EFFECT OF PROCESSING PARAMETERS ON QUALITY AND STRENGTH IN THERMOPLASTIC COMPOSITE INJECTION OVERMOULDED COMPONENTS

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Abstract

Traditional manufacturing processes for pre-consolidated continuous fibre thermoplastic laminates (organosheets) offer excellent mechanical properties but are limited by geometrical design. The integration of an injection moulding stage to an organosheet thermoforming operation allows for the manufacture of combined short and continuous fibre reinforced composites that benefit from high intrinsic mechanical properties, geometric complexity and low production cycle times. This study aims to understand the effects of the processing parameters, specifically, the organosheet pre-heating temperature, holding pressure and clamp force on the yarn deformation, fibre orientation, void content and organosheet matrix displacement in carbon fibre – Polyphenylene Sulphide (CF-PPS) ribbed plates manufactured via injection overmoulding. The bonding of the ribs to the woven fabric organosheet is evaluated by rib pull-off tests using a custom-designed clamping fixture. The holding pressure profile and clamp force predominantly affect the yarn deformation, whilst the pre-heating temperature influences the bonding between the overmoulded ribs and the organosheet plate. The results also suggest that for pressed organosheets (with no overmoulded short-fibre material) the quantity of matrix material displaced from the organosheet increases with clamp force and pre-heating temperature.

1. Introduction

Thermoplastic composite overmoulding (TCO) is a combination of thermoforming and injection moulding technologies and has enabled the rapid manufacture of composite structures with combined continuous fibre and short fibre reinforcements. During part fabrication, a pre-consolidated continuous fibre reinforced laminate with thermoplastic matrix (organosheet) is pre-heated and subsequently thermoformed during closing of the mould platens, upon which a short fibre-reinforced material is injection overmoulded onto the warm laminate to form a fully bonded component. Upon complete filling of the mould cavity, the holding pressure is maintained until the gate freezes, to compensate for the material shrinkage. The holding pressure is considered to affect the quality of the interface between plastic-plastic bonds as well as the fibre orientation in injection moulded coupons [1, 2]. Overmoulded structures benefit from the excellent mechanical properties provided by the continuous fibre base as well as geometric complexity due to the short fibre-reinforced material architecture, which can serve as stiffening, impact absorbing and functional features [3, 4]. Further, such components can be manufactured with very low cycle times due to the fast processing of thermoplastics [5]. This novel hybrid design offers a promising approach for the manufacture of lightweight, high-strength solutions for automotive and aerospace applications that would otherwise be difficult to achieve with traditional processing techniques alone. The consolidation mechanics at the interface between the continuous fibre and short fibre materials are unique to overmoulded components since the regions of the organosheet that are pressed into the cavities experience a substantial level of deformation, a feature observed by Stegelmann et al. [6]. The processing parameters play an important role in the consolidation mechanics at the interface between the continuous fibre and short fibre materials [7]. Pre-heating stages, although not essential for generic overmoulding, facilitate macromolecular diffusion across the overmoulded interface and promote bond development due to the higher average temperature [8]. The clamp force is necessary to prevent separation of the mould platens during the injection stage, since the overmoulded material imparts a force that is proportional to the injection pressure.

In this study, the organosheet heating temperature, holding pressure profile and clamp force are varied to investigate their influence on the manufactured component quality and interface bond strength. The quality is characterised by the yarn deformation, void content, fibre orientation and organosheet matrix displacement through microscopy analysis, whilst the strength development is characterised by the rib-organosheet pull-off force from quasi-static tensile tests.

2. Methodology

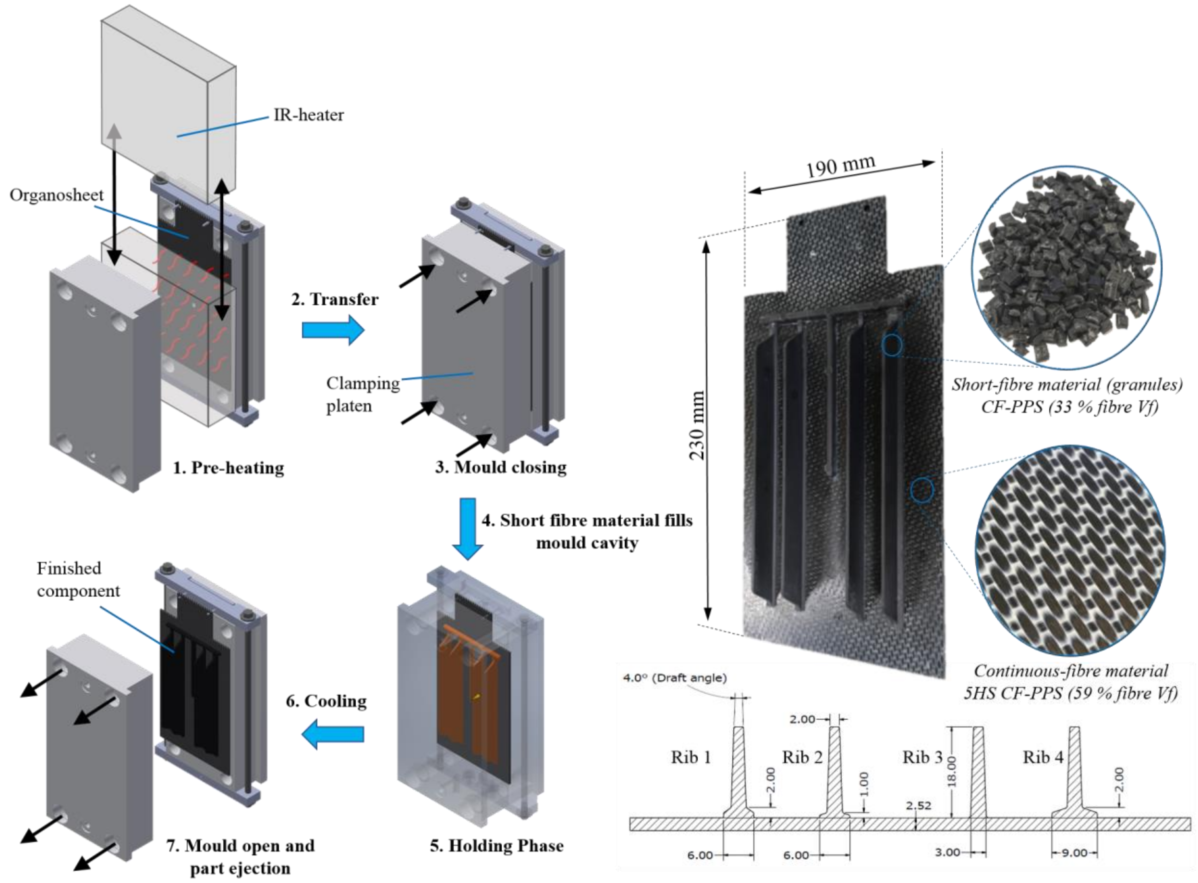
2.1. Manufacturing Setup

A typical injection moulding cycle consists of three key stages: filling, packing and cooling. In this study, an ARBURG 270C ALLROUNDER injection moulding machine was modified and used to overmould 33 % short-carbon fibre reinforced PPS ribs (*Luvocom® 1301-0824,* supplied by *Lehmann & Voss*) onto a 230 x 190 x 2.5 mm organosheet plate (*5HS Cetex® TC1100 CF-PPS,* supplied by *TenCate Advanced Composites*) at various processing conditions. For the pre-heating stage, the organosheet is placed on two guide pins in between the mould platens of the machine and heated using a KRELUS G14-25-2.5 MINI 7.5 IR-heater, thus softening the material to ensure adequate bonding between the plate and ribs. The target pre-heating temperatures are held for 60 seconds, after which the IR heater (mounted on a pneumatic arm) moves out of the machine and the mould platens close for the injection overmoulding stage to commence. After the short fibre material has filled the mould cavity, the holding pressure is applied to compensate for shrinkage. Three different holding pressure profiles were used for this study. The part is ejected and allowed to cool at room temperature. The cycle time from start of pre-heating to part ejection is approximately 140 seconds. The final ribbed plate component is shown in Figure 1(b) and the processing parameter values used in this study are highlighted in Table 1.

Table 1. Process parameter selection for component manufacturing.

Process Parameter	Parameter Value		
Target pre-heating temperature (°C)	-	350	370
Holding pressure profile ([MPa], [seconds])	Low: [52, 44, 32], [6.0, 3.5, 2.0]	Medium: [65, 55, 40], [6.0, 3.5, 2.0]	High: [78, 66, 48], [6.0, 3.5, 2.0]
Clamp force (kN)	-	400	500

In order to investigate solely the effects of the mould closing on the yarn deformation and matrix displacement, additional organosheet plates are heated and pressed using the same method described above, however, the short-fibre overmoulding stage is skipped. The parameters varied for this setup are the organosheet pre-heating temperature and clamp force.

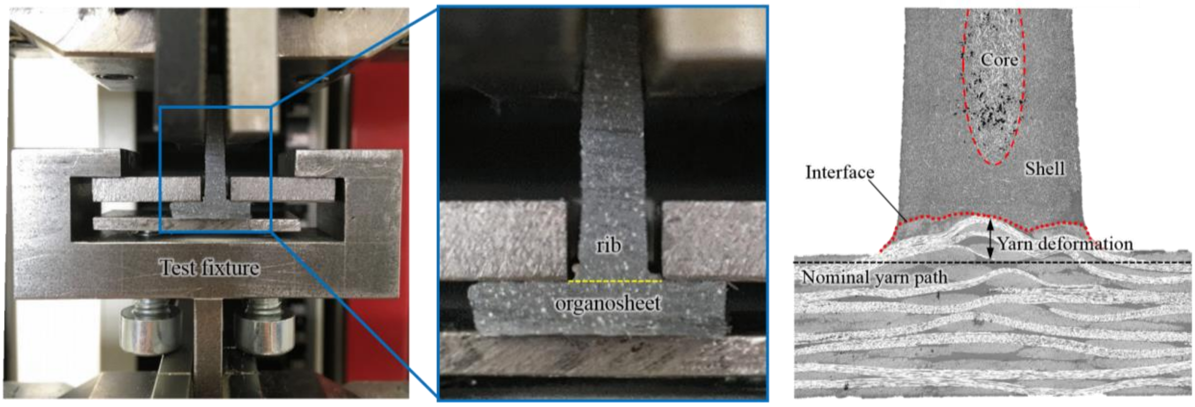


(a) (b)

Figure 1. Overmoulding setup at TU Dresden for ribbed plate manufacture (a) and ribbed plate component dimensions

2.2. Mechanical Testing and Microscopy of Overmoulded Components

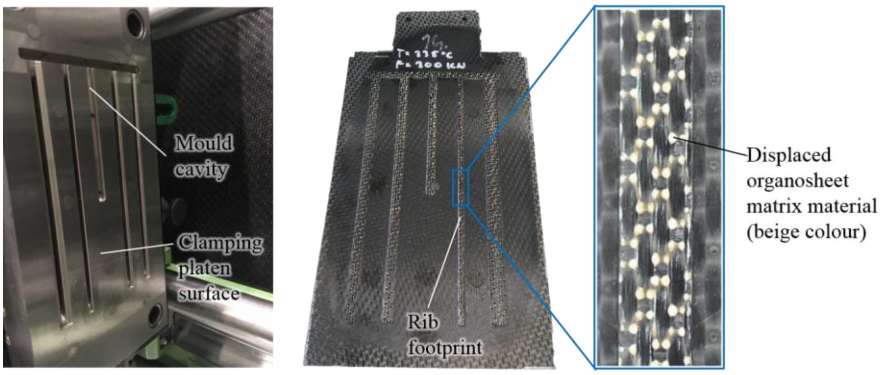
8 mm and 5 mm long specimens for the mechanical and microscopy tests respectively were cut from the mid-span of rib 3. The microscopy samples were mounted in VersoCit-2 acrylic resin, ground, polished and analysed using a Carl Zeiss Imager M2 Optical Microscope at 20x magnification. The mechanical specimens were sprayed with a light coat of white paint to aid in the analysis of the fracture behaviour.



(a) (b)

Figure 2. Mechanical specimen mounted in test fixture (a) with isolated interface. Optical micrograph showing key regions of overmoulded ribbed plate cross-section (b).

A custom fixture was designed and manufactured for the mechanical tests, ensuring that the organosheet remains fixed when the ribs are pulled, thus isolating the interface region (Figure 2a.) The samples were tested in a universal testing machine (Zwick 1445) at 2 mm/min. The bonding force was taken as the peak load, accounting for the actual length of each specimen. The average fibre orientation of the overmoulded ribs was calculated from micrograph cross sections, using a technique based on the method described by Advani et al. [9]. The void content in the ribs was calculated using an image thresholding technique based on the methods proposed by Santulli et al. [10]. The yarn deformation was taken as the measured distance between the nominal yarn path and the central midpoint of the deformed uppermost yarn in the layup as seen by the optical micrograph in Figure 2b. High resolution images (300 dpi, 13 pixels/mm) of the interface region were taken from the pressed plates as seen in Figure 3. Image analysis (thresholding) was used to quantify the amount of organosheet matrix displacement and a Nanofocus µscan laser profilometer is used to measure the yarn deformation.



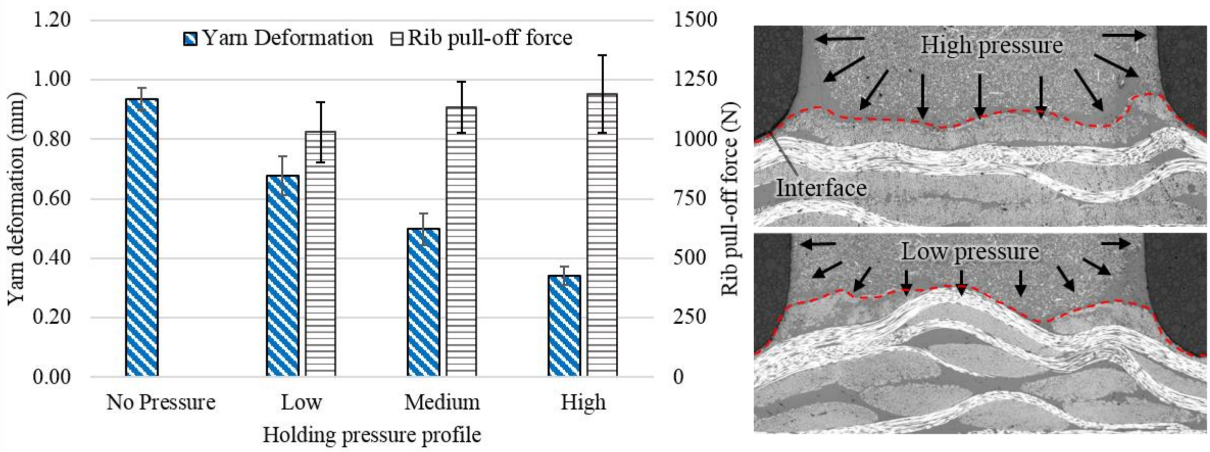
(a) (b)

Figure 3. Clamping platen used for manufacturing both ribbed and pressed plates (a). Photograph of rib footprint (b), showing matrix displacement onto surface of pressed plate.

3. Results and Discussion

3.1. Holding Pressure Profile

Figure 4 shows that increasing the holding pressure profile from the low through to the high setting reduces the yarn deformation by 50 %.



(a) (b)

Figure 4. (a) Yarn deformation and rib pull-off force at different holding pressure profiles for 370 °C pre-heating temperature and 400 kN clamp force settings. Error bars indicate standard deviations. (b) Optical micrographs of ribbed plate interfaces at high (top) and low (bottom) holding pressure settings.

Upon closing of the mould platens prior to injection stage, the organosheet surface begins to freeze immediately at areas in direct contact with the clamping platen surface whilst the regions exposed to the cavity see a much slower cooling rate and remain in a molten state. This causes the yarns to protrude into the rib cavities until the overmoulded material consolidates them via the holding pressure, forcing the yarns partially back to their original state, as can be seen in Figure 4b. A yarn deformation of 0.93 mm (first bar in Figure 4) is measured in the pressed samples and represents the maximum possible deformation due to the absence of the holding pressure.

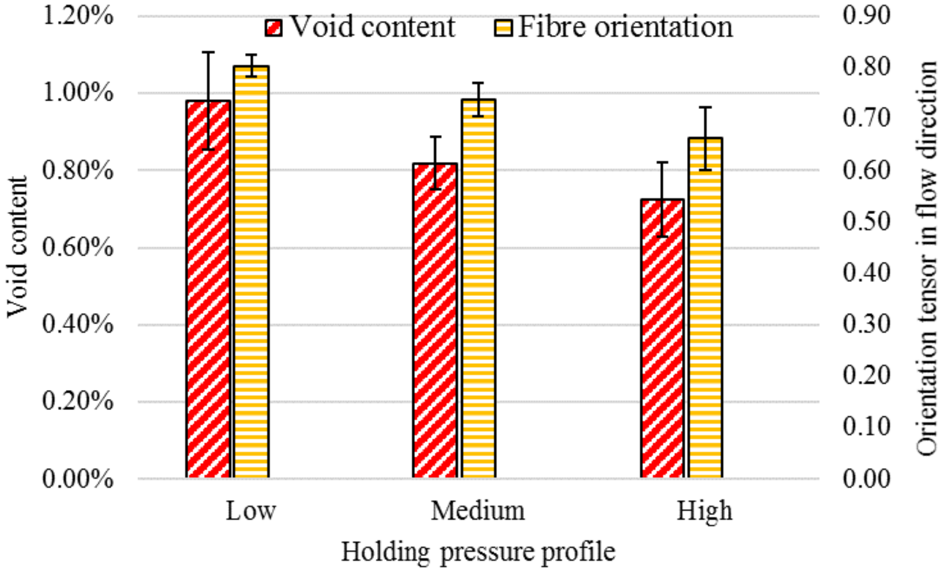


Figure 5. Void content and average fibre orientation at varying holding pressure profiles. 370 °C pre-heating temperature and 400 kN clamp force settings. Error bars indicate standard deviation.

Fibre alignment through the rib thickness is induced by differential solidification, shearing and flow patterns. The layered shell-core-shell structure, typical of injection moulded parts, is easily distinguished in Figure 2b. The core layer, containing predominantly random-oriented fibres, increases in size from the low holding pressure setting to the high setting by 11 %. The effects of this layered structure on the mechanical performances of SFRCs have been reported by Toll et al. [11] and constitute the main difficulty in transferring results of tests performed on specimens to real components. Both the fibre orientation and void content are seen to decrease by 26 % and 21 % respectively between the lowest and highest holding pressure profiles, as seen in Figure 5. Since the fibre orientation has a major influence on the final component's mechanical and physical properties, this effect should be accounted for in order to accurately predict the part warpage for example.

3.2. Organosheet Pre-heating Temperature and Clamp Force

Figure 6 shows an increase in the yarn deformation and rib pull-off force with organosheet heating temperature by 28 % and 27 % respectively. This observation is in agreement with previous studies conducted on thermoplastic-thermoplastic overmoulded samples [12] as the higher average temperature increases the rate of molecular diffusion across the interface. The mechanical test results suggest that very good levels of bonding are achieved during the manufacturing process, as there are no signs of a weld-line (indicating inadequate bonding) in the micrographs. Void emergence is most common in the core region, where the fibres experience higher levels of movement and where the temperature is hottest for longer due to the steady rate of cooling from the mould walls. The void content increases with increasing pre-heating temperature by 40 % from 0.59 ± 0.13 % to 0.82 ± 0.07 %, whereas the average fibre orientation in the flow direction remains unchanged in the ribs.

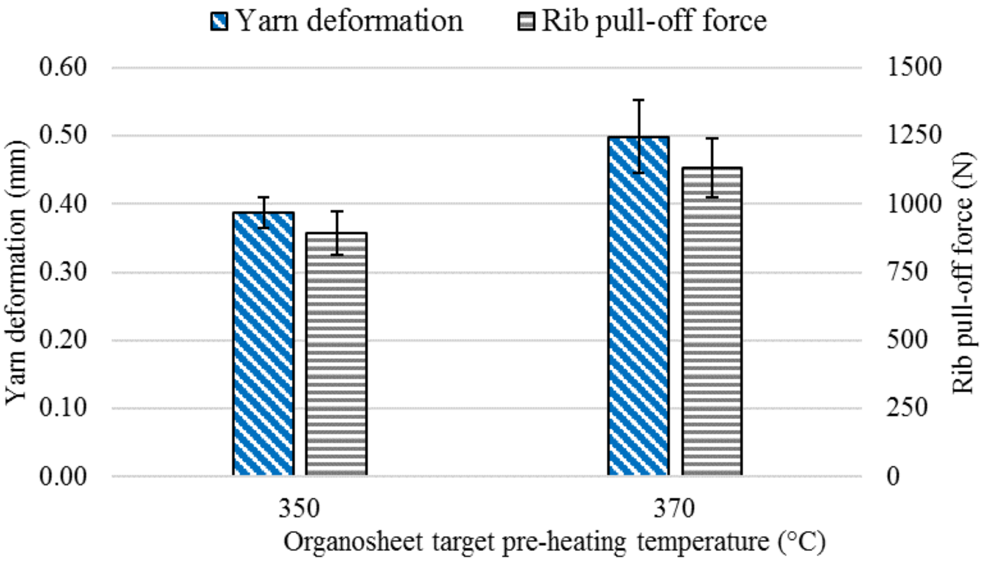


Figure 6. Yarn deformation and rib pull-off force at different pre-heating temperatures. Medium holding pressure and 400 kN clamp force settings. Error bars indicate standard deviations.

The measured yarn deformation in the pressed plates is increases by 29 % as the heating temperature is raised from 350 °C to 370 °C. An increasing clamp force from 400 kN to 500kN causes the the yarn deformation to rise from 0.50 mm to 0.76 mm. Image analysis of the pressed plates allows for quantification of the matrix displacement in terms of the pre-heating temperature and the clamp force, as shown in Figure 7. The results indicate that at higher tempeatures and clamp forces, more matrix material is forced out from the organosheet and onto the its surface.

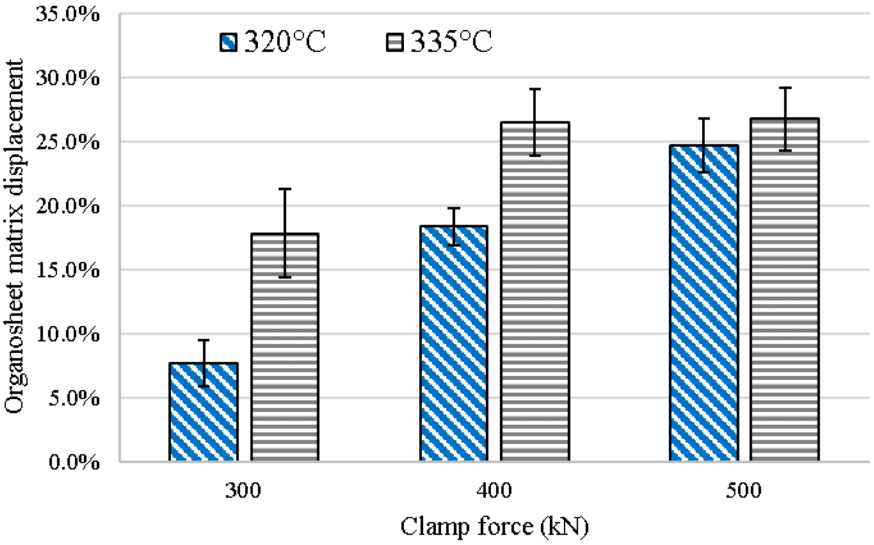


Figure 7. Organosheet matrix displacement onto surface at different pre-heating temperatures and clamp forces. Error bars indicate standard deviation.

This observation is also seen in specimen cross sections of the ribbed plates, obtained via a digital microscope, where the displaced matrix material (white region) protrudes into the rib structure, Figure 8d. This phenomenon is initiated during the closing of the mould platens as the clamp pressure forces the matrix to flow into the regions near the interface due to the lack of local compaction pressure (Figure 8a-c.)

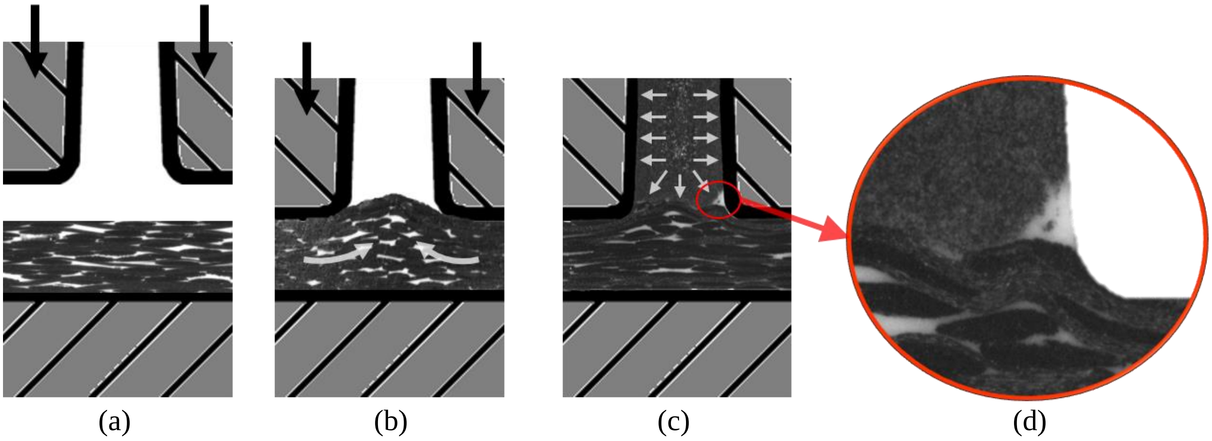


Figure 8. Organosheet with uniform matrix distribution prior to mould closing (a), intital deformation of organosheet during platen clamping (b), final deformation state of organosheet upon pressurisation from overmoulded material (c). Matrix displacement observed at rib edges (d).

The fracture behaviour varies between the components manufactured at different processing conditions. There are a greater percentage of samples (manufactured at low holding pressures) that display interface-dominant fracture behaviour. Samples tested from ribbed plates manufactured at high holding pressures, however, showed a greater percentage of rib-dominant fracture patterns. Further analysis on the fracture surfaces will need to be conducted in order to quanitify the influence of the processing conditions on the failure mode.

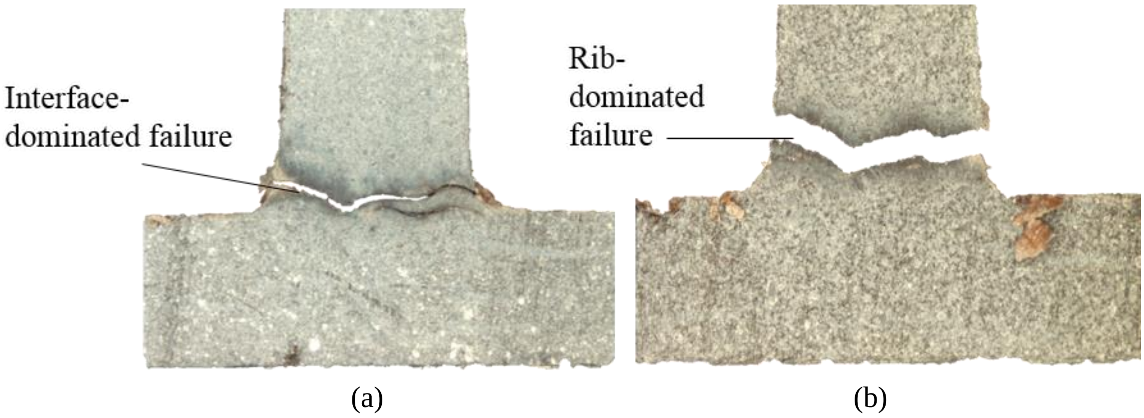


Figure 9. Fracture pattern in ribbed plate mechanical specimens at low holding pressure (a) and at high holding pressure (b).

4. Conclusions

In this study, the quality of manufactured ribbed plates is investigated by measuring the bonding force via quasi-static rib pull-off tests and analysing the process-induced features such as yarn deformation, matrix displacement and void content. It is shown through the analysis of specimen micrographs that the holding pressure is the most influencial factor in terms of affecting the degree of yarn deformation at the overmoulded interface. However, the bonding strength between the overmoulded rib and organosheet is primarily affected by the pre-heating temperature of the organosheet.

The findings show that very good bonding can be achieved between the organosheet and overmoulded ribs, evidenced from the cohesive failure of components manufactured at higher holding pressure settings as opposed to an interface-dominated failure, indicating a weaker bond. This variation in failure type does however imply that the modelling of such components in order to predict mechanical behaviour can become a complex task due to the myriad of process-induced features and parameter-dependent properties developing near the interface and throughout the overmoulded structure. The analysis of such features and properties provides an insight into the consolidation mechanisms taking place during overmoulding and can serve to aid in the design of future components. Future work should focus on characterisation of the injection stage through process simulations in order to capture the full temperature-pressure profiles. This will contribute to the development of the manufacturing knowledge and establishment of Thermoplastic Composite Overmoulded specific design guidelines for different material systems, mould geometries and processing parameters.

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