PROCESS CHARACTERISATION FOR COMPRESSION MOULDING OF HYBRID-ARCHITECTURE COMPOSITES

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Keywords: Compression moulding, High-volume manufacturing, Hybrid fibre architecture, Prepreg, Sheet moulding compound

ABSTRACT

Compression moulding of prepreg and Sheet Moulding Compound (SMC) in a single-shot process combines the superior mechanical properties of continuous fibre composites and the high design flexibility of discontinuous fibre composites. In this study, an experimental characterisation of the processing behaviour for each single material (prepreg or SMC) as well as the interaction properties between the two materials was performed through the squeeze-flow test under typical processing conditions. New constitutive material models for prepreg and SMC were developed from the single material tests. From the hybrid-architecture material tests, critical interaction mechanisms were identified as well as additional deformation mechanisms that were not observed in single material tests. The findings from this work will facilitate the future development of a numerical simulation model for hybrid moulding process.

1 INTRODUCTION

With the advancement in fast cure resin system, compression moulding of fibre reinforced thermoset composites has become an attractive solution for high-volume manufacturing of advanced lightweight automotive structures. This process is commonly associated with either continuous fibre based prepreg or discontinuous fibre-based Sheet Moulding Compound (SMC). While prepreg is ideal for producing high stiffness, high strength structures because of the superior properties offered by continuous fibre reinforcements, SMC is suitable for manufacturing complicated geometry such as ribs and bosses, allowing stiffening mechanisms to be integrated into the geometry. The one-shot hybrid compression moulding process for the combination of SMC and prepreg improves the manufacturability of high performance composite structures by offering the solution for integrating the functionalities of different materials [1]. Understanding uncured materials' deformation mechanisms in a hybrid compression moulding process is the key for predicting the mould filling process and the fibre architecture in the manufactured parts. This requires comprehensive studies of the individual material's behaviour as well as the interactions between the two materials under hybrid moulding conditions.

Rotational rheometers have been widely used in rheological characterisation for polymers and polymetric composites reinforced with fillers. However, they are not suitable for SMCs as the pressure required for SMCs to flow is significantly higher than the maximum pressure applied by these rheometers (~1 bar). The specimen size in these rheometers is limited in the range of standard chopped fibres in SMC materials which is not representative for the actual meso-scale architecture of the material. Alternatively, the squeeze-flow method is considered more suitable for process characterisation of SMCs as it can produce the flow regime and testing conditions similar to those in the actual compression moulding. Early applications of the squeeze flow test involves compressing cylindrical SMC specimens between parallel and non-lubricated plates [2] or lubricated plates [3] at different closing speeds. The compressive force and material shear viscosity were found to be strain rate dependent, but no quantitative data were obtained from these studies and the closing speed was below that during compression moulding [4]. A later study [5] investigated the flow behaviour of SMC at different temperatures and speeds and the extensional flow was found to be the predominant deformation mechanism based on the pressure measurement. The plane-strain or 1D squeeze flow test was adopted by some researchers [6,7] to achieve a rectilinear and more homogeneous flow than the 2D squeeze flow test with cylindrical specimens. However, elastic stress components are usually overlooked in these characterisation studies. SMCs have a network of entangled long fibre bundles and are subject to high compressive force applied over a large surface area during compression moulding. The material deformation is dominated by the interactions between fibre bundles and the compressive stress [8] rather than shear or elongational viscosity in low fibre-content suspension flows [9].

The characterisation of prepreg compaction behaviour have been carried out extensively and involve compressing the prepreg specimen between two parallel heated plates. A review of early research on the compaction behaviour for prepreg is presented in [10]. Chen and Chou studied the elastic compaction deformation of single-layer [11] and multi-layer [12] woven prepreg in liquid composite moulding processes and proposed an analytical 3D compaction model for predicting the deformation and nesting of the material under compaction. Later, Comas-Cardona studied the non-linear elastic-plastic compaction behaviour for woven prepreg by loading and unloading the material during the test and a 1D constitutive law with large deformation formulation and measurable parameters was proposed to model the fibre reinforcement during the unidirectional compression [13]. Authors also suggested that the displacement field within the thickness can be considered homogeneous for think specimens, however, materials were found to be more packed at regions close to platens than at the centre of the specimen. More recently, a ramp-dwell testing regime with cruciform cross-plied specimens was used to characterise advance thermoset prepreg for aerospace applications, which can separate the pressure in fibre bed from resin [14]. This characterisation approach was later used to produce the parameters for a phenomenological model predicting the squeezing and percolation flow behaviour of unidirectional (UD) [15] and woven prepreg [16]. Nevertheless, existing studies are limited to either low rate or low pressure conditions and the material response under these conditions is not representative of the actual compaction behaviour in a high-rate compression moulding setting.

The existing work on process characterisation for hybrid moulding is very scarce and only involves hybrid moulding of SMC and UD prepreg [17]. The deformations in uncured prepreg were quantified using different flow regimes, and the effects of staging was also studied. However the interaction mechanisms and the interfacial properties between SMC and UD prepreg were not investigated. The reason for the extreme fibre distortions in the prepreg is that the pressure required for the SMC to flow (>100 bar) is significantly higher than the pressure required to consolidate the prepreg <20 bar), and the majority of the prepreg has not been designed to retain its fibre architecture under such high pressure. In addition, the in-cavity flow of SMC on one side of the prepreg surface can introduce significantly different deformation in continuous fibres compared to a prepreg-only process where both sides of the material are only in contact with the rigid mould, adversely affecting the mechanical properties of the material. Therefore, it is crucial to correctly model the constitutive behaviour of the SMC and the prepreg, and the interaction properties at the interface in process simulation tool, such that the large distortions in the fibre architecture can be captured and mitigated.

This study aims to deliver good understanding in the critical material deformation mechanisms in a hybrid compression moulding process combining continuous fibre woven prepreg and discontinuous fibre SMC through comprehensive experimental process characterisation. Experimental material characterisation was performed under typical high-rate compression moulding conditions using a squeeze-flow testing rig for woven prepreg, SMC and the combination of both materials. The experimental data and observations from this study will facilitate the development of a process simulation model for compression moulding of hybrid-architecture composites in future work.

2 EXPERIMENTAL METHODOLOGY

2.1 Materials

Both prepreg and SMC materials investigated in this study were supplied by DowAksa and consisted of carbon fibre and the same epoxy resin specially designed for high-volume processing with a 2-minute cure time at 150°C. The woven prepreg has a twill weave with a 12K tow size, 603 gsm areal weight and 55% fibre volume fraction. The SMC was made from the chopped UD prepreg with a fibre length between 27 mm and 54 mm, 1048 gsm areal weight and 53% fibre volume fraction. Further details regarding these materials are not disclosed here due to the confidentiality.

2.2 Material characterisation

Fig. 1 shows the squeeze flow rig used to perform all compaction tests in this study. It consists of two 350 mm × 350 mm parallel heated testing plates fixed to a die set with guide columns to ensure the parallelism. The rig was mounted on a 250 kN servo-hydraulic testing machine. An extensometer with a 100 mm gauge length and ±6 mm range was attached to the testing plates for the direct measurement of the displacement of the moving plate. Five pressure sensors with a 1000 bar range were flush mounted on the top plate from the centre to the edge with an equal spacing of 20 mm.

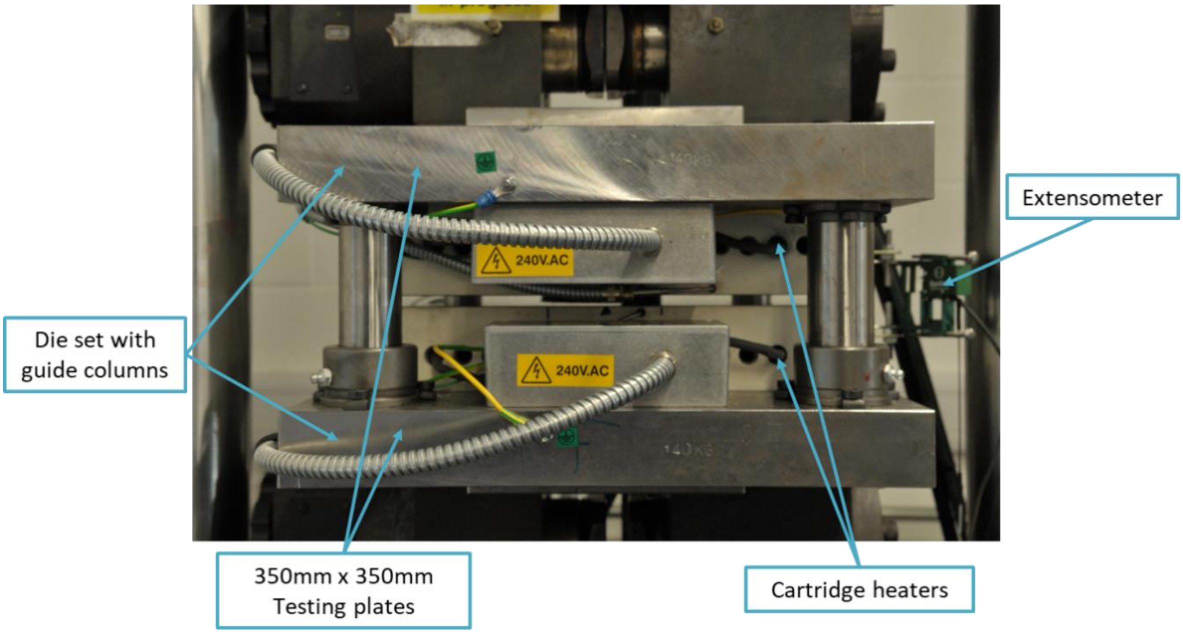


Figure 1: Squeeze flow rig on a servo-hydraulic testing machine.

Table 1 shows a summary of all specimen configurations and their relevant test conditions. Configuration 1 and 2 are single architecture specimens consisting of only one ply of SMC or prepreg (Fig. 2 (a) and (b)) whereas Configuration 3 is a hybrid architecture consisting of one ply of SMC centrally located on the top of one ply of prepreg (Fig. 2 (c)). All tests were performed at 100°C mould temperature as the resin viscosity at this temperature is close to that at the processing temperature (150°C) while the much slower reaction time allowing sufficient time for loading the specimen. A displacement-controlled testing programme with constant crosshead speed was used for all tests with a 200 kN force limit and 0.1 mm position limit. It is worth noting that the actual cavity height is greater than the crosshead position reading due to the compliance of testing machine at very high forces. The specimen was held in the rig at a constant cavity height after the test stopped until the material reached a sufficient degree of cure to be removed with ease.

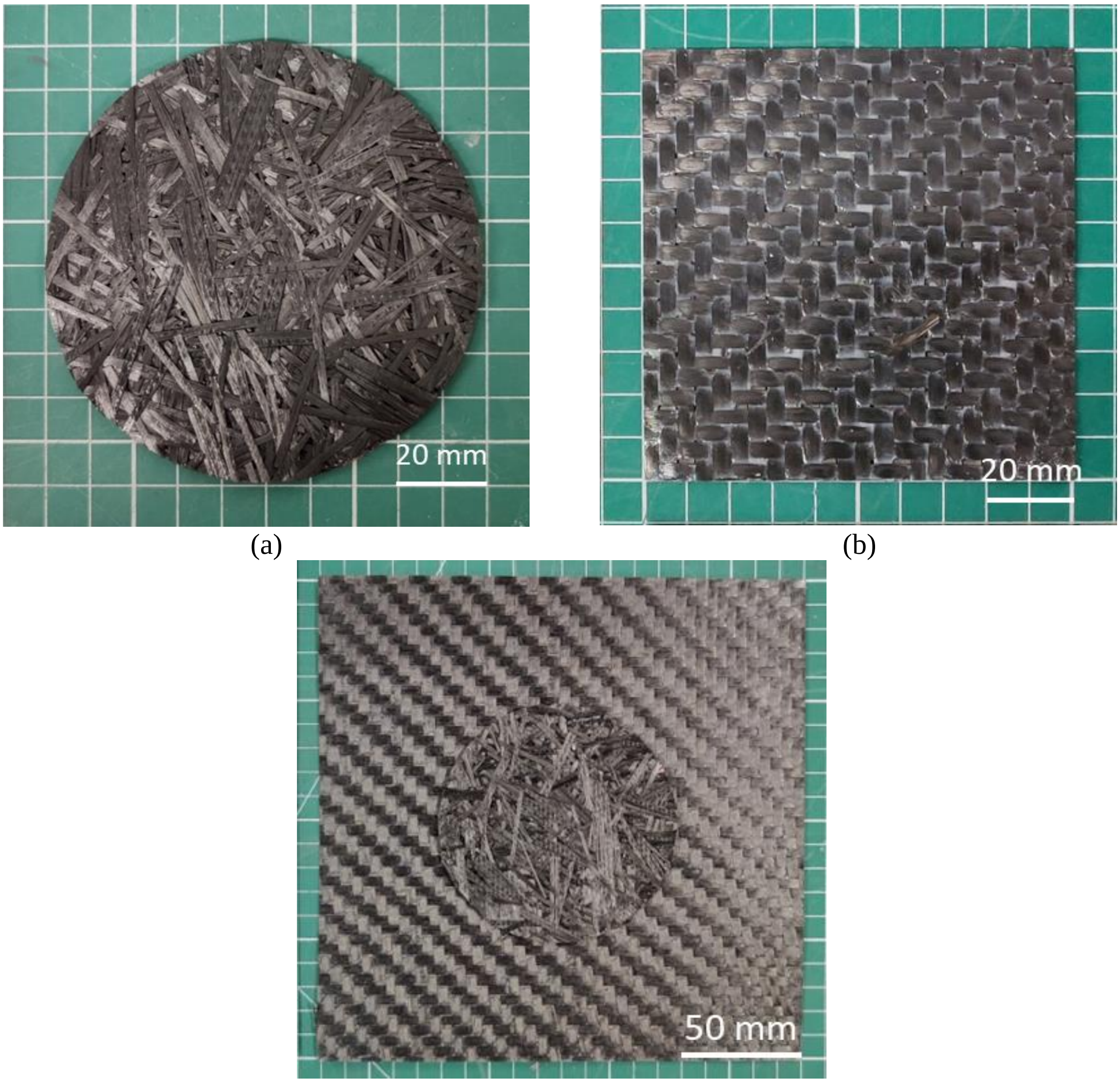


Figure 2: Untested specimens: (a) configuration 1 (SMC only), (b) configuration 2 (prepreg only) and (c) configuration 3 (hybrid architecture).

	Configuration 1	Configuration 2	Configuration 3
Layup	1 ply SMC only	1 ply prepreg only	1 ply SMC + 1 ply prepreg
Shape and dimensions	Circular shape with 98 mm diameter	100 mm × 100 mm square	98 mm diameter circular (SMC) + 200 mm × 200 mm square
Testing conditions	100°C 1 mm/s, 3 mm/s, 5 mm/s	100°C 1 mm/s	100°C 1 mm/s

Table 1: Specimen configurations and test conditions.

To derive the through-thickness constitutive relationship for SMC and prepreg from testing results of configuration 1 and 2, the following assumptions were made:

1. The material deformation/flow is fully homogeneous.
2. The material volume decreases linearly during the test.
3. A perfect slip condition is assumed between the specimen and the surface of testing plates.

The through-thickness compressive stress can be calculated as:

$$\sigma_c = F_c/A. \tag{1}$$

where Fc is compression force obtained from testing machine and A is the momentary contact area between the specimen and plate surfaces. The through-thickness strain can be calculated as:

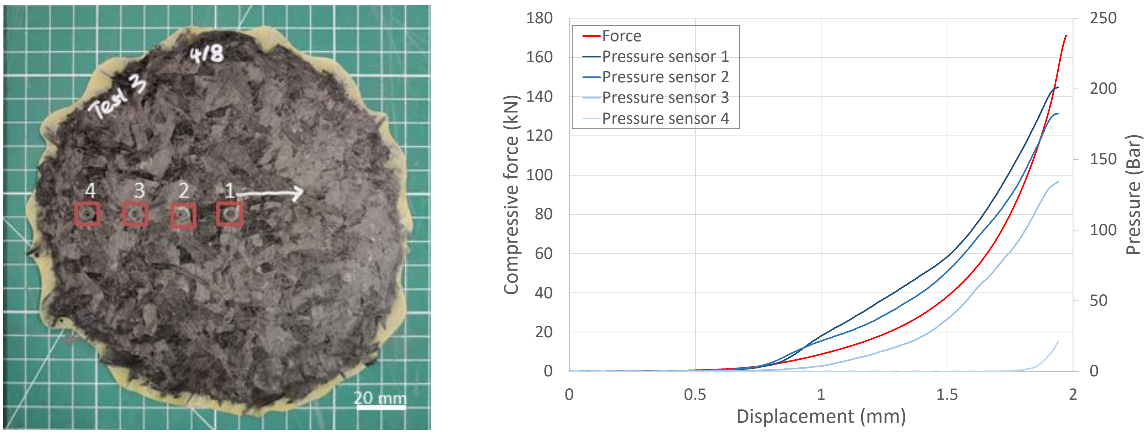
$$\varepsilon_c = ln(h/h_0). \tag{2}$$

where h_0 and h are specimen initial height and momentary height, respectively. The thickness of tested specimens was measured under a Zeiss Axio microscope. Due to surface undulation and fibre crimp of uncured materials, the deviation in initial thickness is too high to obtain an accurate value. Therefore, the initial thickness and momentary thickness of the material during the test were determined from the displacement of the moving plate measured by the external extensometer. The final coverage area of SMC was measured from photos taken after the test using ImageJ image processing software. The momentary volume and contact area between the SMC specimen and plate surfaces can then be determined based on assumption 2 above.

3 RESULTS AND DISCUSSION

3.1 SMC-only specimen (configuration 1)

Fig. 3 (a) shows an SMC specimen after the test where the locations of pressure transducers can be seen from the imprints on the specimen. The shape of the specimen remained virtually circular after the test and its diameter increased by 69%. The resin bleeding around the edge of the specimen was assumed to occur after the test had stopped while the specimen was held at a constant cavity height to be cured. Fig. 3 (b) shows the compression force and pressure data against plate displacement. The pressure readings show the flow of the material as pressure reduces from the centre to the edge of the material along the radial direction. Fig. 4 presents the compressive stress-strain curves for SMC specimens calculated using Eq. (1) and (2). A strong rate-dependency can be observed as the magnitude of compressive stresses increase with the closing speed.



(a) (b)

Figure 3: (a) SMC-only (configuration 1) specimen after the test and (b) compressive force and pressure – displacement curves for an SMC-only specimen tested at 100°C and 5 mm/s.

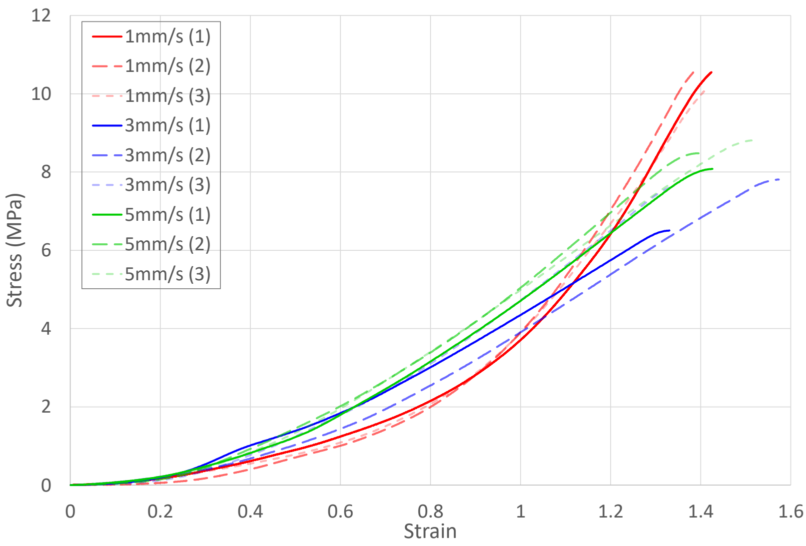


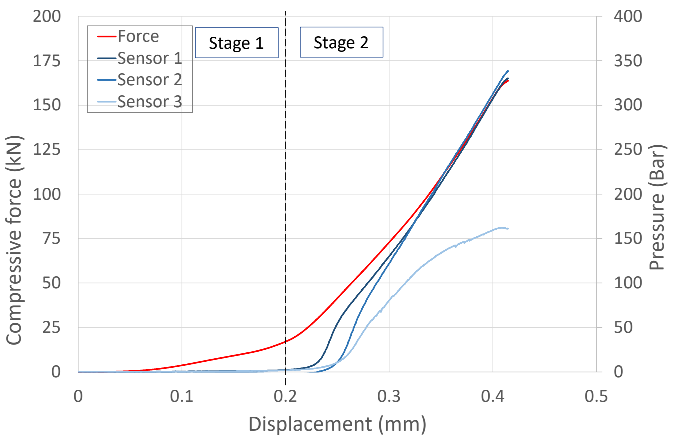
Figure 4: Compressive stress-strain curves for SMC-only specimens tested at different closing speeds.

3.2 Prepreg-only specimen (configuration 2)

The main purpose of testing prepreg-only specimens in this study is to investigate the material behaviour under the hybrid moulding conditions (high pressures). Fig. 5 (a) shows a typical prepreg-only specimen after the test. Although resin bleeding and fibre wash was observed along the specimen edges, the majority of fibre tows remained in place and, consequently, the in-plane dimensions of the fibre architecture remained unchanged at the macroscale.

Fig. 5 (b) shows a bi-linear force-displacement relationship as the force increases at a higher gradient after a turning point at 0.2 mm displacement. The measured pressure at different locations may vary (340 bar at sensor 1 and 2 and 160 bar at sensor 3) due to the small size of pressure sensor. The pressure measured at intersection of fibre tows can be significantly higher than that measured at a resin rich region (e.g. edges, gaps between fibre tows). In Fig. 6 shows a bi-linear compressive stress-strain relationship can be observed again for prepreg specimens with a transition point at 2 MPa stress.

(a)



(b)

Figure 5: (a) Prepreg-only (configuration 2) specimen after the test and (b) compressive force and pressure – displacement curves for a prepreg-only specimen tested at 100°C and 1 mm/s.

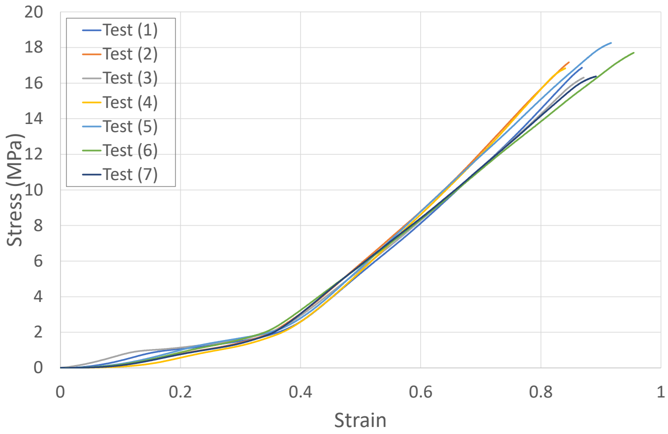
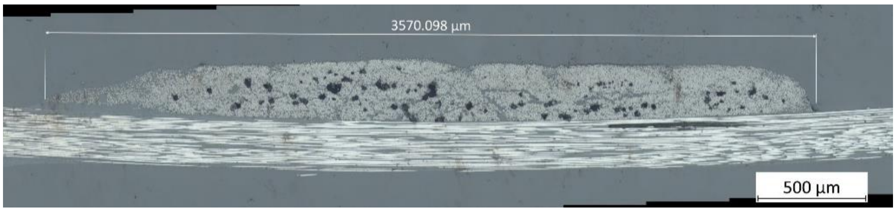
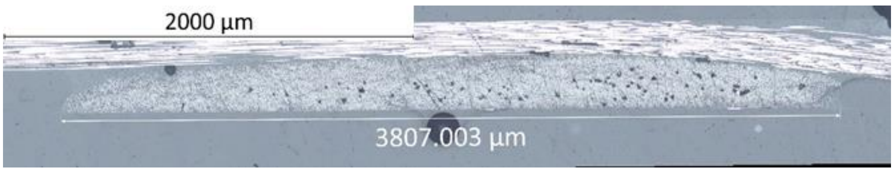
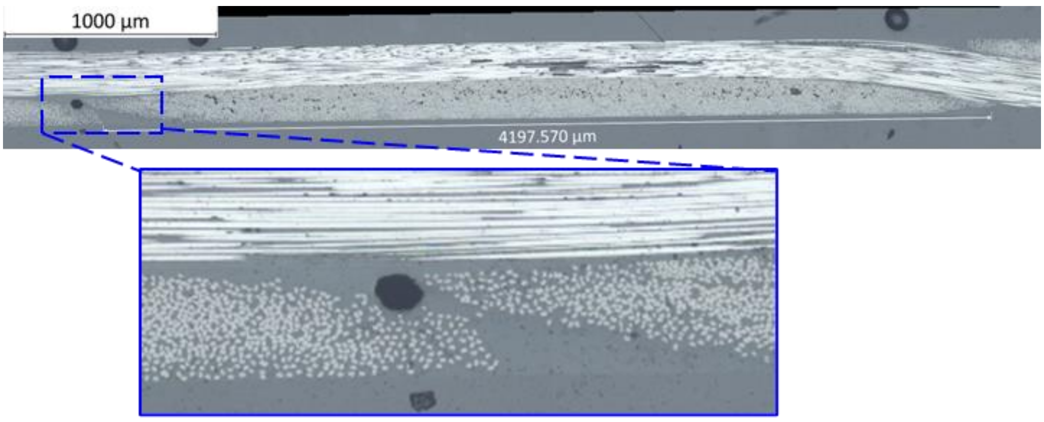


Figure 6: Compressive stress-strain curves for prepreg-only specimens

Fig. 7 shows the cross-section of the specimen at different pressure levels. Except the through-the-thickness compaction, the major deformation mechanism was at fibre tows/mesoscale: in the first 0.22 mm displacement, the nominal width of the fibre tows increased from 3.5 mm to 4.2 mm and the overall profile of the fibre tow remained unchanged; in the second stage the material was further compacted and gaps between adjacent fibre tows almost disappeared as very small resin rich regions. This corelates with the bi-linear material response and explains the reason that the pressure readings only started increasing when fibre tows in the specimen were mostly packed at 0.2 mm displacement.

Plate displacement (mm)/Pressure (bar)	
0 mm 0 bar	
0.16 mm 12 bar	
0.22 mm 24 bar	

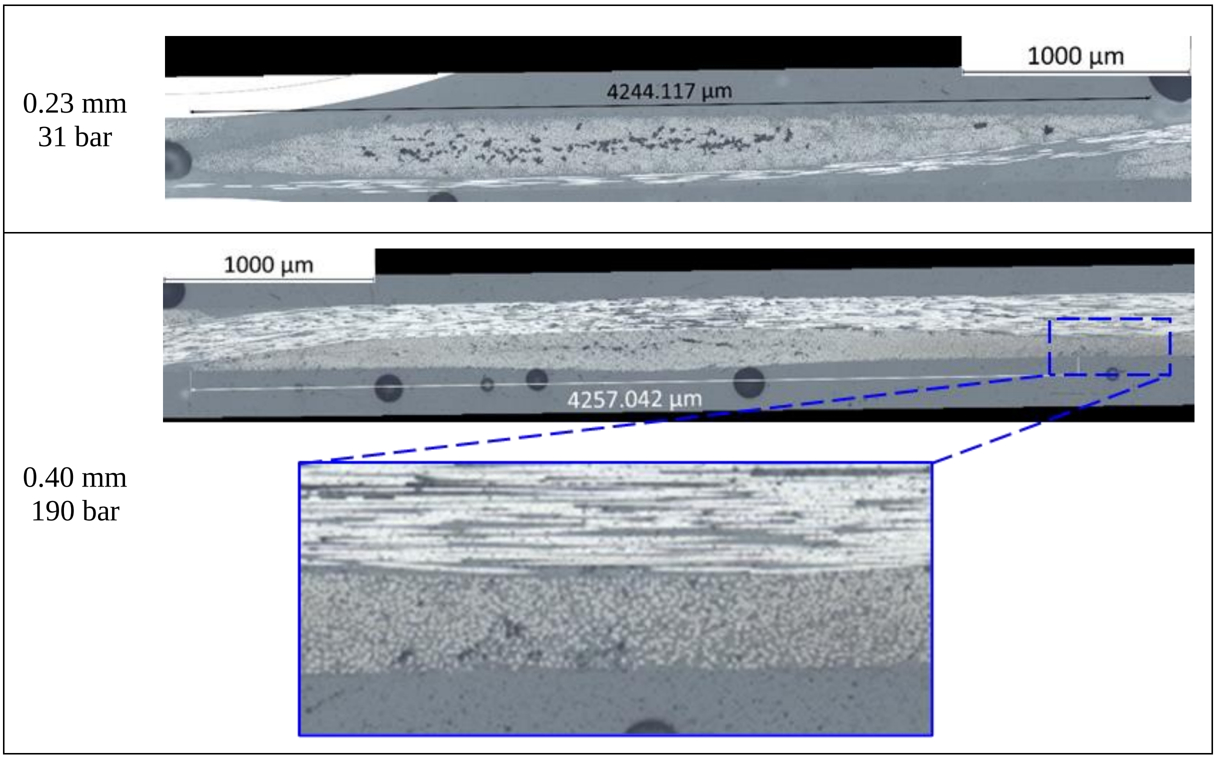


Figure 7: Micrographs of cross-sections of prepreg-only specimens at different plate displacement/pressure levels.

3.3 Hybrid-architecture specimen (configuration 3)

Both sides of a typical hybrid fibre architecture specimen after the test are shown in Fig. 8. In this specimen, the SMC deformed in a similar manner as in an SMC-only specimen. The diameter increased by 60% after the test similar to the level of increase for SMC-only configuration (69%) (Fig. 3 (a)). The overall in-plane dimensions of the woven prepreg in the hybrid-architecture specimen remained as a 200 mm × 200 mm square whereas local deformations occurred mostly underneath the SMC. Apart from the through-thickness compaction, the major deformations for the prepreg in the hybrid-architectures are fibre tow spreading in the centre of the specimen and fibre tow in-plane compaction and some in-plane shearing around the flow front of the SMC. The extreme fibre tow spreading and squeezing are highlighted in the micrographs in Fig. 8. The fibre tow behind the edge of SMC expanded from 3.5 mm to 5.28 mm while the fibre tow beyond the SMC was squeezed to 2.13 mm. In both cases, the boundaries of adjacent fibre tows can be hardly recognised anymore as these rein-rich regions disappeared.

To further investigate the interaction between two materials, a hybrid-architecture specimen was tested with double layers of Biaxially Oriented Polypropylene (BOPP) films inserted between the SMC and the prepreg to eliminate the effects of frictions between two materials (Fig. 9 (a)). With a high tensile stiffness, these films can prevent any other potential tangential interfacial stresses from being transferred between the SMC and prepreg. A grid was painted onto the film prior to the test to prove that the in-plane deformation in the BOPP films was negligible. As shown in Fig. 9 (b), gridlines on both films had any negligible deformations, however, the SMC and prepreg still experienced similar level of deformations to the hybrid-architecture specimen without films. Therefore the critical interaction mechanism between two materials is deduced to be the transfer of the normal stresses rather than tangential stresses including the friction.

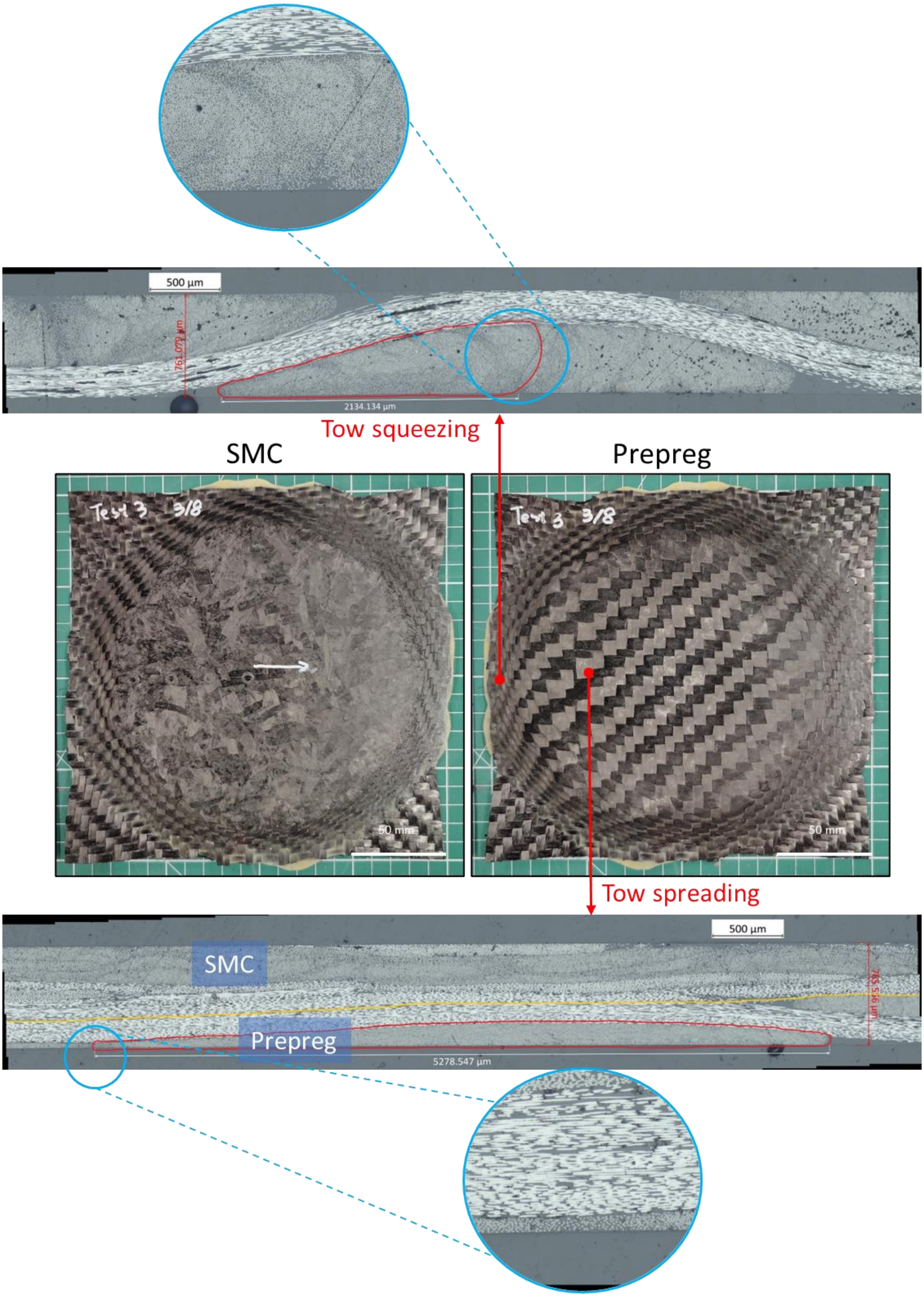


Figure 8: Hybrid-architecture specimen after the compaction test and micrographs of its cross-section.

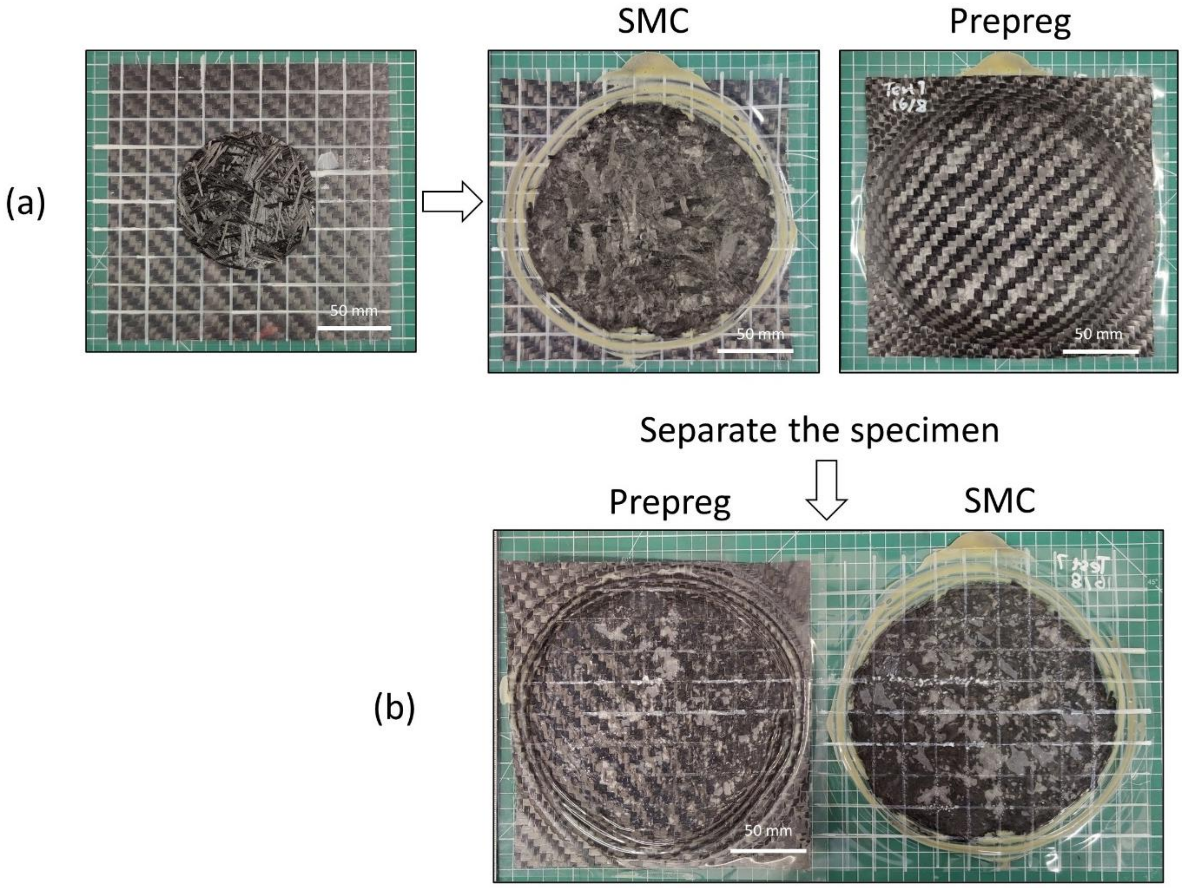


Figure 9: (a) Hybrid-architecture specimen with BOPP films inserted between prepreg and MSC and (b) the interface of two materials

4 CONCLUSIONS

In this study the deformation mechanisms for a fast-cure carbon fibre SMC and prepreg in the hybrid moulding process were characterised through the squeeze-flow test. SMC and prepreg were tested individually and in a hybrid-architecture under industry-relevant hybrid moulding conditions. The SMC showed a rate-dependent stress-strain and a very similar squeeze-flow behaviour under hybrid moulding conditions. The woven prepreg exhibited a bi-linear compressive stress-strain relation with a stiffer response above 2 MPa stress. The fibre architecture in the woven prepreg showed a minimum change in its macroscale in-lane dimensions and the major deformation was fibre two spreading at mesoscale in the first stage below 2 MPa stress. In a hybrid-architecture, additional deformation modes in the woven prepreg were fibre tow squeezing and extreme tow spreading that was not observed in a prepreg-only specimen. The test with BOPP films inserted between two materials revealed that these extreme two deformations were mostly caused by the normal stresses at the interface rather than tangential stresses at the interface.

Further work will include partial closure tests for all three specimen configurations at different load levels to examine the hypothesis of material compressibility made at this stage. Pressure data will be further analysed to help determine the contact area during the test and the flow pattern. The stress-strain data will be sued for the development of a suitable simulation model for compression moulding test of individual materials as well as hybrid-architectures.

ACKNOWLEDGEMENTS

The authors would like to express appreciation for the support of the EPSRC Future Composites Manufacturing Hub [EP/P006701/1] and the China Scholarship Council. The authors would also like to thank DowAksa for donating the materials used in this study.

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