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FLOW CONVERGENCE AND VOID FORMATION IN RESIN-INFUSED CORED SANDWICH STRUCTURES

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SUMMARY: This paper presents preliminary results of experimental work that explores aspects of fibre, core and resin interaction during the infusion process. In particular we observe the nature of regions of flow front convergence, with emphasis on the differences seen in areas containing various types of core, such as wood, sealed wood and closed cell foam. Data on comparative resin absorption for the various cores are also presented. It is found that sealing porous core materials such as balsa does not prevent the absorption of significant quantities of resin. More importantly, completely impervious cores (in this case acrylic) are unable to absorb either air or resin. The result of this is that air trapped during flow front convergence causes a higher degree of void content in the skin laminate, compared to more porous core materials. These phenomena appear to have attracted little research attention to date, and provide significant challenges for both experimentation and process simulation.

KEYWORDS: core material, Resin Infusion (RI), resin absorption, void formation, flow front convergence

INTRODUCTION

Successful implementation of all composites manufacturing processes depends on the selection and specification of appropriate constituent materials. As far as flow processes (e.g. RTM and resin infusion) are concerned, this includes thermosetting resins of suitably low viscosity and reinforcement architectures of high permeability.

Sandwich construction (thin, stiff skins combined with relatively thick, low density cores) is ubiquitous in virtually all industry sectors. Since the early days of closed mould processing of sandwich laminates, it has been recognised that the core itself can also play an important role in enhancing and controlling the long-range flow of liquid resin. Commercial forms of core material, such as foams and balsa, are commonly available with such features as holes drilled through-thickness, kerf cuts in one or both faces and separate blocks of rigid core held together with glass scrim. These features are all regarded as providing some degree of 'flow enhancement', allowing liquid resin to reach both faces of the sandwich laminate and to flow long distances within the part, sometimes eliminating the requirement (in resin infusion) for a surface distribution mesh.

Flow within skin laminate and core is thus complex and three-dimensional, and involves different physical domains, such as porous media and relatively large channels. The likelihood of convergent flow fronts occurring on a variety of scales is much greater than in simple monolithic laminates, and may have important implications for part quality. In resin infusion, flow is further affected by local variations in fibre volume fraction resulting from skin compression, and consequent non-linear effects on permeability [1].

The core material leads to several additional complications in the modelling and control of all LCM processes due to the possibility of absorption and/or desorption of both liquid resin and air at various stages in the manufacturing cycle. The interaction between the core, liquid resin and air is complex and continues throughout the manufacturing operation. Even in notionally sealed cores, absorption of resin occurs, depending on the local processing conditions. Moreover, the exchange of residual air between the skin laminate and the core can influence the appearance of defects, and ultimately affect part quality and performance. As we explore in this paper, a porous core can act either as a sink or a source for trapped air.

The presence of a large volume of porous core material plays a significant role in the commercial resin infusion processing of large components such as wind turbine blades, where a critical vacuum level must be achieved before resin flow can commence. In many cases, the time required to evacuate a complex stack of dry material can be considerably longer than the flow process itself, and has a major influence on the manufacturing cycle time.

This research is a preliminary attempt to understand some of these interactions. Here, we report some phenomenological observations of flow convergence and subsequent void formation in a variety of material combinations.

PREVIOUS WORK

Flow fronts observed in RTM [2], appear to behave independently and in a repeatable manner before convergence. If the fronts converge on a mould edge they will merge as a single front, but if the fronts meet perpendicular to each other there will be increased voidage along the knit line formed. The voids formed at this point may well remain as the driving pressure gradient is removed.

Pearce *et al* [3] found that in areas where void content reached 5 %, this resulted in a reduction in the maximum measured inter-laminar shear strength of the order of 20 %. It was suggested that by using sequential inlet ports, flow front convergence could be reduced. This work only considered monolithic laminates, where no core material is present as a potential flow channel.

Parallel flow front convergence was the worst case scenario [3]. However void formation will also occur at lower angles of convergence, although at a reduced level [4]. These results from RTM investigations may not be directly relevant to the infusion process, as the voids are likely to be larger in the infused part due to the lower pressure differential. Results for multiple angles of confluence showed that void content was around 2 % at a 20° confluence angle, rising to 4 % at an angle of 160°. This work [4] led to the conclusion that convergent flow fronts should be kept to an angle of less than 60° if possible, particularly for layups having more than a single injection point.

Work on infusion of foam cored laminates has been conducted [5] to optimise the form of flow enhancement in terms of process efficiency, weight gain due to core absorption and material usage. No firm conclusion was reached as the resulting laminates had extensive areas of either knit lines, or dry fabric patches. It is notable that the literature on this subject is very sparse, although much anecdotal evidence exists within the processing industry.

Flow convergence can be predicted qualitatively with the help of 2D and 3D resin flow models, and these simulations are useful in the design of overall injection strategy. An example is shown in Fig. 1, using PAM-RTM [6]. The scenario here is that of resin flow in 2D, having emerged from an array of holes drilled through-thickness through a core material. The holes are modelled as a constant-pressure boundary, and flow takes place in a homogeneous porous medium with constant resin viscosity.

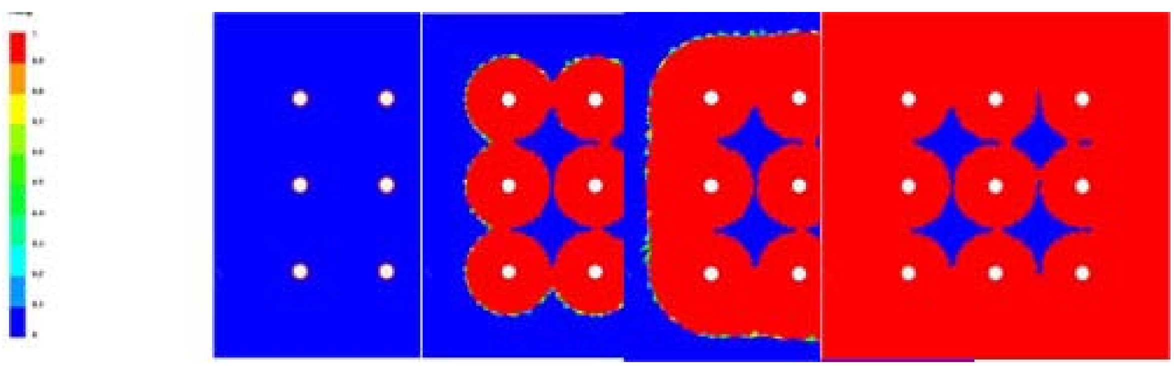

Fig.1 PAM-RTM 2D simulation of resin flow from an array of circular holes, showing schematic flow front convergence.

In Fig. 1, flow ceases once the locked-off regions have been isolated. This paper is concerned with the subsequent behaviour of these regions of trapped air, and how they interact with porous cores.

EXPERIMENTAL

Knit Line Formation

An infusion experiment (using a development epoxy resin) was conducted to recreate knit lines resulting from flow front convergence. Panels were arranged with a central resin injection pipe and two edge extraction paths (Fig. 2). A single skin of EBX936 (Saint Gobain) biaxial noncrimp E-glass fabric was placed on either side of the core. The skin plies were extended beyond the panels to enable calculation of resin absorption in the core materials.

The experiment used five different types of core, with two different through-thickness flow channel arrangements. The impermeable Perspex core was covered in flash breaker tape to allow for later skin removal and analysis. All cores were 25 mm thick. The different materials are listed in Table 1. The core panels were divided in two along their long axis, with 3 mm diameter holes drilled on a 25 mm and 40 mm square grid, either side of this centre line. This allowed observation of core/resin interaction and the effect of flow channel spacing.

Table 1 Core materials used in flow experiments

	Material	*Measured density(kg/m³)*	*Supplier /designation*
1	end grain balsa	130	Baltek. Contourkore, Lamprep D100 (1 inch)
2	surface sealed end grain balsa	135	Baltek. D100, AL600-10, (1 inch)
3	PET foam	144	Fagerdala. Non commercial trial sample.
4	PVC foam	60	Airex.
5	Solid Perspex	-	unknown

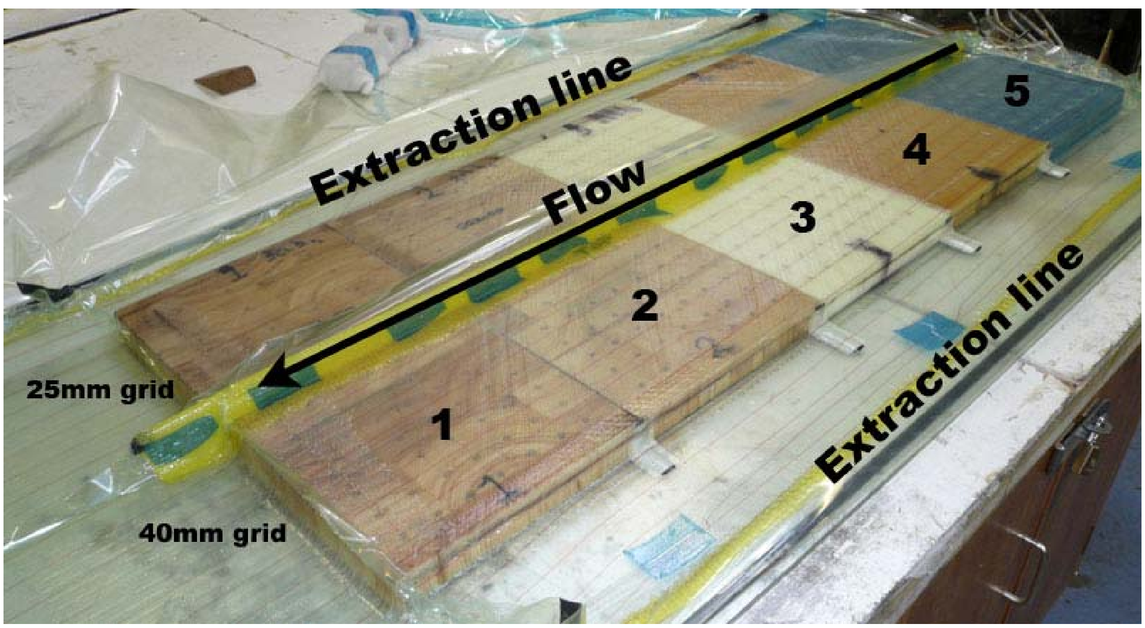

Fig. 2 Infusion experiment used to produce flow front convergence zones.

The experiment produced the required knit lines (visible as surface porosity) resulting from through-thickness flow, in a pattern similar to Fig. 1. It was immediately apparent that the surface porosity was significantly worse in the panel containing the impermeable Perspex core.

A photographic technique was used in an attempt to quantify surface porosity. The panels were coated with a clear matt varnish to prevent reflection during image capture. A light source was placed to give maximum visibility of the defects (the knit lines have higher reflectivity than the surrounding matt surface). Digital images were obtained (Fig. 3), aligned and cropped to the grid edges created by the holes (stages 1 and 2 in Fig. 3), de-saturated and contrast enhanced to make the knit lines more visible (stage 3). ImageJ software [7] was used to measure the percentage area of the image that was occupied by the knit lines (stage 4).

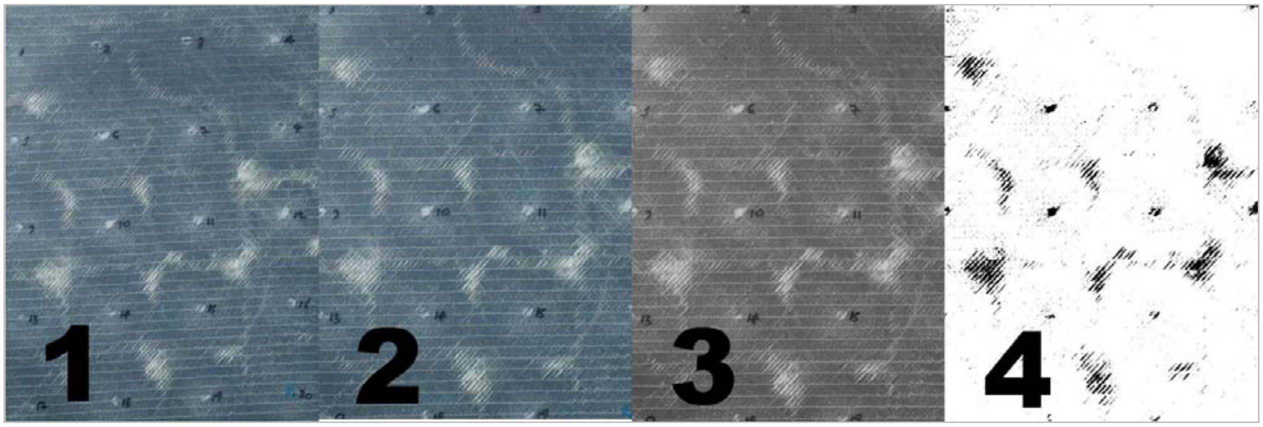

Fig. 3 Stages in image enhancement for quantification of surface voids (1: original image; 2: cropped image; 3: de-saturated; 4: final monotone image).

The percentages of the total area occupied by knit-line voids are shown in Fig. 4. These results are an average of three measurements from each image. The image analysis is unavoidably subjective, but the difference between the different core types is striking.

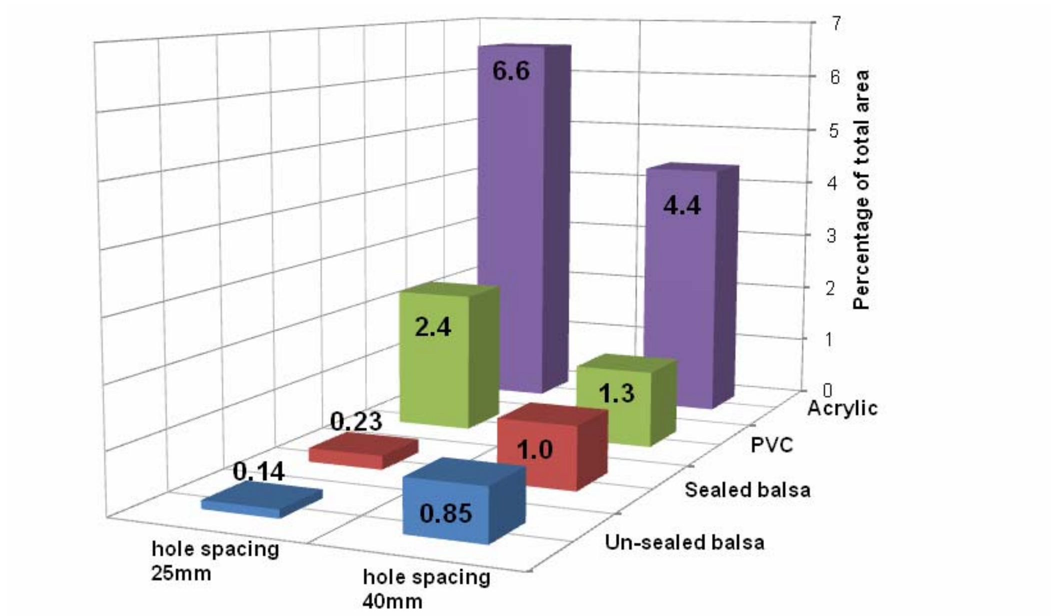

Fig. 4 Knit line surface void area percentages.

Core Resin Absorption

The overall resin absorption during the infusion experiment was calculated for each sample from weight measurements. The results for three of the cores are shown in Fig. 5 (the acrylic is non-porous and the PET foam was found to contain defects that led to erroneous results). A second experiment consisted of a simple preliminary comparison of resin absorption rates in the cores used in the infusion.

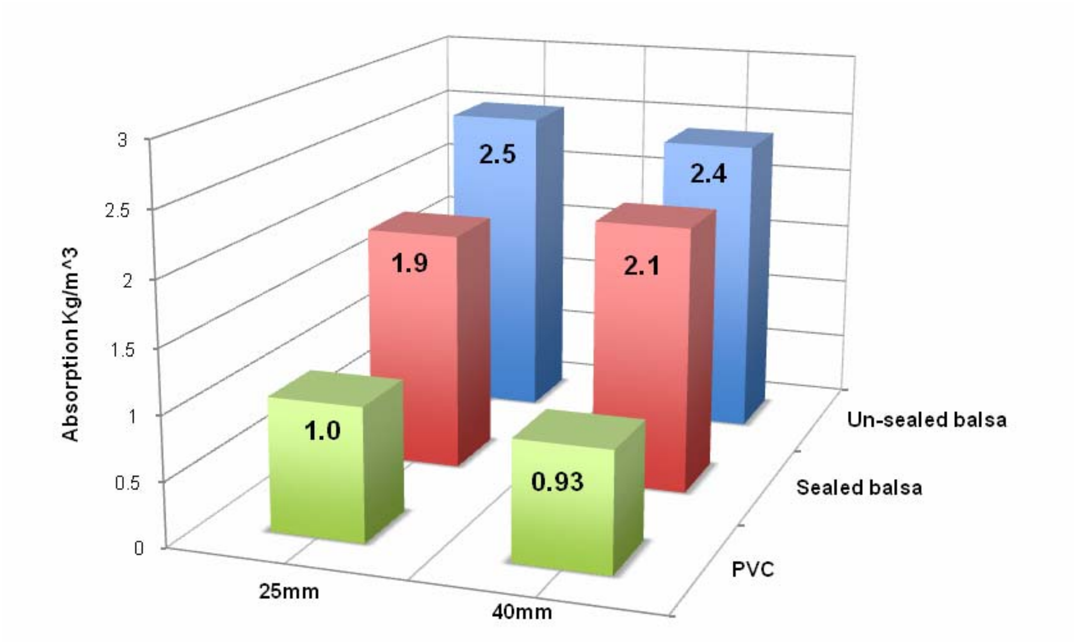

Fig. 5 Resin absorption per metre square.

A 10 mm diameter by 25 mm thick sample of each of the porous cores was bonded to the end of individual acrylic tubes. The tubes had a graduated scale (0.15 ml intervals) on the external surface. 3 ml of mixed epoxy resin was placed in each tube and the changing levels recorded using time-lapse photography. Fig. 6a shows the initial flow over a 40 minute period. Fig. 6b shows the rate of absorption through the cores over 220 minutes, before increased resin viscosity prevented further flow.

DISCUSSION

These preliminary results show that void formation due to knit-lines increases as the core material is more impermeable. It is suggested that this is dependent on the different abilities of the cores to absorb trapped air in the knit-line region. It also appears that the hole spacing has an effect, the reasons for which are under investigation. Absorption of both air and resin occur in all the core materials studied. It is noteworthy that sealed balsa absorbs almost as much resin during the manufacture of the laminate as the unsealed version. As far as we are aware, current flow process models do not yet incorporate full representation of the multi-phase exchange of liquid and vapour between the various components of the sandwich. Future research is likely to require novel instrumentation to determine local pressure variations within regions of flow front convergence, so that physical models can be validated. Consideration of scale effects is also required. These experiments have so far been conducted on a very small scale; commercial manufacture, on the other hand, is often concerned with much larger structures.

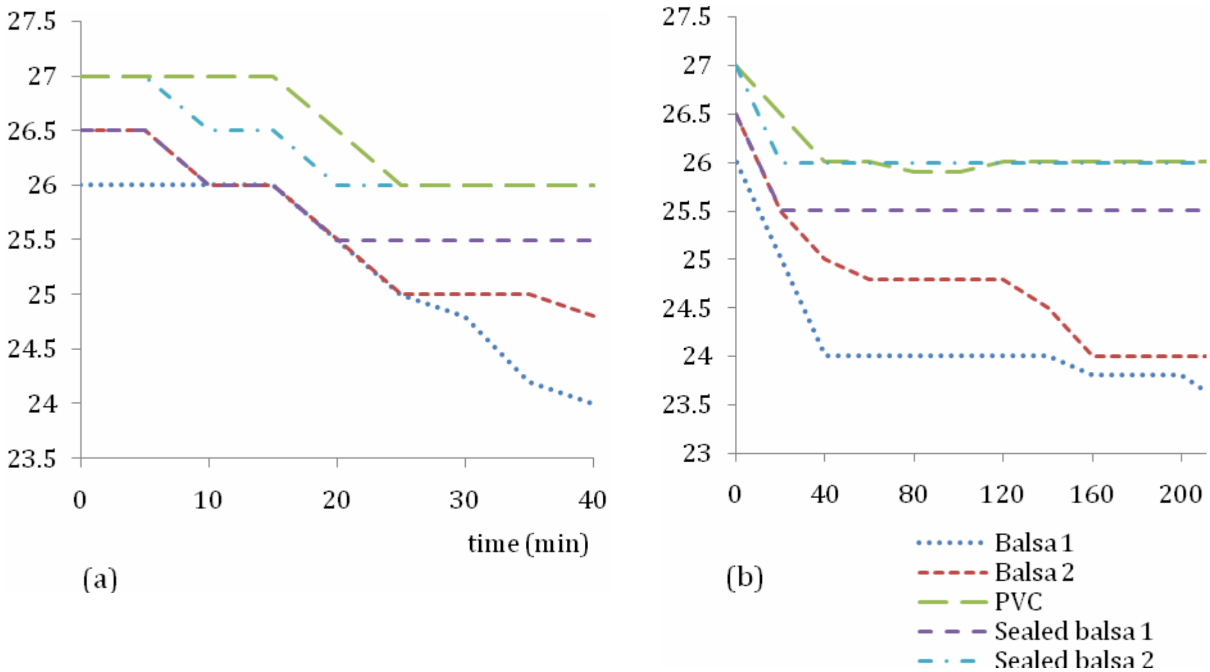

Fig. 6 Resin absorption rates (arbitrary units): (a) first 40 min; (b) complete experiment.

CONCLUSIONS

Results show a high incidence of flow convergence and hence void formation due to through-thickness flow in cored laminates. The amount and distribution of regions containing voids are dependent on the detailed geometry of flow enhancement modifications made to the core.

Void formation is significantly greater in cores of lower permeability/absorbance, the highest being in solid acrylic core. Although sealed cores are often specified for reduction of resin absorption, it is clear that significant absorption occurs in these materials.

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