INFLUENCE OF THE BINDING SYSTEM ON THE COMPACTION BEHAVIOUR OF NCF CARBON FIBRE REINFORCEMENTS

S. Aranda[1]*, F. Klunker[1], G. Ziegmann[1]
[1] Institute of Polymer Materials and Plastics Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, Germany
* Corresponding author (santiago.aranda@tu-clausthal.de)

Keywords: *liquid composite moulding, preforming, binder, non-crimp fabrics, compaction*

1 Summary

The compaction behaviour of textile reinforcements must be considered for the design and optimisation of closed mould manufacturing processes. The deformation of the reinforcement during preforming and processing has a direct impact on the production parameters as well as the final product characteristics. The presence of powder binder and fleece between layers as tackifier has an influence on the compaction response of the material. In this work, compaction-relaxation-release tests were performed for three non-crimp fabric lay-ups combined with two different binding systems. The experiments were carried out at preforming temperature (120°C). The compaction behaviour depending on the material and compaction temperature are analysed in this paper.

2 Introduction

The transversal compaction behaviour of fibre reinforcements has to be considered in the design of the manufacturing process chain, from preforming to after-infusion.

The preforming phase is critical for the achievement of high production ratios, which are necessary to spread the use of carbon fibre reinforced plastics in new applications like automotive industry for example. During the preforming operations the fibrous reinforcement gets close to the actual component geometry and is prepared for a convenient impregnation. Preforming requires accurate specification of the fibre orientations besides the fibre volume content (FVC) which is essential to achieve the targeted mechanical properties. Furthermore, the handling of the preform in the steps before the impregnation must be assured as well. Indeed, the preform must be sufficiently stable to conserve its integrity and geometry during automatable steps like storage and transfer to the mould [1]. In order to achieve this net-shape-preform, thermoset or thermoplastic binders (tackifiers) are applied between layers. Being solid at room temperature, they melt at their corresponding activation temperature, allowing the textile plies to bond together after the preforming cycle.

An important requirement is that the preform must properly fit to the mould cavity in RTM-processes: on the one hand if the preform is too thin, it will not be possible to assure a predictable flow front progress. On the other hand, if the preform is too thick, additional pressure must be applied to close the tooling before impregnation. Problems associated to the spring-back effect derived from relaxation of the fibres must be also taken into account, such as potential difficulties during the operations previous to impregnation. These challenges can be addressed with a systematic and process-oriented study of the compaction response of the fibre reinforcement. [2] and [3] reported a higher fibre volume content as well as a lower spring-back effect when the preforming was performed at higher temperature and using binders. Together with the concentration, size and type, the location of the binder will determine the minimum thickness achievable under compression and the magnitude of the spring-back effect. As reported by [3], an easier compression and a better controlled spring back are achieved when the binder is located in the interlayer (outside the tows) than within the tows. Their work also pointed out that a higher concentration of binder in the interlayer would slightly increase the spring-back control, but decrease the degree of compaction.

Transversal compaction must also be considered during the impregnation stage, since the flow and the compaction behaviour are strongly coupled. The dependence of the reinforcement permeability on the fibre volume content has been already widely reported [4]. Recent works suggest that the compaction velocity has an influence on the transversal permeability K_z [5]. The evolution of the transversal compaction behaviour becomes quite complex during the infusion because of the difference between dry and wet compaction [8] and the expected lubrication caused by the resin.

The power law (Eq. 1) is the most commonly used expression to model the dependence between fibre volume content and compacting pressure [6], [7] .

$$\sigma = a \cdot V_f^k \qquad \text{Eq. 1}$$

Where σ represents the transversal stress, V_f is the fibre volume fraction and a and k are material parameters. Adjusting a and k, the dry and wet behaviour can be described. Although this model fits well to experimental data, it presents a singularity when the applied compaction pressure is still zero, as it implies that the fibre volume content is zero and thus, the thickness of the laminate is infinite. It makes the implementation of these models in simulation a difficult task. A more realistic model was presented by the authors [9] which considers the fact, tat even uncompressed fibres have a finite thickness and a initial fibre volume content V_0 (see Eq. 2).

$$\sigma = a \cdot (V_f - V_0)^k \qquad \text{Eq. 2}$$

A lot of effort has been paid to the study and modelling of the compaction behaviour for a variety of materials. Van Wyk [10] studied the properties of wool and derived the power equation for the compaction of a 3D network of randomly oriented fibres. The physical model assumes that the fibres behave like bending beams that transmit loads through contact points. The compaction pressure increases with the 3^{rd} power of the fibre volume content. One disadvantage of this early approach is that it is not able to handle with aligned fibres. Gutowski *et al.* [11] studied the consolidation of pre-impregnated reinforcements and proposed different versions of a compaction model for aligned and undulated fibres, where fibres are initially bent and straightened under pressure. In [12] Batch and co-workers measured compaction pressures of different sorts of reinforcements. They fitted their experimental data to a model where the fibre is modelled as a bulking arc contacting at two single points at the beginning of the compaction, increasing the contact region gradually as the compaction pressure increases. Fibre volume content is linearly related with applied pressure at the beginning of the compaction but presents a nonlinear relation for higher values of pressure. Some other models have been proposed to describe the compression behaviour of fibrous reinforcement like the exponential fit of Kang [13].

None of the above mentioned models take into account effects like the permanent deformation remaining after compression, hysteresis or the effects of cyclic loading [14]. Comas-Cardona *et al.* [15] proposed a non-linear elastic-plastic model which considers finite strains for loading and unloading of glass fibre woven fabrics.

Bickerton and Kelly [16][17] modelled both the compression and relaxation phases by means of the same viscoelastic model. They showed the effect of the compression rate on maximum stress required to reach the desired compaction degree and the relaxation effect at a held deformation. In [18] a new formulation considering stored and frictional dissipated energy are presented.

More recently Bayldon [19] presented an interpolation model based on Gutowski´s approach that describes the compaction stages in typical flexible bag processes considering partial unloading and reloading cycles.

Nevertheless, much attention has not been yet paid in the literature to study the influence of the temperature on the compaction behaviour which is mostly related to the behaviour of binders. In [20] the influence of a preheating treatment on the compaction of a non-crimp fabric with a thermoplastic fleece was presented. This work is the continuation of this investigation line, exploring the influence on the preforming and liquid composite moulding processes.

3 Materials and Experimental Method

In the present work, the compaction behaviour of three different non-crimp carbon fibre stacking sequences at preforming temperature is studied. It comprehends the compression phase at constant velocity, the relaxation at constant deformation and the release of the load at the same velocity than compression.

The three layups combine with two different types of binding material used to facilitate the fabrication of preforms. In the one hand, a thermoplastic fleece layer (based on a polyamide copolymer) with a medium areal weight of 6 g/m^2 is added to the inter-layer of a triaxial and a biaxial non-crimp fabric. In the other hand an epoxy powder binder (average particle size of 0.1 mm) also with 6 g/m^2 is placed on one face of the biaxial or triaxial reinforcement. The combination of fibre arrangements and tackifiers is summarised in Fig. 1. The areal weight is 550 g/m^2 for the biaxial and 820 g/m^2 for the triaxial carbon fibre reinforcement. The carbon fibres are of the type HTS40, with a density of 1.77 g/cm^3 and a filament diameter of 7 µm. In the Fig. 2, the concentration of binder (either powder or fleece) related to the carbon fibre weight is presented. The average areal weight of the stitch (PES SC) is in both cases 6 g/m^2.

The samples used in this study are square cuts of fibres (approx. 6 cm*6 cm) stapled in stacks, remaining invariable the number of layers. The textile is always cut from the same roll with a roll cutter, avoiding the pre-compaction of the material before testing as much as possible.

The tests are carried out on a universal testing machine. The compression takes place between two parallel steel plates. A thin steel plate placed directly under the sample concentrates the pressure on a well defined area of 5 cm*5 cm during the experiments. To measure the reaction force of the sample, the machine is equipped with a 10 kN load cell.

The compaction experiments are run in a heated chamber at a constant temperature of 120°C. In order to assure a homogeneous temperature distribution within the sample as well as the correct warming of the tooling, the samples are pre-heated during 15 min at the experiment temperature.

As mentioned before, each test is performed through three phases:

- Compression: 0.5 mm/min from 1 N till attaining a fibre volume content of 60% or up to a maximal pressure of 0.9 MPa,
- Relaxation: the maximum level of deformation is held for a defined time (6 minutes), allowing the structure to reorganise,
- Release: the discs are driven apart at 0.5 mm/min, down to a force of 1 N.

For the evaluation of the fibre volume content, a well known expression (Eq. 3) is used

$$FVC = \frac{n \cdot w}{\rho_f \cdot t} \qquad \text{Eq. 3}$$

where n is the number of layers, w is the areal weight, ρ_f represents the fibre density and t is the instantaneous thickness of the sample.

To analyse the deformation of the material related to its original configuration, the strain is defined as shown in Eq. 4

$$\varepsilon = \frac{t_0 - t}{t_0} \qquad \text{Eq. 4}$$

where t_0 is the initial thickness of the stack.

Five replications of each experiment are performed to assure the reproducibility.

In order to verify the effectiveness of the binding effect, it has been manually verified that the samples keep stuck after the compaction experiment.

4 Results

In the first set of experiments, the six textile-binder combinations are compacted to a FVC=60%, in a heated atmosphere at 120°C. The thickness of the stack before compaction, the force needed to reach the targeted FVC, the pressure after relaxation as well as the thickness and remaining deformation after the whole cycle are recorded, together with the time depending progress of pressure and thickness.

The second set of experiments is aimed to give the compaction behaviour by relative high levels of pressure, typical for preforming operations. Accordingly to this, the stacks are compacted up to 0.9 MPa.

The analysis of the results shows different compaction behaviour depending on the textile arrangement and especially on the binder system. The textiles with powder spread on the surface give higher initial FVCs and a slightly higher final FVCs (after the release of the load) compared to the fleece, as shown in Fig. 3. This has been attributed to the easier penetration of the powder in the intralayer of

the fabrics, together with a lubrication effect between filaments above the activation temperature.
Nevertheless, the textiles containing the thermoplastic fleece undergo the higher maximal strain as well as the higher permanent strain (see Fig. 4). The stronger deformation of the material would be associated to the appreciated higher initial thickness, produced by some swelling undergone by the fleece sheet during heating, as reported in [20]. The fleece would mainly act in the interlayer, blocking the compaction of the material but producing a higher binding between layers.
Another interesting parameter to quantify how easily a material can be deformed under transversal compaction is the force needed to reach the desired FVC. Consistently with the previous results, the layups containing powder binder need less pressure to achieve the targeted fibre volume content, than those using the thermoplastic fleece (Fig. 6). This would result specially interesting when selecting the binder system to be used, in order to reduce the necessary preforming pressure as well as the clamping forces in a RTM-process.
The compaction cycles performed with a maximum compression pressure of 0.9 MPa confirmed the trends obtained from the first series. Additionally, it is noticed that the fibre volume content reached at the maximum load is slightly higher when adding powder binder than when intercalating a fleece sheet. This tendency can be appreciated in the Fig. 5, where the thickness per layer before compaction, at the maximum pressure level and at the end of the release is displayed.
The presence of the binder system modifies the fibre volume content to be reached at each stage of the preforming process, what can be confirmed considering the mass ratio between binder system and carbon fibre. In this sense, the stacks with lower %-mass of binder (triaxial) present higher volume content than the biaxial samples. As expected, the stacks combining biaxial and triaxial plies present intermediate values. This suggests that independently of the type of binder (powder binder or fleece), the increase of binder concentration influences negatively the fibre packing. This negative effect can be assigned to a blocking effect on the compression in the interlayer.
To evaluate the effect of the temperature on the compaction behavior, tests at room temperature are also performed. The Fig. 6 summarizes the experimental results. It can be observed that the increased temperature reduces the pressure needed to achieve the desired fibre volume content. Furthermore, it can be concluded that the temperature effects on the compaction behaviour minimizing the influence of the binder type and concentration.

5 Conclusions

This paper presents the results of an experimental program, where the compaction behaviour of a carbon fibre non-crimp fabric with two different binder systems is examined. The influence of the binder type and concentration at high temperature on fibre volume content, deformation and compaction pressure are analysed. Despite in some cases the impact of these factors on the packing effectiveness, the reorganisation of the textile microstructure or the spring-back is relatively reduced, it should not be ignored in order to achieve a knowledge-based design of the manufacturing process. By means of this kind of characterisation, suitable parameters (temperature, binder selection, compaction pressure) can be chosen to get optimised preforming and impregnation steps.

6 Tables and Graphics

	TRIAX	BIAX	Combination TRIAX/BIAX
Fleece (F)	+45/0/-45/F// //-45/0/45/F	0/90/F	+45/0/-45/F// //90/0/F
Powder Binder (PB)	PB/+45/0/-45// //PB/-45/0/45	PB/0/90	PB/+45/0/-45// //PB/0/90

Fig. 1: Summary of the combinations of textile arrangement and binder system

	TRIAX	BIAX	Combination TRIAX/BIAX
% of binder to CF	0.73	1.1	0.87

Fig. 2: concentration of binder related to the carbon fibre areal weight

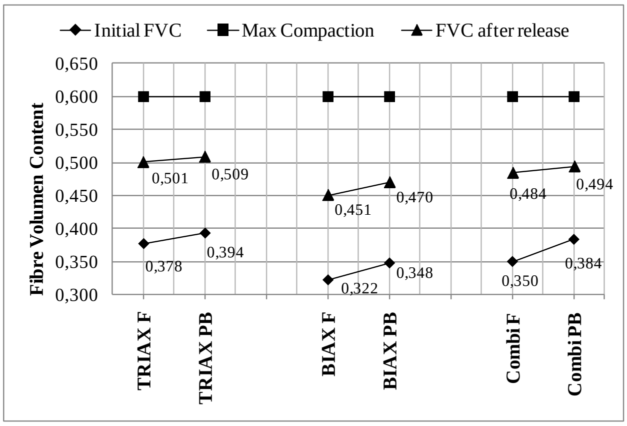

Fig. 3: Initial FVC, target FVC (0.6) and FVC after load release (120 °C).

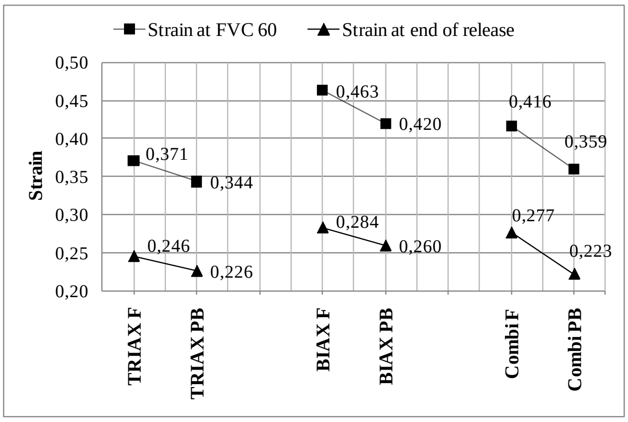

Fig. 4: Strain of the samples at 120°C, compacting until a 60% FVC and at the end of the release phase.

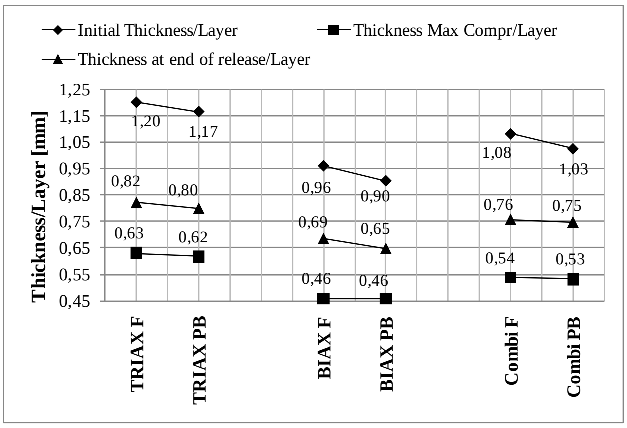

Fig. 5: Thickness per layer in the compaction test until 9 bar.

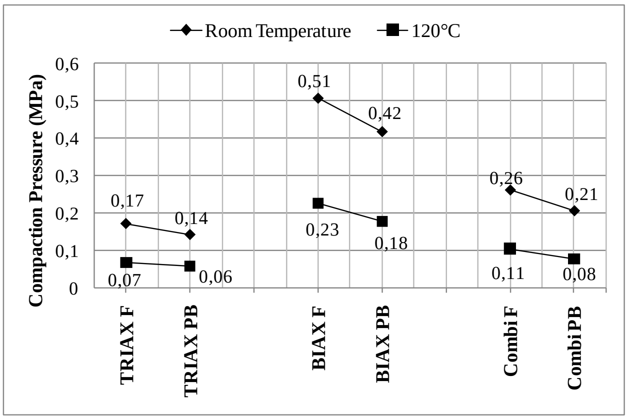

Fig. 6: Compression pressure needed to reach a 60% FVC at 120°C and room temperature.

References

[1] Rudd, C. D., Long, A. C., Kendall, K. N. and Mangin, C. G. E. (1997): Liquid Moulding Technologies, Woodhead Publishing Ltd., Cambridge.

[2] Rohatgi, V.; Lee, L. J. (1997): Moldability of Tackified Fiber Preforms in Liquid Composite Molding. In: Journal of Composite Materials, 31, 7, 720.

[3] Shih, Chih-Hsin; Lee, L. J. (2001): Tackification of Textile Fiber Preforms in Resin Transfer Moulding. In: Journal of Composite Materials, 35, 21, 1954–1981.

[4] Estrada, G.; Vieux-Pernon, C.; Advani, S. G. (2001): Experimental Characterization of the Influence of Tackifier Material on Preform Permeability. In: Journal of Composite Materials, 36, 19, 2297–2310.

[5] Ouagne, P.; Bréard, J. (2010): Influence of the Compaction Speed on the Transverse Continuous Permeability. July 11-15, 2010, "FPCM10". Ascona, Switzerland.

[6] Pearce, N.; Summerscales, J. (1995): The compressibility of a reinforcement fabric. In: Composites Manufacturing, 6, 1, 15–21.

[7] Robitaille, Francois; Gauvin, R. (1998): Compaction of Textile Reinforcements for Composites Manufacturing. I: Review of Experimental Results. Polymer Composites, 19 (2), 198–216.

[8] Robitaille, F.; Gauvin, R. (1998): Compaction of Textile Reinforcements for Composites Manufacturing. II: Compaction and Relaxation of

Dry and H_2O-Saturated Woven Reinforcements. Polymer Composites, 19 (5), 543–557.

[9] Klunker, F.; Aranda, S.; Ziegmann, G.; Fideu, P.; Baisch, P.; Herrmann, A. (2008): Permeability and Compaction Models for Non Crimped Fabrics to Perform 3D Filling Simulation of Vacuum Assisted Resin Infusion. The 9th International Conference on Flow Processes in Composite Materials (FPCM 9), Montreal, Canada, July 2008.

[10] Van Wyk, C. M. (1948): J. Text. Inst., 39, T285.

[11] Gutowski, T. G.; Cai, Z.; Bauer, S.; Boucher, D.; Kingrey, J.; Wineman, S. (1987): Consolidation Experiments for Laminate Composites. Journal of Composite Materials, 21, 650–669.

[12] Batch, Gibson L.; Cumiskey, Sean; Macosko, Christopher W. (2002): Compaction of Fiber Reinforcements. Polymer Composites, Vol. 23, (3), 307–318.

[13] Kang, M.K.; Lee, W.I.; Hahn, H.T. (2001): Analysis of vacuum bag resin transfer molding process. Composites Part A, 32 (11), 1553–1560.

[14] Somashekar, A. A.; Bickerton, S.; Bhattacharyya, D. (2006): An experimental investigation of non-elastic deformation of fibrous reinforcements in composites manufacturing. 7th International Conference on Flow Processes in Composite Materials, USA. Composites Part A, 37 (6), 858–867.

[15] Comas-Cardona, S.; Le Grognec, P.; Binetruy, C.; Krawczak, P. (2007): Unidirectional compression of fibre reinforcements. Part 1: A non-linear elastic-plastic behaviour. In: Composites Science and Technology, 67, 504–517.

[16] Bickerton, S.; Buntain, M. J.; Somashekar, A. A. (2003): The Viscoelastic Compression Behaviour of Liquid Composite Moulding Preforms. Composites Part A, 34 (5), 431-444.

[17] Kelly, P. A.; Umer, R.; Bickerton, S. (2006): Viscoelastic response of dry and wet fibrous materials during infusion process. Composites Part A, 37 (6), 868–873.

[18] Kelly, P. A. (2008): A Compaction Model for Liquid Composite Moulding Fibrous Materials. The 9th International Conference on Flow Processes in Composite Materials (FPCM 9), Montreal, Canada, July 2008.

[19] Bayldon, J. M.; (2008): A New Interpolated Model for Preform Compaction in Vacuum Assisted Resin Transfer Molding Process. The 9th International Conference on Flow Processes in Composite Materials (FPCM 9), Montreal, Canada, July 2008.

[20] Aranda, S.; Klunker, F.; Ziegmann, G. (2009): Compaction Response of Fibre Reinforcements Depending on Processing Temperature. "17th International Conference on Composite Materials (ICCM 17)". Edinburgh, July 2009.