A STUDY OF THE PRESSURE DISTRIBUTION IN THE HAND LAYUP AND VACUUM BAGGING PROCESSES

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Abstract

This study considers the effect of pressure in the hand layup and vacuum bagging processes. Firstly, the layup method is considered. The use of rollers is common shop-floor practice, but the results presented suggest that rolling plies can lead to areas of trapped air in laminates, as visualised by laying up a ply on a glass plate. The bagging process, designed to remove air and aid consolidation is a further opportunity for introducing variability in manufacture. Using a pressure mapping system, common bagging defects such as bridging and wrinkling are examined in the context of their effect on part quality. It is shown that bag pressure is far from hydrostatic when these features are present.

1. Introduction

1.1. Further opportunities for variability

Laminator induced variability in prepreg hand-layup components has been explored in previous work [1], where it was shown that there is considerable variation in layup style, layup times and even quality from person to person, even when considering professional laminators. However, even if a layup is carried to specification, the bagging process offers a further opportunity for operator/process variability to be introduced.

It is difficult to inspect a finished bag; the only tool available is the vacuum pressure gauge. This only gives information about the bag's ability to hold a vacuum and highlights the presence of leaks or punctures. However, even if a bag is found to be under full vacuum, it is no guarantee that it will produce a good quality part.

The effect of layup technique is also important. For modern prepreg systems, the level of resulting voidage is principally determined by the amount of air which is trapped during layup as well as the pressure applied during cure [2]. To address the former, rollers are traditionally used in prepreg hand layup as a means of consolidating a laid-up ply. Rollers are usually stiff and made of hard rubber or plastic. While the consideration of all parameters related to the use of rollers is recognised as critical for the production of quality laminates in the field of automated layup technology [3][4], it does not appear to be the case with manual layup, where they are used in an uncontrolled way. In this study, the purpose and effects of rolling are contrasted.

1.2. The hydrostatic assumption

It is reasonable to assume that in flat plates and very simple geometries, vacuum pressure is uniformly distributed over the laminate surface. However, when the geometry is complex, this assumption does not necessarily hold.

For example, if there is not enough bagging material, the bag will have to stretch over geometric features in the part/tool. These effects are particularly important in out of autoclave (OOA) prepreg systems, where the sole source of consolidation force is the applied vacuum. Therefore, if the vacuum bag is not in contact with the laminate, there will be no local consolidation force being applied in any areas where this is the case.

Consequently, the quality of these areas may be poor, especially when it comes to thickness variations, since it is the normal pressure applied by the vacuum which is mainly responsible for consolidation and final thickness. For example, it is mentioned in [5] that bag bridging may occur at the end of flanges in a C-spar laid up on a male mould, creating a low pressure region into which resin can ‘pool’. Further, the authors describe by means of free body diagrams why corner thinning might occur in this type of configuration and go on to explain why caul sheets can be used to remedy this unwanted effect.

It has been suggested previously that vacuum bag only (VBO) processing is more sensitive to variations in process parameters, especially those related to the elimination of voids [6], an aspect which is covered briefly in this study.

However, to the authors’ knowledge, no previous work has considered the pressure distribution in a vacuum bag, or considered the effects of different layup/bagging practices on bag quality. These aspects are considered in the present paper.

2. Method and experimental approach

2.1. Consolidation trials

The consolidation trials were carried out by laying up a single 170x170mm ply of Gurit SE70, low temperature cure UD carbon prepreg onto a 10mm thick polished glass plate, which was then held in a frame allowing a sequence of digital images to be taken from below.

The ply was carefully laid up by hand by an experienced laminator using either hands only or layup rollers. The glass plate and laminate were then vacuum bagged according to standard bagging approach, i.e. ply, release film, breather material, vacuum bag. In some cases, the ply was allowed to “relax” in cleanroom conditions prior to vacuum consolidation.

In order to understand the effects of bagging practice and to visualise the pressure distribution in the bag, a pressure sensitive film was included in some of the layups (pressurex-micro® Green PMG1 - Sensor Products Inc., Madison, NJ, USA.). The film is composed of a donor film (red) and a receiver film (white). Conceptually similar to litmus paper, the operating principle is that dye microcapsules are transferred from the donor to the receiver when pressure is applied. It is not possible to assign a numeric value to the pressure, but qualitatively, the scale ranges from white (no pressure) to dark red (maximum pressure applied). The indicated pressure range is 1 – 40 N/cm^2.

Enough bagging material was used to ensure no stretching was required to conform to the geometry.

Two main aspects were investigated:
1. The effect of bagging procedures and placement of pleats/wrinkles
2. The effect of layup method, i.e. roller or no roller

2.2. Pressure sensor

To further investigate the effect of bagging configuration on pressure distribution, a digital flexible capacitive sensor was used (XSENSOR PX200.100.100.10 - Xsensor Technology Corporation, Calgary, AB, CA.). The sensor allows for a real time evaluation of pressure values and distribution. The resolution is 2.54mm, the sensing area 250 x 250mm and the maximum sensing pressure 10.3N/cm^2.

For these experiments, the sensor was draped over a non-metallic male C-section tool 600 (L) x 45 (W) x 70 (H) with corner radii ~ 5mm. The tool was then bagged using the aforementioned process (Figure 1). Pleats were placed to allow for enough excess bagging film to accommodate the height and width of the tool without stretching.
The effect of commonly seen scenarios are considered:

1. Bag distributed to cause insufficient bagging material: bag stretched over corners
2. Bag poorly distributed: bridging female corners and bunched around male corner

Figure 1. Flexible sensor and breather fabric laid up on C-section tool.

3. Results and Discussion

3.1. Consolidation trials

Figure 2 shows the results for a consolidation trial where the ply was laid down lightly on the glass plate, followed by the pressure sensitive film, and debulked. Pleats were introduced into the bag and deliberately routed across the laminate to investigate their effect. Here, the areas where the ply is in contact with the plate appear darker, whilst the air gaps are lighter in colour. Prior to debulking, the gap content in the ply's central area is over 90% (Figure 2. b), as identified by image processing, using thresholding to identify regions of low contact.

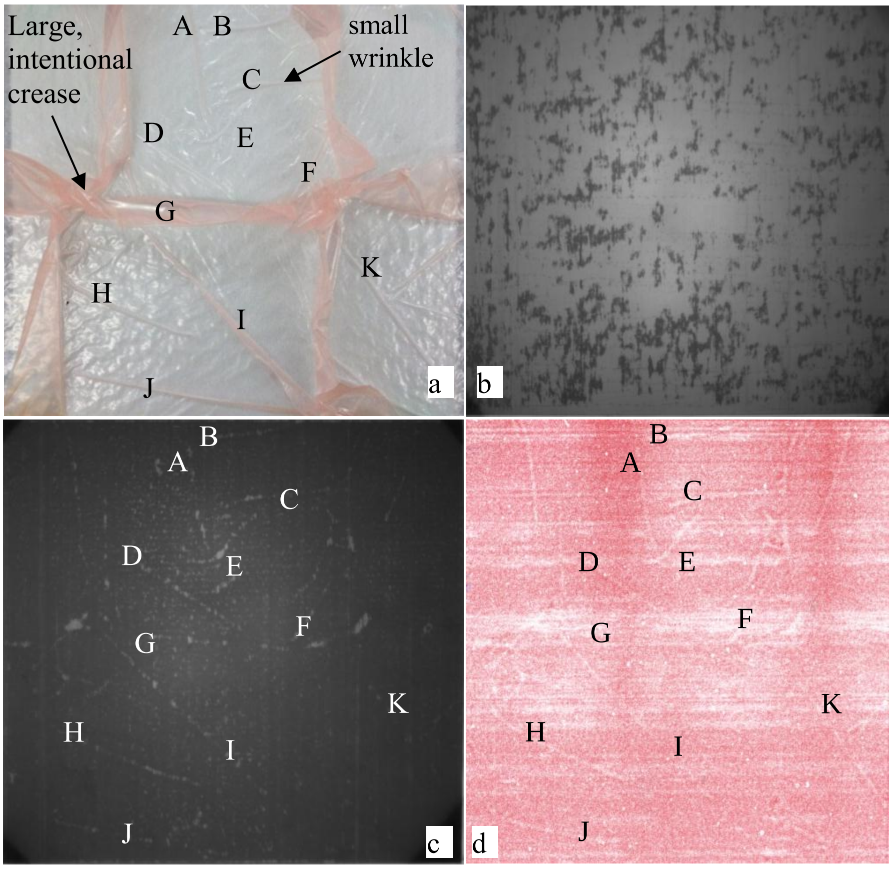


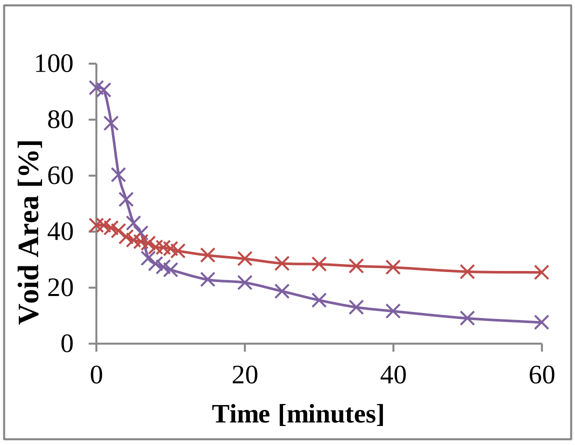
Figure 2. a) finished vacuum bag with unintentional wrinkles labelled A-K, b) pre-debulk photograph from below showing areas in contact as dark and air gaps as light, c) photograph after 20 minute vacuum debulk d) image of pressure film, light areas show zones of low pressure. Note, the bag wrinkles in (a) can be seen in both laminate and pressure film post-debulk (c and d).

Figure 2. c) shows the ply after 20minutes under vacuum. The void area is now 21%, a considerable reduction. Perhaps surprisingly, the main pleats have not led to any accumulation of air and have had not had a visible effect on the pressure distribution. The intense dark areas in the centre of the film are artefacts, related to the roll storage and handling.

Conversely, the small unintentional wrinkles do result in low pressure areas and are accompanied by visible air pockets. The wrinkles and their effects can be seen clearly in the bag, the film and ultimately, the laminate.

Figure 3 (left) is a plot of gap content (void area) against time under vacuum for two experiments where an identical layup was attempted. The starting void content and evolution are very different, showing the level of variability possible in this process. However, a high rate of air removal in the initial stages under vacuum, followed by a reduction to steady state is a trend also observed by other authors studying the permeability of laminates [7]. This suggests that the approach of studying the ply-glass interface is representative of what occurs in multiple ply laminates.

Interestingly, it seems that having a large air gap content is favourable for gas extraction during consolidation. Figure 4 (right) supports this hypothesis, showing a trend for lower air content in laminates which started off with more trapped air. This is assumed to be related to large void areas coalescing and forming in-plane pathways for the transport of air



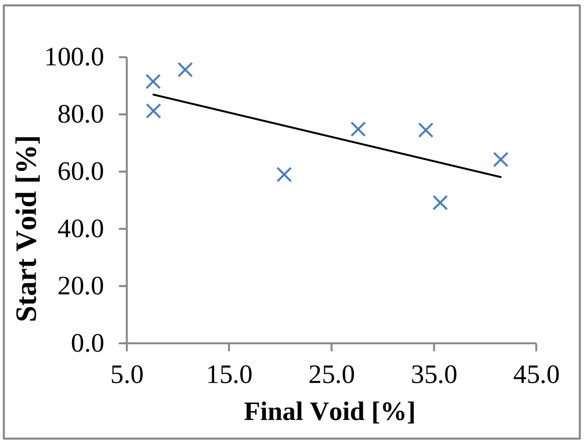


Figure 3. Left, evolution of air pockets in the layup with time under vacuum. The lines show two separate experiments laid up in the same way. **Right**, Measured voidage prior to debulk vs. air content after 60 minutes under vacuum.

3.2. Rolling

The pressure sensor was used to evaluate the footprint of a traditional roller as well as a novel conformable roller (Figure 4) for use in automated layup, the pressure maps are shown in Figure 5. Contrary to common expectation, plies laid down using the traditional roller were no better in terms of consolidation than the plies laid down lightly by hand. All rolled plies had a very regular distribution of small voids (Figure 6), which were caused as a result of point contacts forming between the glass and the inherent irregularities of the prepreg (akin to surface roughness) as the surfaces are rolled. These point contacts have the effect of locking off pathways for air removal, which leads to the dispersed distribution of air gaps shown in Figure 6 (centre).

Figure 4. Left, compliant silicone roller. **Right**, conventional roller.

High roller stiffness, resin viscoelasticity and relatively fast rolling speed are all thought to lead to low contact times and consolidation. The use of compliant silicone rollers is believed to improve local compaction and air removal, as shown by Figure 5 and Figure 7. Their cross section and low stiffness causes a gradual application of pressure and leads to small areas of complete contact between ply and plate. However, adjacent roller passes can lead to locked in air pockets after debulking, as seen in Figure 7. These experiments highlight the potential drawbacks of using rollers, which can be counterintuitive and counterproductive in layup.

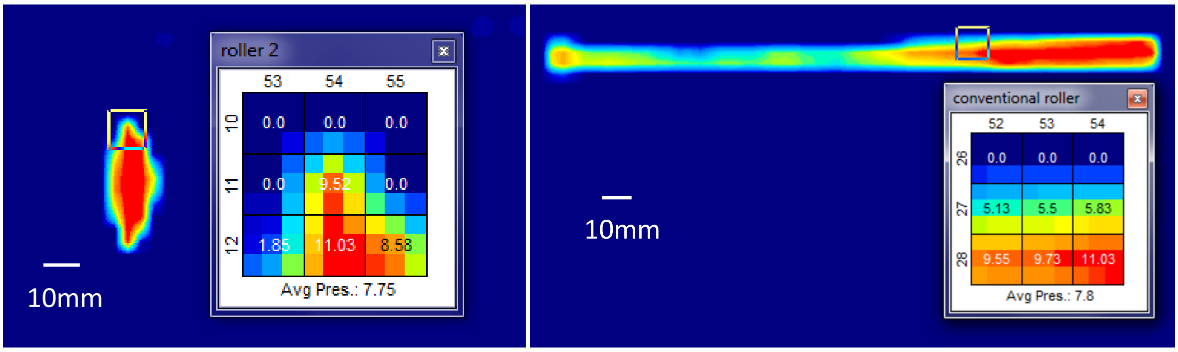


Figure 5. Left, pressure footprint of conformable roller. **Right,** conventional roller, obtained using regular laminating force. Units in N/cm^2

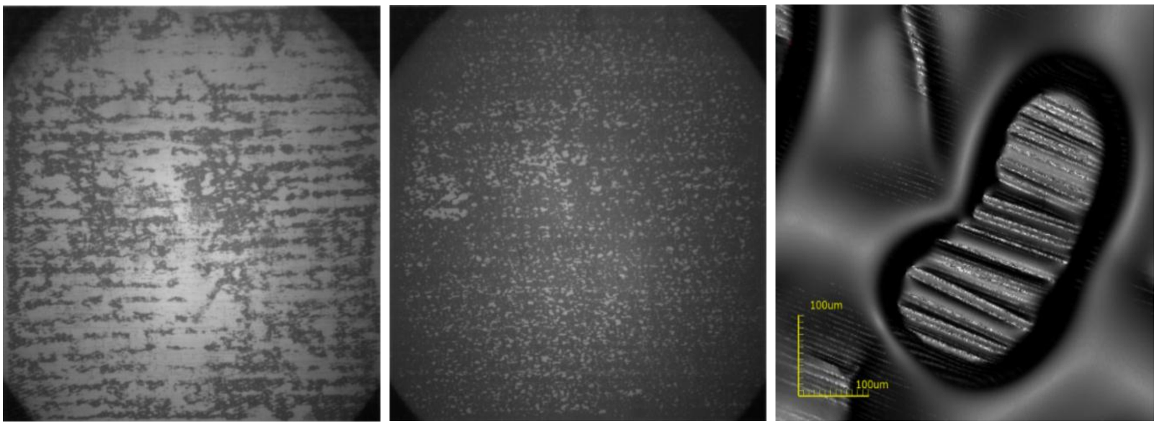


Figure 6. Left, Ply as laid down using conventional roller. **Centre**, ply after 60 minute debulk showing regularly distributed air pockets. **Right**, micrograph of prepreg surface showing a dry spot, giving an idea of the inherent surface roughness. Scale bar is 100µm.

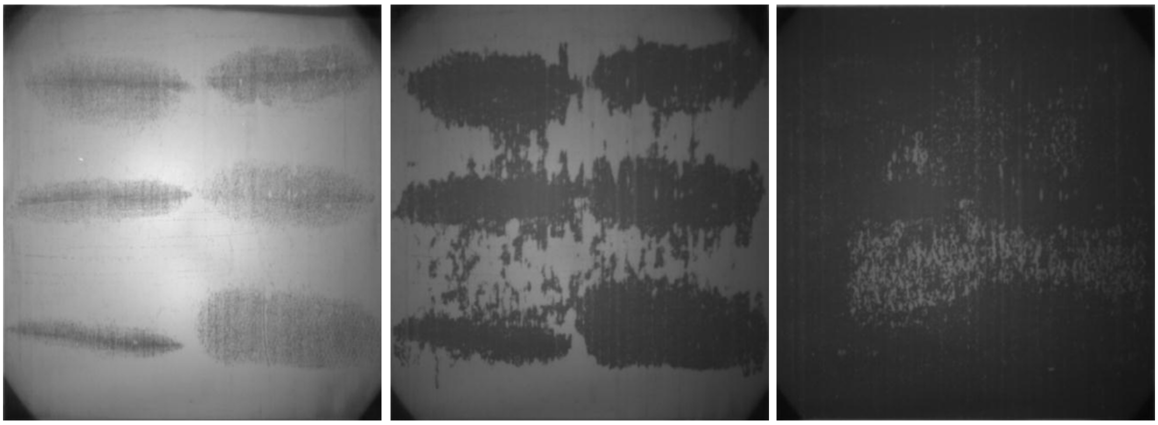


Figure 7. Left, Ply as laid down using 6 different conformable rollers. **Centre,** ply after 1 hour relaxation in cleanroom conditions. **Right,** ply after 20 minute debulk, with trapped air pockets visible between roller passes.

3.3. Pressure sensor and bag configurations

Examples of the effect of bag configuration when laying up over a prismatic C-section tool can be seen in Figure 8. In the first trial, the vacuum bag was allowed to naturally follow the corners, which caused wrinkling of the bag and breather running across the whole length of the part (Figure 8, left).

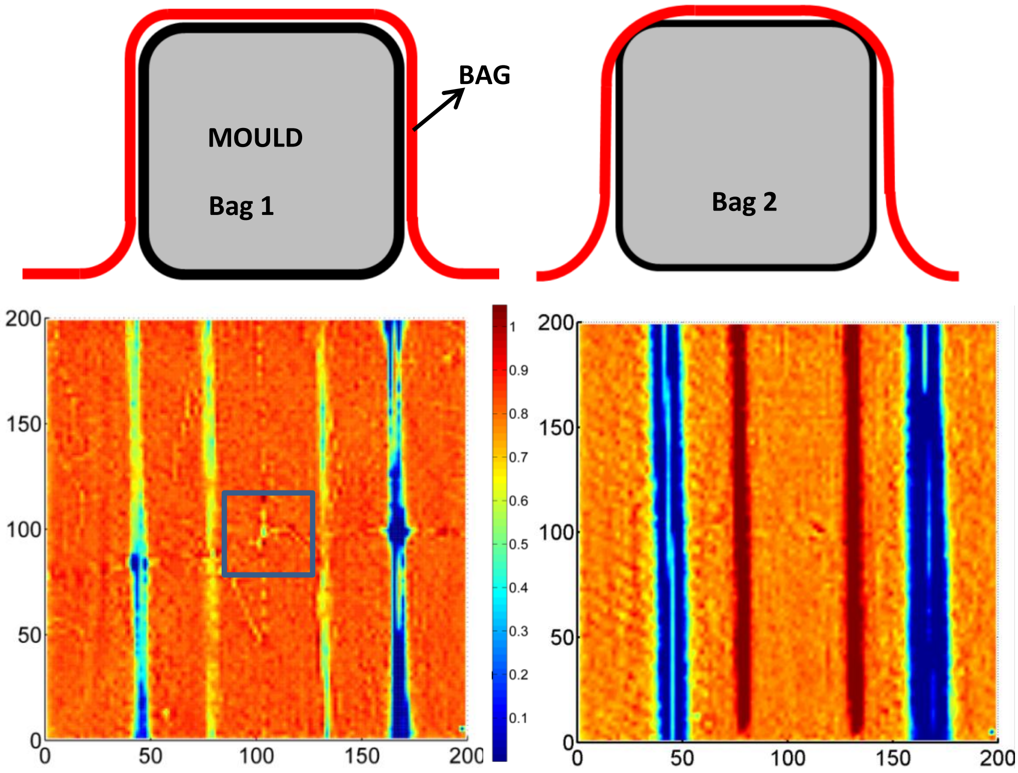


Figure 8. Pressure distribution in the vacuum bags, axes show position in mm on the sensor, scale in bar. **Left**, bag 1 - uncontrolled positioning of vacuum bag leads to excess accumulating along corners. **Right**, bag 2 – insufficient bagging material leads to tension in the bag as it is pulled over the top (male) corners and bridges the bottom (female corners).

Where the bag is wrinkled, it is not in contact with the laminate. This causes visible low pressure areas on the mould corners. Although the laminate was not cured, it is not unreasonable to assume that the low pressure regions will have an effect on local consolidation of the part, most likely leading to local thickening, resin rich areas and even ply wrinkling. The implications of these defects on mechanical properties have been extensively reported [8]

Figure 8 (right) shows the pressure distribution when there is insufficient bagging material available to cover the geometry adequately. Here, the pressure over the male corners is actually higher (>1 bar) than the vacuum pressure in the rest of the bag (the bag is pulled over corners tightly). For the female corners, the opposite is the case, as they have been bridged and are not in contact with the bag, resulting in zero pressure. This case is perhaps more easily detected than the first, but is by no means obvious and not necessarily identifiable from visual inspection.

Another interesting observation is that in the first case, a small cruciform wrinkle was deliberately introduced on the C-section web. This wrinkle is representative of the ones that are seen in finished bags, although, unlike the pleats, small wrinkles are usually uncontrolled. However, although they appear small, they show up as clear areas of reduced pressure. Hence a detrimental effect on the laminate is expected. This was also seen in the aforementioned experiments using the pressure film.

Conclusion and future work

From the initial results presented in this paper, the following conclusions can be drawn:

- The use of rollers and layup tools does not necessarily achieve the intention of consolidating plies and removing air.
- A trend between pre-vacuum and post-debulk air content has been identified – plies laid down lightly tend to have lower void content after being held under vacuum than plies which are laid down with traditional rollers.
- Pleat/crease placement is critical to ensure that pressure is evenly distributed across a geometry. In the example geometry considered in this study, poor bagging can lead to both low and high pressure regions.
- Some features in the bag transfer to the laminate, such as small wrinkles and creases. These often translate to low pressure regions, which could result in voidage or loss of dimensional accuracy in the cured part.

3.4. Future work

Future work will include the investigation of other geometries including examples of male/female tooling. It is also desirable to cure laminates manufactured replicating the different bagging configurations and deposition methods considered. Cured laminates can then be sectioned to examine dimensional variability and voidage. Lastly, it has been assumed that the contact between ply and glass plate is representative of what occurs between plies. Further study is required to validate this.

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