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Direct Forming of All-Polypropylene Composites Products from Fabrics made of Co-Extruded Tapes

B. Alcock · N. O. Cabrera · N. M. Barkoula · T. Peijs

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Abstract Many technologies presented in literature for the forming of self-reinforced or all-polymer composites are based on manufacturing processes involving thermoforming of pre-consolidated sheets. This paper describes novel direct forming routes to manufacture simple geometries of self-reinforced, all-polypropylene (all-PP) composites, by moulding fabrics of woven co-extruded polypropylene tapes directly into composite products, without the need for pre-consolidated sheet. High strength co-extruded PP tapes have potential processing advantages over mono-extruded fibres or tapes as they allow for a larger temperature processing window for consolidation. This enlarged temperature processing window makes direct forming routes feasible, without the need for an intermediate pre-consolidated sheet product. Thermoforming studies show that direct forming is an interesting alternative to stamping of pre-consolidated sheets, as it eliminates an expensive belt-pressing step which is normally needed for the manufacturing of semi-finished sheets products. Moreover, results from forming studies shows that only half the energy was required to directly form a simple dome geometry from a stack of fabrics compared to stamping the same shape from a pre-consolidated sheet.

Keywords Self reinforced composites · Thermoforming · Thermoplastic composites · Fabrics/textiles

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B. Alcock (✉) · N. O. Cabrera · N. M. Barkoula · T. Peijs
School of Engineering and Materials Science and Centre for Materials Research,
Queen Mary University of London, Mile End Road, E1 4NS London, UK
e-mail: b.alcock@gmail.com

N. O. Cabrera · T. Peijs
Eindhoven Polymer Laboratories, Eindhoven University of Technology,
P.O. Box 513, 5600 MB Eindhoven, The Netherlands

N. M. Barkoula
Materials Science and Engineering, University of Ioannina, P.O. Box 1186, 45 110 Ioannina, Greece

1 Introduction

The selection of a specific market area for the introduction of a new material depends on many parameters including: performance, risk, cost and volume [1]. Replacing an existing material by a new one implies both risks and opportunities for the designer of the new material. Furthermore, the cost of a new material is often as high as development costs, and production investments need to be reimbursed. As a result, applications in which the cost of the product is less sensitive to material or tooling costs are good candidate applications for the introduction of a new material. Low volume applications based on cheap tooling can be more suitable because they are often more labour intensive, whilst high volume applications are usually more sensitive to material costs and risks. These initial low volume applications can be used to show the potential of a new material.

In recent years, "self-reinforced" polymer composites have been proposed as an alternative to traditionally reinforced composites for a wide range of applications. Although the focus of this paper is on polypropylene (PP)-based composites, a range of processing routes are presented in literature based on different polymers including polyethylene [2–7], polypropylene [8–17], polyethylene terephthalate [18–20], polyethylene naphthalate [21], poly(methyl methacrylate) [22–25], polyamide [26] and liquid crystal polymers [27, 28]. The examples of forming routes described in this paper use polypropylene based composites, however the concepts presented here may also be readily adapted to many other polymers. Self-reinforced composites based on PP may have specific ecological advantages over composites based on glass or natural fibres reinforced PP, since many self reinforced composites are entirely thermoplastic and so can be melted down at the end of the product life without the need for separate fibre recovery. Upon thermal recycling, a PP blend is obtained which can be reused to make PP composites again, or alternatively, can be used for other PP-based applications. Two main routes have been proposed so far for the manufacturing of such self-reinforced composites. The first was the 'hot-compaction' process which was developed at the University of Leeds, UK, as a route to produce self-reinforced polymers [29]. This hot-compaction method is a highly innovative processing route for thermoplastic composites as it selectively melts the surface of (mono-component) polymer fibres and welds them together to form a composite of retained fibres embedded in a melted and recrystallised matrix. Because there is no need for impregnation of additional matrix polymer, since all the matrix material originates from the melted surfaces of the reinforcing fibres, this process therefore eliminates one of the key problems in traditional thermoplastic composite manufacturing. A disadvantage of the process is the rather small temperature window in which the hot-compaction process operates [30]. For this reason one processing route for hot-compacted self-reinforced polymer composites commonly involves first forming laminates in a hot-press or double-belt press, at a well controlled temperature, to give an intermediate sheet product, and subsequently thermoforming of these sheets at a temperature below the compaction temperature into the final form. More recently, the small temperature processing window associated with these hot compacted composites has been expanded through the combination of monoextruded fibres or tapes stacked with films [31]. These films provide extra matrix material between the reinforcing fibres which is expected to ease processing with only a small decrease in mechanical properties due to the slightly reduced volume fraction of reinforcement. Because a double belt-press implies a high investment, stamping of all-PP sheets cannot be easily adapted to low volume applications. There is therefore an interest to develop other processing routes that avoid the use of pre-consolidated sheet material.

An alternative technology route was proposed by a research team from Queen Mary University of London (UK), Eindhoven University of Technology and Lankhorst Indutech

BV (The Netherlands) [32–44], to allow production of an all-polypropylene (all-PP) composite with a very much larger temperature processing window. This large processing window not only simplifies part manufacture but also allows direct forming of parts without the need for an intermediate sheet product. This technology is based on the use of co-extruded (bi-component) polypropylene tapes. The developed tapes consist of a homopolymer PP core coextruded with thin PP copolymer skins of a lower melting temperature than the core material. Solid state drawing of the tapes leads to a high degree of molecular orientation of the homopolymer core, which results in high-strength/high-modulus tapes. The thin copolymer skins act as an adhesive layer to bond the highly oriented tapes together when heat and pressure are applied, while providing a large processing temperature window (typically 20–30°C) for the creation of all-PP composites products [36]. The type of PP copolymer coextruded as the skin layer of the tapes determines the lower limit of this processing window (the melting temperature of the copolymer) while the upper limit of the processing window is determined by the melting temperature of the highly oriented PP homopolymer core (the molecular relaxation temperature of the homopolymer).

Temperature and pressure are the main process parameters involved in the consolidation of these all-PP composites. As compaction temperature is increased, the oriented molecules can more easily relax, resulting in a loss of molecular orientation (shrinkage) and hence reduction of the mechanical properties of the all-PP composite [32]. Lateral constraining during the compaction process helps to prevents this relaxation [36, 45] and minimises the shrinkage. Conversely, if excessive pressures are applied, squeeze flow of the molten copolymer component of the tapes may lead to a distorted fabric microstructure. In practice, the manufacturing equipment used limits the maximum applicable pressure. The acceptable temperature and pressure ranges in which all-PP composite laminates can be successfully compacted can be schematically represented to occur within a temperature-pressure processing window shown in Fig. 1 [36].

It has been shown previously that all-PP composites can be successfully consolidated in processing temperatures between 130 and 170°C [35] and pressures between 0.1 and

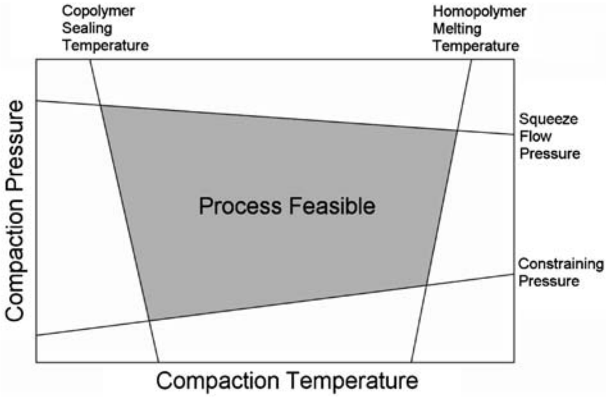

Fig. 1 Schematic illustration of the process feasibility window for the compaction of the all-PP composites based on co-extruded tapes, as described in this paper. The processing temperature window is limited at the lower extreme by the copolymer sealing behaviour and at the upper extreme by the relaxation of the oriented molecules in the core of the tape. The processing pressure window is limited at the lower extreme by the minimum pressure required to constrain and consolidate the part and at the upper extreme by the squeeze flow pressure

12 MPa [36]. In addition to creating a large processing window, one of the other main innovations is that reinforcement manufacturing and matrix impregnation are achieved in a single step, while the reinforcement to matrix ratio is extremely high (~90%); this is considerably higher than traditional glass fibre reinforced composites. If based on bi-directional woven fabrics these all-PP composites can possess Young's moduli of 5–6 GPa and tensile strengths of 180–200 MPa which makes them an interesting alternative to replace traditional engineering composites, such as natural- or glass fibre reinforced PP [46–50] in a wide range of applications, notably those requiring high impact resistance [41].

Crucially, because of the large temperature processing window, the all-PP composites based on co-extruded tapes presented here can be potentially manufactured directly from fabric or tape by filament winding [40], direct stamping or vacuum bag or autoclave moulding from stacked fabric plies. Direct stamping and vacuum bag moulding are presented in this paper. Forming composites directly by filament winding tapes has been used to produce unidirectional laminates for mechanical characterisation [34] and also to investigate a range of all-PP cylindrical pipes and pressure vessels [40]. Vacuum bagging processes are traditional low investment composite processes that can be used for both thermoplastic and thermoset matrix composites [51–55]. During vacuum bagging processes to consolidate all-PP composites, the primary function of the vacuum pressure is not so much a forming force but a compaction pressure. This process is isothermal as both the mould and the part are heated and cooled at the same time. Because the mould is typically single sided, inexpensive and is not limited in size, this process is particularly well suited for small production numbers of large volume parts (e.g. boat hulls) and prototyping. These vacuum bagging processes are limited to atmospheric pressure (~0.1 MPa) to effect composite consolidation.

Stamping directly from woven all-PP fabric is a process similar to the all-PP sheet stamping process described earlier [44], but is distinct from previous studies because in the direct forming route described in this paper, no intermediate sheet production step is required [56]. Direct forming processes such as stamping from fabric or vacuum bagging are only feasible if it is possible to consolidate composites with a sufficiently large processing window. This route is viable in the case of the all-PP composites presented here, because of the use of co-extruded tapes. These low cost processing routes give all-PP composites based on co-extruded tapes clear advantages over other self-reinforced polymer systems.

2 Materials

All-PP products were manufactured from plain weave fabrics woven from co-extruded tapes, made at Lankhorst Indutech BV (now Lankhorst Pure Composites BV), The Netherlands. These tapes consist of a PP homopolymer (T_m=160°C) which represents 90% *v*/*v* while the two skin layers, each representing 5% *v*/*v*, are based on a PP copolymer (T_m=135°C). The total draw ratio, λ, of the tape is 17 and has a total thickness of 80 μm, a width of 2.2 mm, a Young's modulus of 15 GPa and tensile strength of 500 MPa. The low density of the tape (0.72 g cm^{-3}) is due to the formation of defect regions, probably voids, in the core layer of the tape due to the high draw ratio [34, 57]. The tapes, which are currently marketed by Lankhorst under the name of Pure®, were woven into plain weave fabrics by BW Industrial (The Netherlands) and had a nominal weight of 105 g/m^2.

3 Manufacturing Routes and Methods

3.1 Vacuum Bagging Directly from Fabrics

It has previously been shown possible to consolidate flat all-PP laminates by using a vacuum bagging technique at temperatures between 130°C and 160°C [36, 41]. In this paper, this vacuum bagging concept will be extended to demonstrate the feasibility of consolidating all-PP fabrics directly into simple geometries, without the need for an intermediate laminate product. This is achieved by cold draping all-PP fabrics over a moulding tool, enclosing the tool and fabric in a vacuum bag and effecting consolidation by applying temperature in a hot oven while simultaneously applying negative pressure to the inside of the vacuum bag. The application of negative pressure to the inside of the bag results in atmospheric pressure forming and consolidating the part.

Figure 2 illustrates the stages of the vacuum bagging process to form a simple geometry. The all-PP fabric is placed over a mould, and covered by an aluminium foil (Fig. 2a). The aluminium foil is covered in a bleeder cloth to ease subsequent evacuation of air. The mould is then sealed in a standard nylon vacuum bag (Fig. 2b), containing an appropriate vacuum valve and vacuum pressure gauge. The whole assembly is then transferred to an oven, where the vacuum bag is connected to a vacuum pump line (Fig. 2c). The vacuum bag is evacuated, resulting in a 0.1 MPa atmospheric pressure being applied to the stacked all-PP fabric plies. Once pressure is achieved, the oven can be heated to the desired consolidation temperature. After heating for the required time (typically 20 min, depending on part thickness), the vacuum bag, containing the mould, is removed from the oven (while vacuum is maintained) and cooled, before opening the vacuum bag and removing the consolidated all-PP part.

3.2 Direct Stamping from Stacked Fabric Plies

A laboratory stamping press has been specifically designed to produce simple all-PP geometries, and has been presented previously in work, by the same authors, investigating the stamping behaviour of all-PP composite laminates compared to glass reinforced PP laminates [44]. The stamping press used to produce the hemispherical domes is shown in Figs. 3 and 4, and for completeness, shall be briefly described here. A hydraulic pump (ENERPAC GPER-5000) powering a precision double acting 80 kN ENERPAC cylinder controls the movement of the upper component of a matched stamping tool. Thus, by extending the cylinder, the stamping tool closes and simple geometries can be formed by deforming laminates or consolidating preheated, stacked plies of all-PP fabric. With this pump, the cylinder can move at either of two discrete speeds: 7.5 m/min at a load of up to 6 kN, or 1.3 m/min at loads between 6 and 80 kN. A displacement transducer was attached to the press to measure the position of the punch and a pressure transducer was used to measure the pressure of the hydraulic system. This allowed for the derivation of the force developed by the cylinder.

In the direct stamping process, a stack of all-PP fabric plies is heated and shaped non-isothermally. A hemispherical geometry was chosen for the matched metal die mould. The cavity of the matched tooling component had an inner diameter of 60 mm, and was used in combination with a 56 mm diameter hemispherical punch. The mould was preheated to 40°C. Nine layers of all-PP fabric were clamped between upper and lower steel rings (100 mm inner diameter and 140 mm outside diameter) so that the shrinkage in the fabric plane is physically reduced during preheating. The stack of unconsolidated all-PP fabric

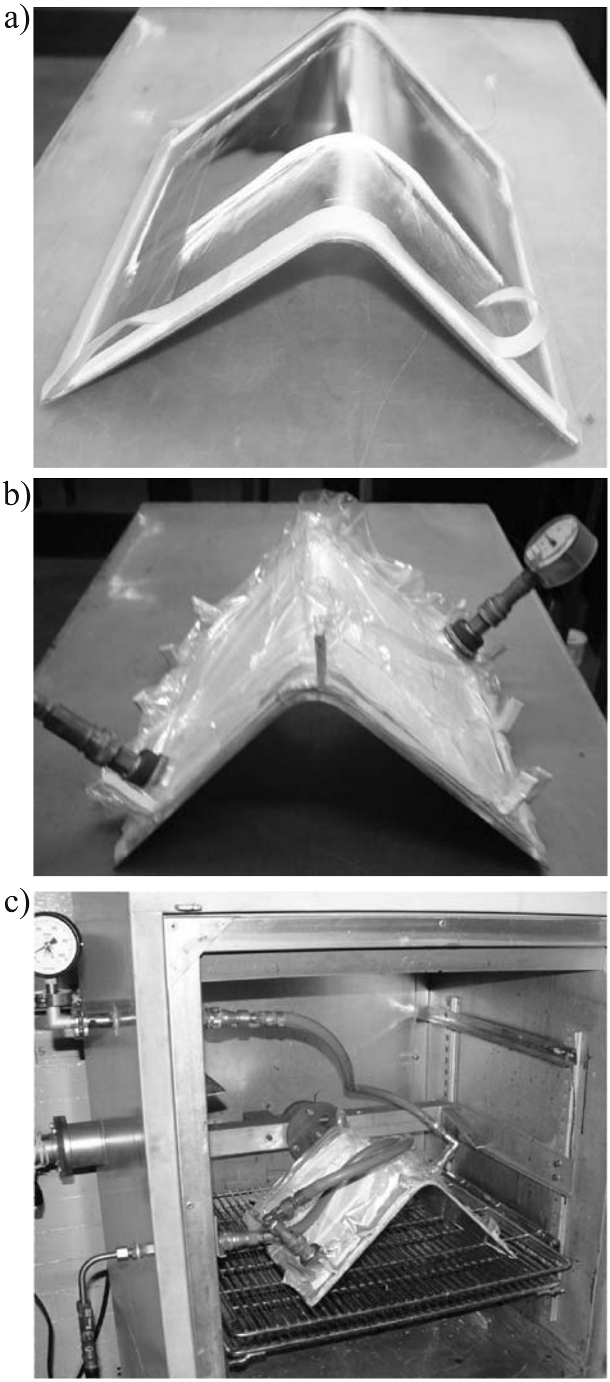

Fig. 2 The different steps of the isothermal vacuum bagging process. **a** All-PP fabric plies are laid over the mould, **b** the fabric plies are sealed in a vacuum bag (nylon film and sealing tape) and **c** the sealed vacuum bag is connected to vacuum line, and placed in an oven for the heating and cooling (consolidation) cycle

Fig. 3 Photograph of the non-isothermal hydraulic stamping press used to produce hemispherical all-PP domes. The preheating oven is shown on the right hand side of the photograph, while the stamping press is shown on the left. Figure 4 shows a more detailed photograph of the matched metal mould used to form the all-PP domes

was only partially clamped with four screws placed at 45° to the tape directions in the fabric, passing through the fabric plies, and tightened with a torque of 2 N m). In addition, lateral clamping of the fabric stacks in this way facilitates handling. Prior to stamping, the clamped stack of all-PP fabric plies was preheated in a convection oven to a temperature of 150°C. Figure 5 shows a stamped dome formed in this way from stacked fabric plies. Perpendicular lines have been drawn on the surface of the dome to illustrate the deformation of the fabric surface. When stamping from a pre-consolidated plate, as presented earlier [44], pressure is required to deform the plate and close the mould. When stamping directly from stacked fabric plies, only a very low pressure is needed to deform the fabric, but additional pressure is needed at the end of the mould closure to obtain a

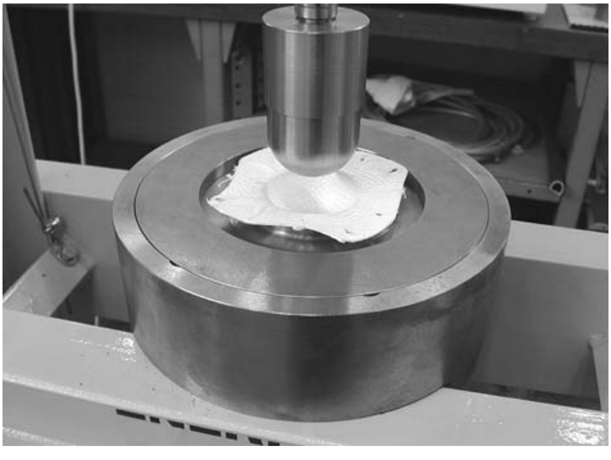

Fig. 4 Photograph of the matched metal mould used to produce hemispherical all-PP domes. The male (moving) component of the mould is shown in a raised position, while the female (fixed component) is shown containing a formed all-PP dome

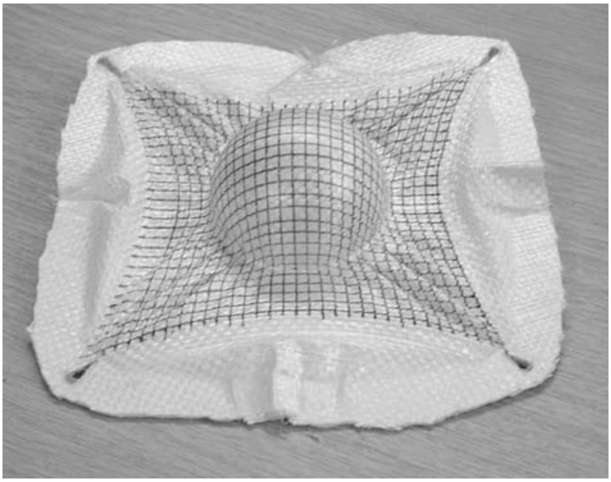

Fig. 5 Photograph of a stamped all-PP dome, with lines drawn on the surface ply at 4 mm intervals to illustrate the deformation of the surface. Clearly visible are the four screw holes located at each corner of the fabric to constrain the stacked fabric plies during preheating

well consolidated part. Therefore, three different levels of stamping force were investigated: 11 kN, 45 kN, 67 kN, which correspond to an average pressure over the dome surface of approximately 2 MPa, 8 MPa and 12 MPa, respectively. The temperature of the preheated stack of fabric plies, the punch force (from the hydraulic oil pressure) and the displacement of the punch were recorded by an independent data acquisition system (Spider8, HBM).

As a reference to compare stamping behaviour, pre-consolidated all-PP composite laminates were pressed first into laminates from nine layers of fabrics in a continuous double belt press at 155°C under a pressure of 2.5 MPa at the Institut für Verbundwerkstoffe GmbH (Kaiserslautern, Germany) into 1.3 mm thick all-PP sheets. These were subsequently used to investigate the differences in structure between domes formed from stamped all-PP preformed laminates, and domes formed directly by stamping stacked fabric plies. To obtain microscopy images, the all-PP composites were cooled to sub-ambient temperatures using liquid nitrogen and cut using a Leica RM2165 microtome equipped with a glass knife. The microscopy images were captured using a Zeiss Stemi SV11 stereomicroscope equipped with a high resolution, digital camera.

4 Results and Discussion

4.1 Vacuum Bagging Directly from Fabric

The simplicity of vacuum bagging as a direct route to manufacture simple geometries from stacks of all-PP fabric plies means that many geometries can be investigated without significant investment. Vacuum bagging is limited in this paper to using atmospheric pressure to consolidate and shape the plies of fabric. The use of an autoclave to apply an elevated pressure to the outside of the vacuum bag may allow the application of pressure above atmospheric pressure, but this is outside the scope of this paper. The creation of hollow, vacuum bag consolidated all-PP structures also appears feasible based on routes presented elsewhere in literature for glass reinforced PP composites [54], although this too is outside the scope of this paper. Two example geometries which have been formed by vacuum bagging are shown in Fig. 6; the moulds used in this case are simple sheet steel forms, emphasizing the nature of vacuum bagging as a low investment processing route.

The mechanical properties of composite laminates consolidated by a vacuum bagging approach at a range of temperatures have been characterised previously, and are also presented here in Table 1 for completeness [36]. It is clear that the precursor tapes have a lower density than bulk polypropylene (~0.91 g cm^{-3}) due to micro-voiding within the tape (intra-tape voiding) during the uniaxial tape drawing process [32]. Following consolidation of all-PP laminates by vacuum forming, the density of the laminates is even lower than the precursor tapes, indicating that the pressure used to consolidate composites in this way can be insufficient to close all the voids between fabric plies within the laminate. Figure 7 shows representative cross sections of all-PP composite laminates consolidated either in by vacuum bagging or by hot pressing, at either 140°C or 160°C. Although all of the tapes which make up the woven fabric plies are identical, the microtoming action used to create these cross-section images, results in the tapes which are oriented normal to the plane of the page having a dark appearance, while the tapes which are oriented parallel to the page have a lighter appearance. Interply voids are clearly visible in the vacuum bagged all-PP composite laminates, as indicated by white arrows in Figs. 7a and 7b, showing all-PP composite laminates consolidated at 140°C and 160°C respectively. The presence of these interply voids will contribute to the low densities for these specimens presented in Table 1. The overall densities of the direct formed all-PP composite laminates can be estimated by comparing the densities of the consolidated plates, as presented in Table 1, with the density of the precursor tapes. Assuming that the intra-tape voids are not closed at these pressures and temperatures, it can be estimated that the all-PP laminates consolidated by vacuum bagging have a void content of 13% (when consolidated at 0.1 MPa pressure and 140°C) and 7% (when consolidated at 0.1 MPa and 160°C). This degree of porosity is greater than reported elsewhere for glass fibre reinforced polypropylene composites [55, 56, 58, 59]. The thermal stability of glass fibres means that glass fibre reinforced polypropylenes can be consolidated at higher temperatures allowing greater matrix flow and so lower void content in the final parts. It is conceivable that the presence of such voids in all-PP composites may create problems when the composite laminates are exposed to environmental fluids. However, it has been shown that the environmental properties of these all-PP composite are not significantly affected by these high void contents [60].

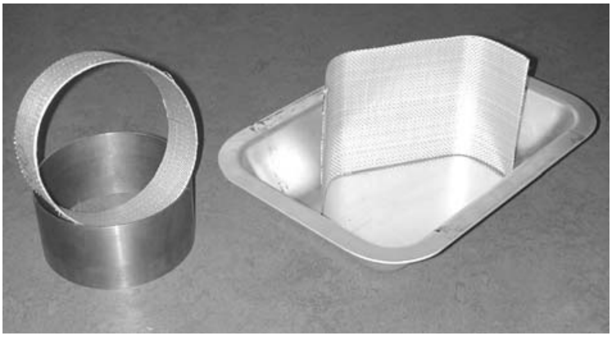

Fig. 6 Photograph of two all-PP geometries formed by vacuum bagging stacked fabric plies in sheet steel moulds. The simple nature of the moulds used to forms these parts further emphasises the low investment nature of vacuum bagging as a processing route for all-PP composites

Table 1 The tensile mechanical properties of all-PP laminates consolidated by vacuum bagging stacked plies of woven tapes, compared to the mechanical properties of all-PP precursor tapes, and all-PP laminates consolidated at higher pressures by hot pressing

	All-PP precursor tape	All-PP woven tape composite laminate (consolidated by vacuum bagging)		All-PP woven tape composite laminate (consolidated by hot pressing)	
Consolidation temperature [°C]	–	140	160	140	160
Consolidation pressure [MPa]	–	0.1	0.1	12.4	12.4
Density [g cm^{-3}]	0.732	0.638	0.679	0.838	0.861
E_{11} [GPa]	15	3.73	3.96	7.00	7.43
E_{11}/ρ [GPa g^{-1} cm^{3}]	20.5	5.85	5.82	8.35	8.63
σ_{11} [MPa]	450	129	130	229	232
σ_{11}/ρ [MPa g^{-1} cm^{3}]	615	202	191	273	269

Presented here are tensile modulus, E_{11}, and tensile strength, $\sigma_{11,}$ and also specific tensile modulus, E_{11}/ρ, and specific tensile strength, σ_{11}/ρ, normalised for density [36]

Table 1 further describes that following consolidation of all-PP composites at much higher pressures in a hot press, the density of the final laminates can be even greater than that of the precursor tapes, suggesting that in addition to the closure of interply voiding, intra-tape voiding may also be reduced at these much higher pressures. Table 1 also lists the mechanical properties of the all-PP plates consolidated by vacuum bag moulding at a temperature of 140°C and 160°C. Young's modulus and tensile strength of fabric based laminates consolidated at these temperatures are fairly similar, especially if their specific properties are considered. In fact, the relatively high void content in vacuum bagged materials can partly compensate for the loss in properties compared to laminates consolidated at a much higher pressure. The effect of processing parameters on the mechanical properties of all-PP composites has been described in great detail previously [34, 36]. During consolidation, there is a processing parameter window, as shown in Fig. 1, in which pressure is required to consolidate the all-PP composites from stacked fabric plies into a thermally bonded composite structure. During the heating required to achieve this consolidation, there is a risk of molecular relaxation of the highly oriented PP tapes. The lower specific moduli of specimens consolidated by vacuum bagging, as shown in Table 1, indicate that vacuum bagging may allow some molecular relaxation of the tapes, due to the consolidation pressure of 0.1 MPa being insufficient to fully laterally constrain the fabrics. The possible relaxation of tapes in vacuum bagged all-PP composites, in addition to the closure of intraply voiding and so greater density of all-PP composites consolidated by hot pressing, may account for the lower specific modulus seen in all-PP composites that have been processed via a vacuum bagging method, compared to those consolidated by a hot pressing method.

Fig. 7 Photograph of cross sections of all-PP composite laminates consolidated by vacuum bagging at **a** 140°C, 0.1 MPa and **b** 160°C, 0.1 MPa, and by hot pressing at **c** 140°C, 12.4 MPa and **d** 160°C, 12.4 MPa. *White arrows* in image (**a**) and (**b**) indicate the presence of interply voiding in the plates consolidated by vacuum bagging. Images (**c**) and (**d**) illustrate the greater compaction of the plies achieved by consolidating at higher pressures

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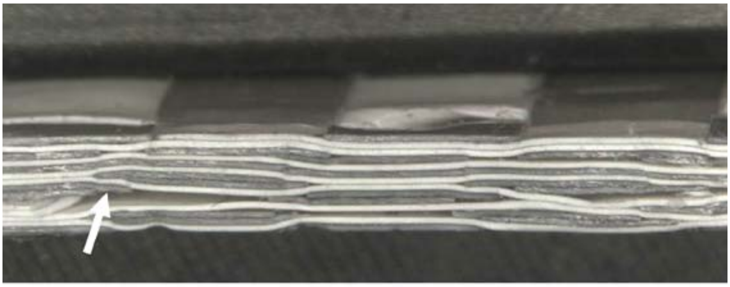
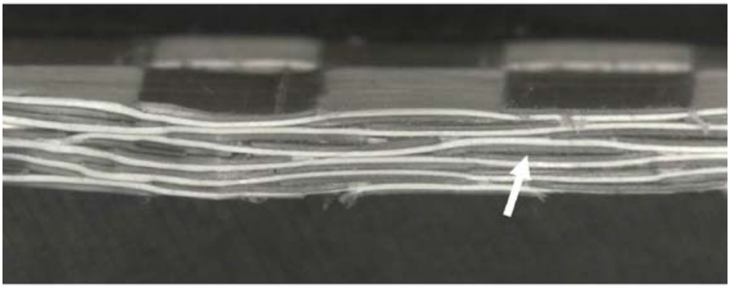
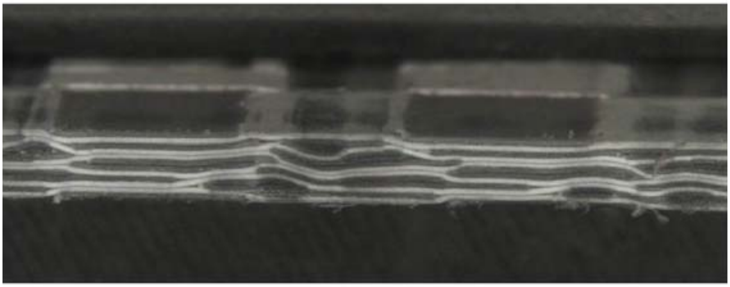


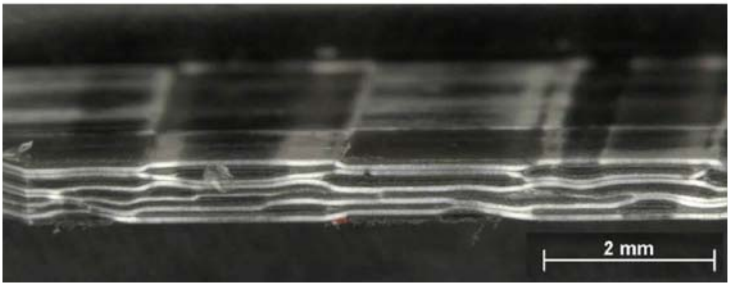
a) All-PP Woven Tape Composite Laminate
(Consolidated by Vacuum Bagging at 140°C)



b) All-PP Woven Tape Composite Laminate
(Consolidated by Vacuum Bagging at 160°C)



c) All-PP Woven Tape Composite Laminate
(Consolidated by Hot Pressing at 140°C)



d) All-PP Woven Tape Composite Laminate
(Consolidated by Hot Pressing at 160°C)

4.2 Direct Stamping from Fabric

4.2.1 Stamping Force and Stamping Energy of Fabric Stamping Versus Pre-Consolidated Sheet

Stamping directly from a non-consolidated stack of all-PP fabric plies differs significantly from the thermoforming process commonly used to form composite laminates by the fact that the hot-pressing or double-belt pressing stage for the manufacturing of a semi-finished sheet is avoided [33]. The driving force to bypass the pre-consolidation stage is economics, as the high investments involved with double-belt pressing increases the total manufacturing cost of the part. To investigate the different forces required to form a pre-consolidated all-PP laminate and a stack of all-PP fabric plies, all-PP composite hemispheres were stamped from either stacked layers of fabric or belt-pressed pre-consolidated plates. During the forming operation, the punch forces were recorded and are plotted against the punch position in Fig. 8. The stamping conditions and the total number of fabric layers (nine layers) were identical for both cases.

The punch position is described at 0 mm when it touches the all-PP fabric or laminate, while it is measured to be at 31 mm when the mould is closed. The stamping energy to close the mould is defined as the area under the curves shown in Fig. 8. The energy required to stamp the dome from the stacked all-PP fabric plies is 37 J, which is only half of the energy required to stamp the same part from the pre-consolidated all-PP laminate (75 J), which was previously shown to be again approximately half that required to form the same dome from a glass fibre reinforced PP laminate (143 J) [44]. Figure 8 shows that a significantly lower force is necessary during closure of the mould when forming a dome from unconsolidated stacked fabric plies compared to when forming a dome from a pre-consolidated all-PP laminate, although the same force is ultimately reached when the mould is completely closed. The reason for this lower force initially is that high bending stresses are generated during deformation of the pre-consolidated all-PP laminates while the non-consolidated fabric plies can be shaped simply by inter-ply shearing. In the case of direct

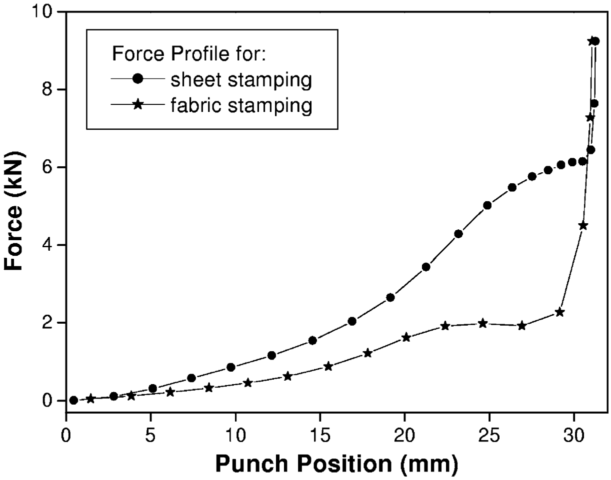


Fig. 8 Influence of pre-consolidation on the stamping force profile of a 60 mm diameter hemisphere from a pre-consolidated all-PP laminate (“sheet stamping”) or a stack of all-PP fabric plies (“fabric stamping”). The punch position is 0 mm when it reaches the all-PP material and 31 mm when the mould is closed

forming all-PP stacked fabric plies, the pressure increases rapidly at 2 mm before the mould is closed which corresponds to the pressure required to compact and consolidate the layers [44].

In a typical non-isothermal thermoplastic composite forming process, it is important to close the mould before the matrix solidifies. The stamping press used in this study and typical industrial hydraulic presses both have a two-stage pressure build-up, in which the press closing speed switches to a lower rate above a certain pressure threshold. The high/low speed ratio is usually approximately 5–10. The stamping press used in this study closes at a speed of 7.5 m/min up to 6 kN stamping force while the speed is reduced to 1.3 m/min to apply the maximum stamping force. Although direct forming of stacked all-PP fabric plies requires a higher pressure for the full consolidation of the part, the mould could be closed quicker if the press were to operate for the entire closing process at the higher speed since higher pressures are only reached at the end of the mould closure. In principle, this could increase the speed of the forming process.

4.2.2 Influence of Compaction Pressure on Fabric Stamped Hemispheres

In order to investigate the degree of consolidation of the all-PP domes stamped directly from fabric, domes were formed using three different average pressures over the hemisphere surface: 2 MPa, 8 MPa and 12 MPa. The greatest of these is a similarly high consolidation pressure as used for the hot-compaction of the flat laminates listed in Table 1. Sections for stereomicroscopy observation were studied parallel to meridians of the hemisphere, as shown in Fig. 9. Section 1 goes through the pole of the dome parallel to one of the tape direction while Section 2, oriented at 45° to the initial tape directions, is cut in the region where shear deformation is greatest. The pressure over the hemisphere is not uniform during forming and it is locally higher where the surface is perpendicular to the punch displacement direction such as the pole of the hemisphere (Section 1, Fig. 9). Good compaction is achieved in this region and no large voids are observed even at the lowest forming pressure, as shown in Fig. 10. However, the thickness of the section decreases

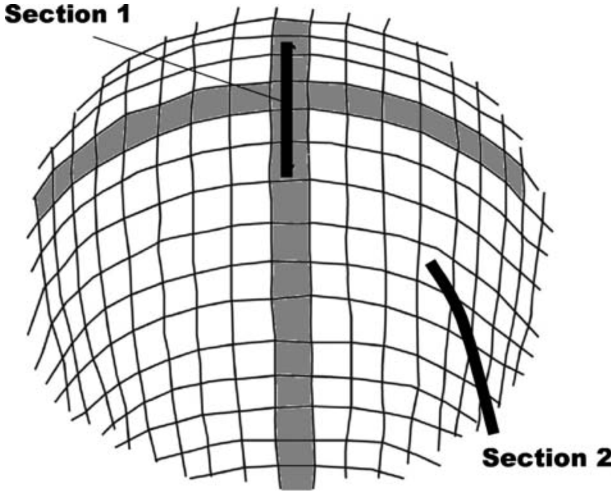
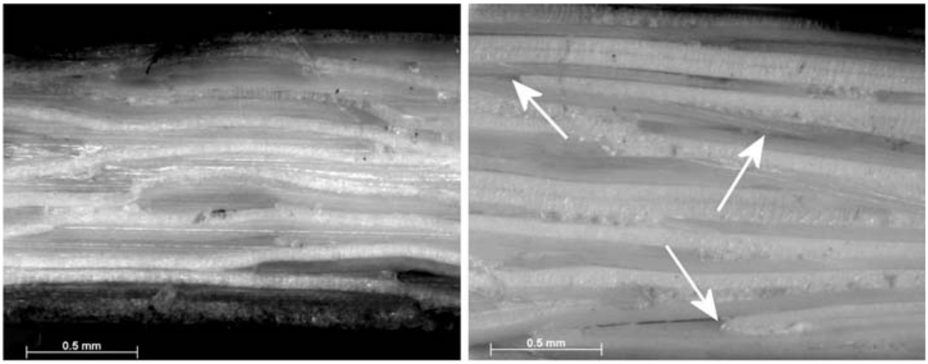
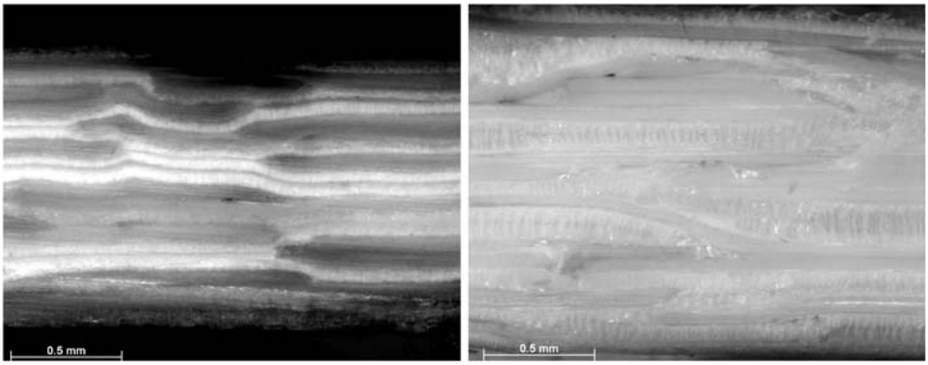


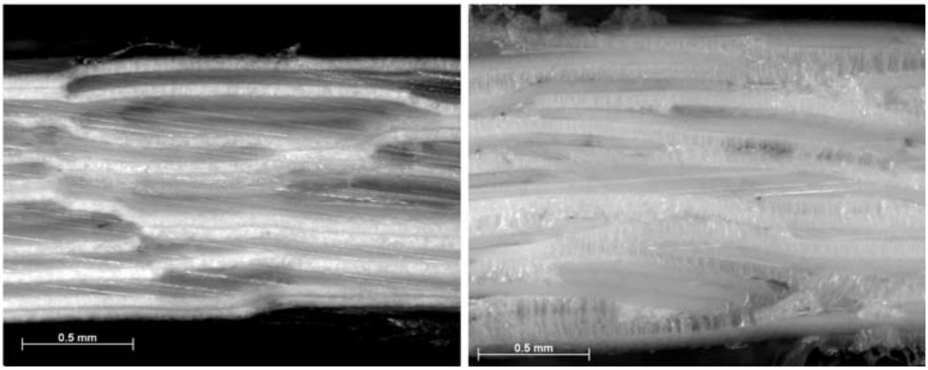
Fig. 9 Position of the hemisphere sections for the capture of optical microscopy images as indicated by *thick black lines* on the diagram of the dome surface. Section 1 is cut through the pole of dome, parallel to one tape axis in the fabric, while Section 2 is cut between the tape axes in the region where shear deformation is greatest



Section 1, 2MPa Section 2, 2MPa



Section 1, 8MPa Section 2, 8MPa



Section 1, 12MPa Section 2, 12MPa

Fig. 10 Cross-sections of hemispheres for three forming pressures (2, 8, 12 MPa). Note the lower thickness of Section 1 compared to Section 2, and the decrease in thickness with increasing forming pressure. Locations of Sections 1 and 2 are defined in Fig. 9 and in each image, the *upper side* of the image is the outer surface of the dome. *White arrows* indicate the presence of voids in specimens formed at lower forming pressures

slightly as pressure is increased. As shown in Fig. 9, Section 2 corresponds to an area of highest shear deformation in the dome surface. The overall dome thickness in Section 2 is substantially greater than in Section 1, although no voiding can be observed in the specimen formed at 12 MPa pressure. The reason for the increase in thickness in this area is the intraply shear of textile fabrics [44]. In Section 1, the thickness decreases as the pressure increases but there is no difference in thickness between 8 MPa and 12 MPa forming pressure. Overall, the consolidation quality of the hemispheres is comparable to that of isothermally pressed all-PP sheets at similar pressures demonstrating that direct forming of stacked plies of all-PP fabric should be considered a viable processing route [36].

5 Conclusion

The potential of forming simple geometries directly from a fabric of co-extruded all-PP tapes has been investigated. It is important to note that these processes are feasible due to the large temperature processing window possible with this technology. This large temperature processing window is the result of the co-extrusion process used during tape production. Such processes are unlikely to be possible with alternative all-PP systems based on mono-extruded fibres or tapes.

In addition to the sheet stamping process described in previous publications, all-PP parts can also be thermoformed directly from stacked plies of fabric. Although the fabric must be physically constrained by clamping to minimise relaxation of the fabric during preheating, stamping of stacked plies requires only half the energy compared to that required to stamped the same shape from a pre-consolidated all-PP sheet. The profile of the forces observed during mould closure is also different, because force is mainly required to consolidate the fabrics, and only a small force is needed to form the part. A comparison of hemispheres stamped from stacked plies of fabric at different pressure levels showed that the consolidation quality was similar to that of isothermally pressed all-PP sheets at similar pressure levels. The vacuum bagging process has also been shown in this paper to be a simple, low investment route to produce large parts or prototypes in very small series to be manufactured.

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