The decrease in thickness is more evident and is maintained as the flow continues for a further 2000 + s. Note that there appears to be an inflection in the thickness trace at around 1750 s. The deflection of the fabric due to upstream lubrication can be detected in advance of the flow front reaching the LVDT, although this may be exaggerated by the spreader plates located under the LVDTs.

The experiments were continued until the mould filled, at about 8400 s. At this point the vacuum was maintained but the resin inlet valve was closed. The result was a steady decrease in resin pressure, accompanied by a further compaction of the laminate at LVDT1 (*Figure 4*). Constant thickness was maintained at LVDT2. The pressure is maintained at the time of clamping the inlet, and thus it is expected that resin flows/drains towards the vacuum port.

Note that the experiment times are very long for an unsaturated polyester resin (UPE) at ambient temperatures. Minimal quantities of catalyst were used in order to extend the cure time, and the plates were heated to promote cross-linking *after* completion of the flow experiment. It would seem unlikely that large components can be fabricated from standard fabrics using polyester resins because of the low fabric permeability when fully compressed. It may be practical to use UPE for small components, or for large items reinforced with flow-enhancing fabrics or random mats, or by maintaining a lower pressure differential to maximise the fabric pore space. For sandwich panels with fabric surfaces and random mat cores the process should prove to be an effective production method.

CONCLUSIONS

A preliminary experimental study of the changes in laminate thickness during the RIFT process has been presented. The compaction of the reinforcement is complex, consisting of an initial reduction in thickness under the influence of the vacuum. The presence of the flowing resin appears to have a lubricating effect, and results in a further compaction. However, since the net pressure on the laminate falls after the passage of the resin, thickness subsequently increases. These interacting, dynamic mechanisms are currently the subject of a more theoretical investigation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Higher Education Funding Council for England (HEFCE) for Development of Research funding. Thanks are also due to Jotun Polymer (UK) Limited and to SP Systems Limited for the provision of materials and to the industrial advisors to the project for their advice.

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