Thermoplastic composites manufacturing by thermoforming

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6.1 Introduction

The area of composites forming embraces a range of forming processes that can be applied to deform a fibre-reinforced preform (or "blank") into the shape of the final component. This can be achieved by manual drape (or hand layup) or by rigid and flexible tools applying external pressure (including vacuum). The preform can be a dry fabric (possibly commingled from both structural and polymer matrix fibres), a ply of preimpregnated fibres (a "prepreg"), or a full laminated stack of those layers. The fibres can be discontinuous or continuous, in a random orientation, aligned in one direction, or in a structured textile (see Figure 6.1) such as a woven, a braided, or a stitched fabric, of a primarily two-dimensional or three-dimensional nature. Both thermoset and thermoplastic matrices can be used to bind these fibres to form a fibre-reinforced composite.

Process cycle times are important for large series production of composite parts. In composites forming approaches, the cycle time includes the preform manufacturing, the forming stage of the component, trimming when necessary, and assembly of the component into the total (sub)structure. The structural performance is often best suited by aligned continuous fibres, whereas biaxial textiles provide good drapeability and ease of handling. Especially, the forming stage can be executed rapidly with preconsolidated thermoplastic composite laminates, as only heating is required to transform the material from a strong and stiff to an easily formable state and subsequent cooling to achieve the reverse transformation. Both temperature conversions can be achieved relatively quickly, faster for lower melting temperature materials and for smaller thickness laminates.

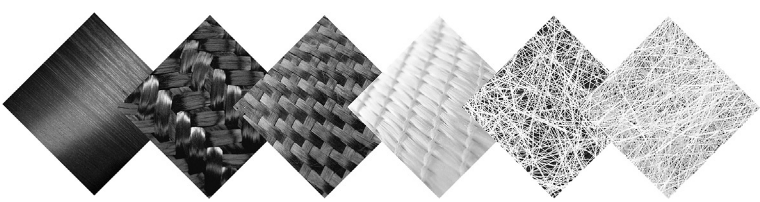

Figure 6.1 Various reinforcements in polymer composites. From left to right: unidirectional ply, triaxial braided fabric, biaxial woven fabric, stitched or noncrimp fabric, chopped strand mat, continuous filament mat.

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Relatively complex shapes can be achieved by such a thermoforming process, as demonstrated by the stiffener ribs manufactured for a wing leading edge designed and built by Fokker Aerostructures (Figure 6.2), thanks to the good drapeability of the woven structure of the reinforcing glass fibres. The actual formability of these materials in these processes is, however, constrained by the nature of the material used, amongst others. In other words, the design of the component is limited by the ability of the material (or lack of it) to deform from the initial preform into the desired shape. Without applying proper knowledge of the forming process, the development of a thermoformed component will go through a long and mostly costly trial-and-error process. The limitations will be illustrated in the next sections. Woven fabric laminates are the most commonly used materials in this respect. More recently, the interest is shifting toward the application of unidirectional reinforcements, achieving higher performance but exhibiting different forming behaviour. Their available configuration as preimpregnated tapes allows the automated tape placement technique to make local

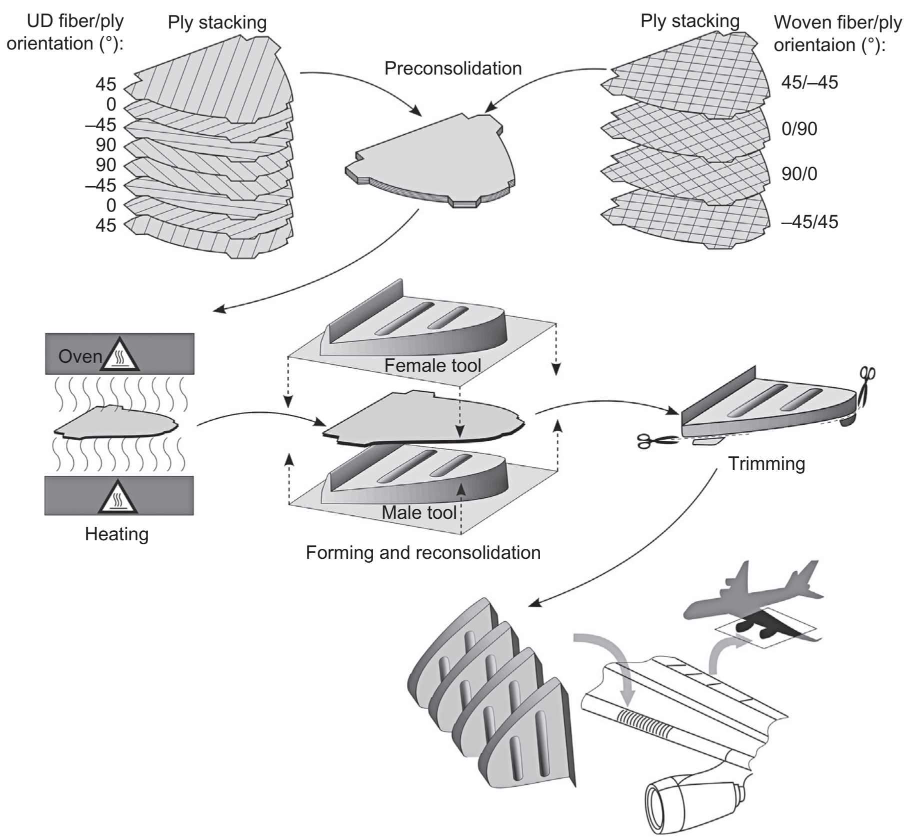


Figure 6.2 Processing thermoplastic composite stiffener ribs for the J-nose leading edge structure as present in the Airbus A380 main wings.
Reproduced from Sachs (2014).

(or tailored) reinforcements feasible in series production. The chapter concludes with an overview of the next steps in composite design for manufacturing employing thermoforming processes.

6.2 Fabric-reinforced laminates

Woven textile structures are often used as reinforcement in composite materials. Their ease of handling, low fabrication cost, good stability, balanced properties, and excellent formability make the use of woven fabrics very attractive for structural applications in, for example, the automotive and aerospace industries. As already mentioned, thermoforming can be used to manufacture products with a thermoplastic matrix material, which enables a relatively high production rate compared to more conventional autoclave processes.

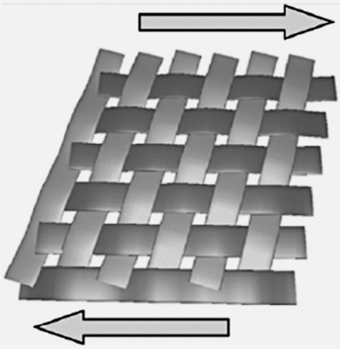
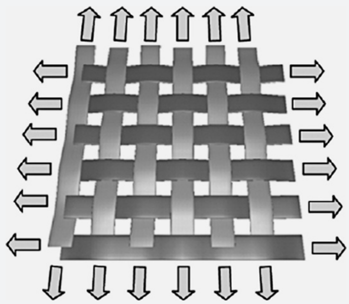
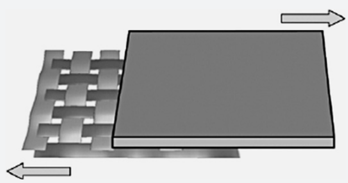
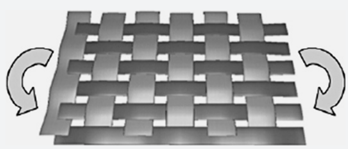
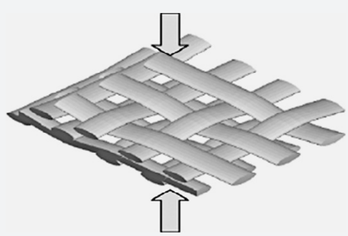
Various deformation mechanisms can be invoked in woven fabric-reinforced composite materials during these forming processes, as summarised by Long and Clifford (2007), who distinguished intraply shear and tensile loading, ply/tool or ply/ply shear, ply bending, and compaction/consolidation (see Table 6.1). Obviously, the resistance to intraply shear and ply bending is relatively low, whereas fibre tensioning and laminate compaction will exert a far higher resistance to deformation. Compared with the softened thermoplastic matrix, the fibres can be considered to be virtually inextensible during these forming processes.

Textiles (technical woven textiles in particular) obtain their good formability especially thanks to the ease of shear and bending operations. This is illustrated with the classical drape experiment on a hemisphere (or part of it). Various authors have published the results of single ply drape or press forming experiments. The double curvature geometry can be formed due to in-plane shear deformation. When this becomes more difficult (which can be interpreted as physical in-plane "shear locking"), the ply may tend to respond to the external loads by means of alternative deformation mechanisms, such as bending. A bent region of a ply could eventually transform into a wrinkle.

In contrast to conventional ply-by-ply layup of thermoset composites for autoclave processing, thermoplastics can be formed in one forming step from a preconsolidated laminate that already contains the full stack of bonded plies with the desired ply orientations. For this, the laminate needs to be heated to a temperature where the thermoplastic matrix is softened sufficiently to allow for these laminate deformations. Typically, infrared heaters are used on both sides of the laminate to achieve short heating times.

The multiple fibre orientations in such a laminate significantly affect the formability of the laminate as a whole, which makes the process essentially different from the single ply layup process. Such a laminate forming process is by no means the sum of single ply drape processes. Ten Thije and Akkerman (2009) illustrated this phenomenon by press forming circular blanks to shallow domes with a radius of 125 mm and a height of 35 mm, as illustrated in Figure 6.3. The blanks were cut from four-layer

Table 6.1 Deformation mechanisms in fabric-reinforced materials during forming

Mechanism	Schematic	Characteristics
Intraply shear		• Rotation of between parallel tows and at tow crossovers, followed by intertow compaction • Rate and temperature dependent for prepreg • Key deformation mode (along with bending) for biaxial reinforcements to form 3D shapes
Intraply tensile loading		• Extension parallel to tow direction(s) • For woven materials initial stiffness low until tows straighten; biaxial response governed by level of crimp and tow compressibility • Accounts for relatively small strains but represents primary source for energy dissipation during forming
Ply/tool or ply/ply shear		• Relative movement between individual layers and tools • Not generally possible to define single friction coefficient; behaviour is pressure and (for prepreg) rate and temperature dependent
Ply bending		• Bending of individual layers • Stiffness significantly lower than inplane stiffness as fibres within tows can slide relative to each other; rate and temperature dependent for prepreg • Only mode required for forming of single curvature and critical requirement for double curvature
Compaction/ consolidation		• Thickness reduction resulting in increase in fibre volume fraction and (for prepreg) void reduction • For prepreg behaviour is rate and temperature dependent

Reproduced from Long and Clifford (2007).

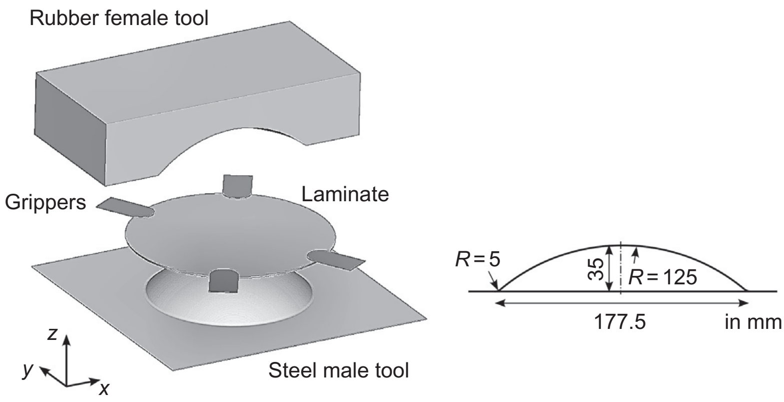


Figure 6.3 Geometry of the shallow dome moulding tools.
Reproduced from Haanappel (2013).

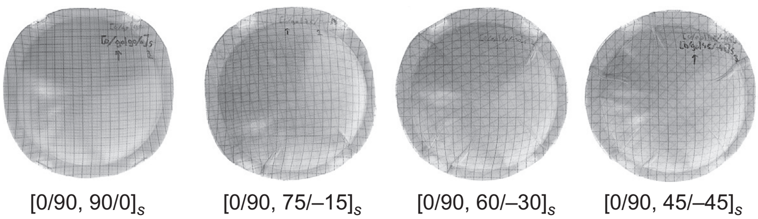


Figure 6.4 Press formed shallow domes formed from glass/PPS laminates with increasing offset in the layup angle.

glass/PPS laminates (with an 8-harness fabric reinforcement, Ten Cate Cetex® SS303) with varying orientations $[0°/90°, (90°-\theta)/-\theta]_s$ with $\theta = 0$, 15, 30, 45°, spanning a range from a cross-ply (CP) to a quasi-isotropic (QI) $[0°/90°, 45°/-45°]_s$ layup. Blue tracer yarns were woven into the glass weave in a 10 mm × 10 mm grid pattern, with negligible effect on the mechanical behaviour of the fabric. The circular blanks with a diameter of 217.5 mm were loosely clamped at four points around the circumference. After heating to 325 °C, the blank was quickly transported to the press and formed between the rubber and steel mould halves, closing at 100 mm/s apart from the last few millimetres, when the speed was reduced to 10 mm/s.

The resulting laminates after forming are depicted in Figure 6.4. The translucent material makes it possible to observe also the orientations of the inner plies. The left specimen with the cross-ply layup presents the same excellent formability as to be expected from a single ply drape experiment. However, once the orientations deviate from a cross-ply layup, the specimens exhibit wrinkling, with increasing severity when further approaching the quasi-isotropic layup.

Apparently, the separate plies restrict each other's deformations in various directions due to their different fibre orientations. Interlaminar friction is the cause of this effect, which is inherent in a laminate with adhesion between the plies. The laminate will "choose" the deformation mechanism that consumes the least amount of energy. Sliding of the plies while the individual plies shear in-plane in different directions may cost more energy than wrinkling of the laminate as a whole, or ply debonding followed by concentrated wrinkling in a few plies of the stack. In this case, one of the latter deformation mechanisms will occur, leading to undesired processing defects in the formed product. Accurate predictive computational tools can help to prevent these processing defects without an expensive trial-and-error process in which multiple tool design and manufacturing steps need to be taken before an acceptable part can be produced.

Obviously, to make these predictive tools reliable, it is required to have appropriate constitutive models and material property data. The NSF Workshop on Composite Sheet Forming at the University of Massachusetts Lowell in September 2001 initiated a number of collaborative benchmarking efforts (Cao et al., 2008; Sachs et al., 2014) on material characterisation and numerical methods by a worldwide community to support the development of reliable and robust simulations of forming processes.

Going into more detail, the process of forming the laminate can be achieved with different types of tooling, which will also affect the material deformations. Rubber press forming employs one rigid tool and one flexible tool on either side of the laminate. The rigid tool (usually steel or aluminium) dictates the shape of the part and the surface quality on that side of the laminate. The elastomeric other side of the tooling can be simply an initially flat elastomer block surrounded by a metal box (Sala, 2001), a shaped elastomeric block that more or less conforms to the rigid tool (Bersee and Robroek, 1991), or even a container with rubber particles (Antonelli et al., 2009). The surface quality of the product at the side of the flexible tool will be more corrugated than the other side. Further, the thermal and the mechanical boundary conditions exerted by both mould halves will be different: a good conductor and a rigid surface on one side versus a good thermal insulator and a stretchable surface on the other side. This provides ample ingredients for unbalanced residual stresses in the resulting composite parts, as was elucidated by Wijskamp (2005). These residual stresses make it difficult to produce press formed composite parts with high geometrical precision. Moreover, the elastomer will degrade over time at elevated temperatures such that variability in the quality of the parts is inevitable.

Based on these factors, industry nowadays tends to prefer matched metal dies on both sides of the laminate. As these no longer provide any flexibility, it becomes impossible to exert consolidation pressure on part sections perpendicular to the press movement. This requires the use of draft angles to compact the laminates at all locations, limiting the freedom of shape of the press formed parts. Compared to elastomeric tooling, matched metal dies are far less "foregiving" and require very narrow tolerances in the tooling, the blanks, and the blank positioning. The laminate thickness increase due to in-plane shear needs to be accounted for in the tool design to enable a properly distributed compaction pressure on the whole part (or even to be able to close the moulds during press forming). Such consequences are inevitable when moving toward large series production of thermoplastic composite parts.

Various stiffener ribs, clips, and brackets have been and are manufactured with part numbers well over 1000 for various current aerospace programmes, such as the Airbus A340, A380, the Gulfstream G650, and the Boeing 787 aircraft, both with flexible and matched metal tooling. These all consist of woven fabric laminates, employing their ease of handling and drapeability. However, unidirectional materials are also considered for future thermoplastic composite applications.

6.3 Unidirectional reinforcements

Already in the early days of thermoplastic composites there was great interest in unidirectionally reinforced materials. These provide higher performance (specific stiffness and strength), at least for the fibre-dominated in-plane properties, possibly with a lower impact performance due to the lack of interlacement. In the 1980s, the manufacturing processes were mainly based on autoclave technology. Double diaphragm forming is such an autoclave-enabled forming process with similarities to thermoforming of unreinforced thermoplastic sheets. Vacuum pressure only was found to be insufficient for reinforced laminate forming. Instead, a combination of elevated pressure and vacuum can be used to form a laminate placed between two thin deformable sheets (the so-called diaphragms). These restrict laminate deformations during forming and can prevent processing defects such as wrinkling and splitting. Although excellent formability can be achieved in this manner, such a (double) diaphragm forming process (Mallon and O'Brádaigh, 1988; Krebs et al., 1998) does not fully exploit the fast processing capabilities of thermoplastic composites, as the whole setup needs to be heated and cooled down during each cycle, and mounting a new stack of plies for the new cycle is relatively time-consuming.

This drawback is obviously circumvented by press forming preconsolidated laminates as described previously. The only difference is that the plies now have unidirectional (UD) rather than fabric reinforcement. As a first step, exactly the same process chain can be employed: starting with preconsolidated laminates of uniform thickness and stacking sequence, cutting the blank, followed by rapid heating, press forming, consolidation, trimming, and assembly. The forming stage will now induce a different set of deformation mechanisms than observed in fabric reinforcement, as the basic material differs to some extent from fabric-reinforced laminates (see Figure 6.5).

In particular, the in-plane shear deformation mechanism can be different from the trellis shear imposed by a biaxial fabric structure. Some normal strain is possible transverse to the fibre direction (denoted as the X_2-direction in Figure 6.5), although this is rather limited by a splitting/tearing mechanism that occurs at low extensional strain already. Further, the UD plies will shear relatively easily transverse to the laminate plane (in the X_1-X_3 and the X_2-X_3 planes in Figure 6.5). Laminate bending-will result in significant transverse shear (Scherer and Friedrich, 1991) but may also

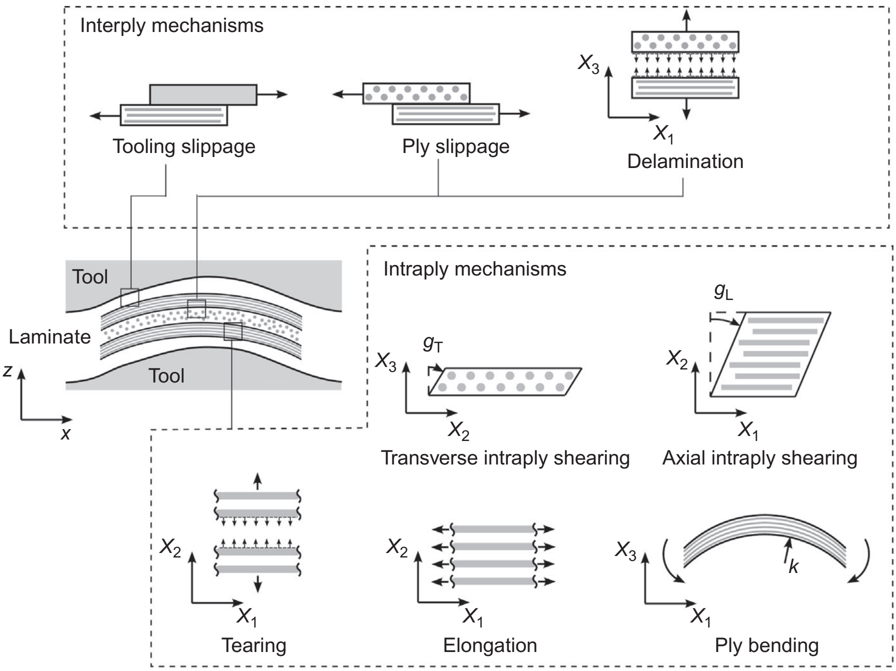


Figure 6.5 Deformation mechanisms in a laminate with unidirectional reinforcement. Reproduced from Sachs (2014).

Figure 6.6 Ply wrinkling on the inner radius of a V-bend specimen (unidirectional carbon-PEKK). Reproduced from Sachs (2014).

lead to local delamination and ply wrinkling on the inside of the bent laminate, as illustrated in Figure 6.6.

In order to study the effect of the differences in forming behaviour between unidirectional and fabric reinforcements, the shallow domes were manufactured once more, now with 8-ply laminates of unidirectional carbon/PEKK plies of nominally 0.14 mm thickness (Haanappel, 2013). Circular blanks with a diameter of 217.5 mm were cut, after which line marks were applied to obtain an indication of the deformations in the formed parts. In this case, only the cross-ply and quasi-isotropic laminates were press formed, now with laminate temperatures of 380 °C. Four grippers were applied to transport the blank through the process. Figure 6.7 shows the resulting deformed shapes.

Contact of the laminate with the steel tooling was initiated in the centre of the dome, which is referred to as the drape front origin. At a certain distance from this origin, the onset of wrinkles can be detected. We refer to this as the wrinkle initiation front. The quasi-isotropic layup of $[0, 90, 45, -45]_s$ for the UD carbon/PEKK laminate (Figure 6.7a) shows a wrinkle initiation front that is close to the centre of the product. For the cross-ply layup of $[0, 90]_{2s}$ of the same material in Figure 6.7c, the first wrinkle is formed at a considerable distance from the centre. An almost wrinkle-free product was obtained. This demonstrates that the change in layup once again significantly affects the laminate formability. Also, it is clear that considerable in-plane shear can be realised in these unidirectional laminates if the conditions are favourable.

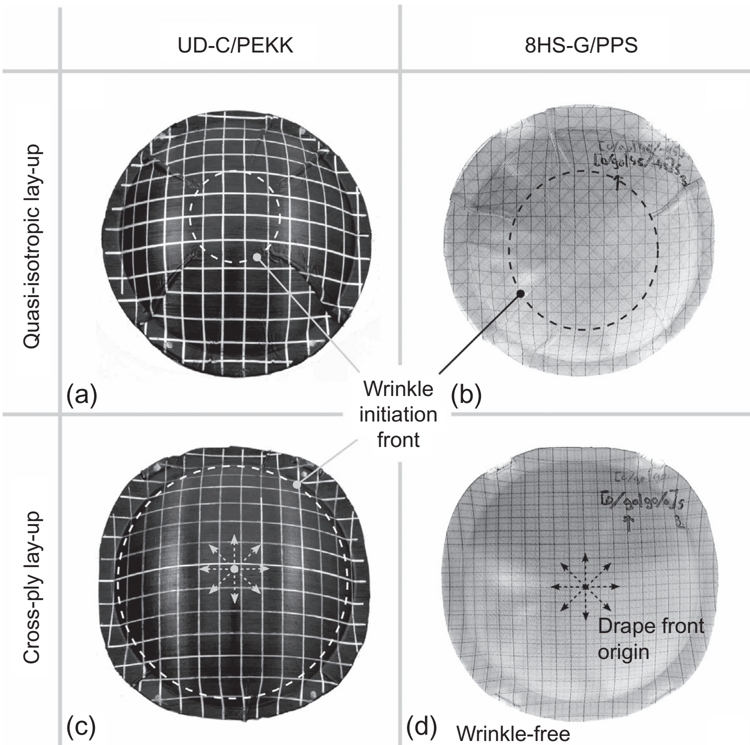


Figure 6.7 Effects of material (UD Carbon/PEKK versus 8 Harness Satin woven Glass/PPS) and lay-up (Quasi-isotropic vs. Cross-ply) on wrinkling for a shallow dome geometry. The dashed line separates the regions with and without wrinkling.
Reproduced from Haanappel (2013).

The formability of the 8HS glass/PPS laminates is illustrated in the same figure. The cross-ply layup in Figure 6.7d shows no wrinkling at all. As concluded before, a change in layup significantly affects the laminate deformations. The quasi-isotropic 8HS glass/PPS in Figure 6.7b shows severe wrinkling, just as observed for the QI UD carbon/PEKK laminate. However, when checking the onset of wrinkling it can be observed that the wrinkle initiation front is further remote from the centre compared to the UD carbon/PEKK product, which results in higher shear angles in the wrinkle-free area. In general, the QI layup does not combine very well with double curvature and rapidly leads to wrinkling.

The forming process was stopped at several intermediate positions in order to study the deformation behaviour of the QI carbon/PEKK laminate, while it was being formed into the dome-shaped geometry. Figure 6.8 shows the intermediate deformations of the QI carbon/PEKK laminate. The first stage, when the tools are at 20 mm closing distance, shows severe buckling around the grippers. These areas are mainly turned into wrinkles in the subsequent stage over the full thickness of the laminate. A small and a large wrinkle develop next to each gripper. The wrinkles are further compressed into the laminate when the tooling is completely closed. Some minor buckled areas in the first stage do not always end up in wrinkles. Instead, some intraply shearing is induced locally. The observed global laminate deformations are summarised in Figure 6.9. The actual deformed shape of the laminate will be determined by the resistance against the various deformation modes. When intraply shear with some interply slippage provides the easiest way of deformation, then option 1 without wrinkling will be achieved. When this mode of deformation provides too much resistance, then a fold as shown in option 2 can occur. Or, when the bending resistance is sufficiently low, then multiple smaller wrinkles will be formed (option 3), which again can be straightened by shear or folded (options 1 or 2, respectively).

Notably, the clamps and the size and shape of the excess area outside the product significantly affect the (shear) buckling or wrinkling phenomena. Preventing these processing defects can involve various factors, such as the product design, the laminate layup, the blank geometry, but also the tooling materials, the process conditions, the gripping system, and the blankholder system can be varied to achieve better forming results.

The amount of parameters involved makes it difficult to identify an acceptable or, even better, an optimum geometry–material–process combination before fixing the part design. Of course, process simulations can (and should) be used to generate prior knowledge about the expected result for each individual combination. However, as in every simulation, the outcome depends on the input, where it may be difficult to determine the material property data reliably and accurately. Forming simulation studies have been conducted to demonstrate the sensitivity to material parameter input. For example, Hamila and Boisse (2008) demonstrated the effect of in-plane shear stiffness in the drape simulation of a textile sheet over a circular table, and Boisse et al. (2011) showed the effect of bending stiffness in a drape simulation of a textile on a hemisphere. Haanappel (2013) applied a sensitivity study to the case where a QI laminate was formed to the dome geometry addressed earlier. In-plane shear, interply friction, and bending properties were all varied in the finite element simulations.

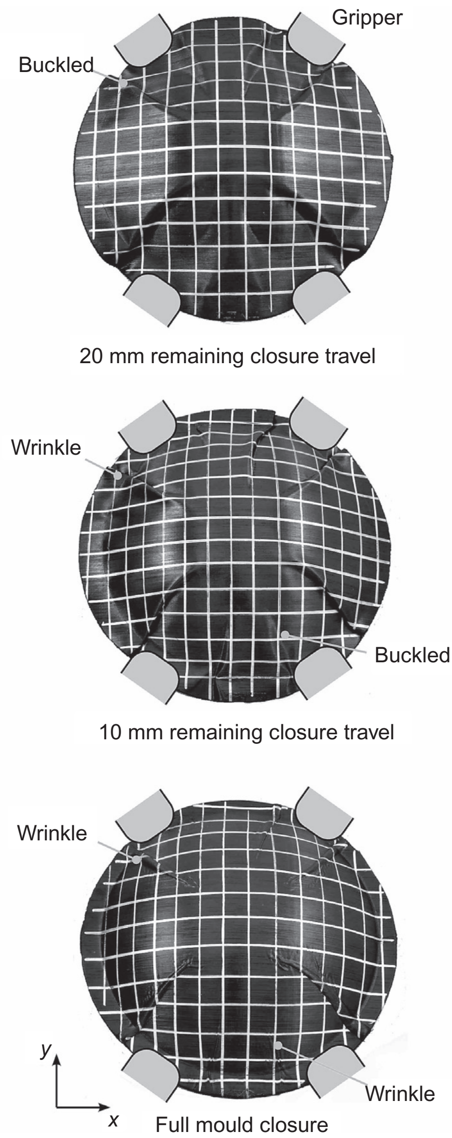


Figure 6.8 Intermediate stages of the forming process of a UD carbon/PEKK shallow dome. Reproduced from Haanappel (2013).

Intraply shear and friction were modelled as a viscous phenomenon, whereas bending was described with an orthotropic elastic formulation. Each of the parameters involved was changed substantially using a factor of 10 difference between the small, medium, and large values, as the material property data may be subject to a similar degree of uncertainty (Harrison and Clifford, 2005).

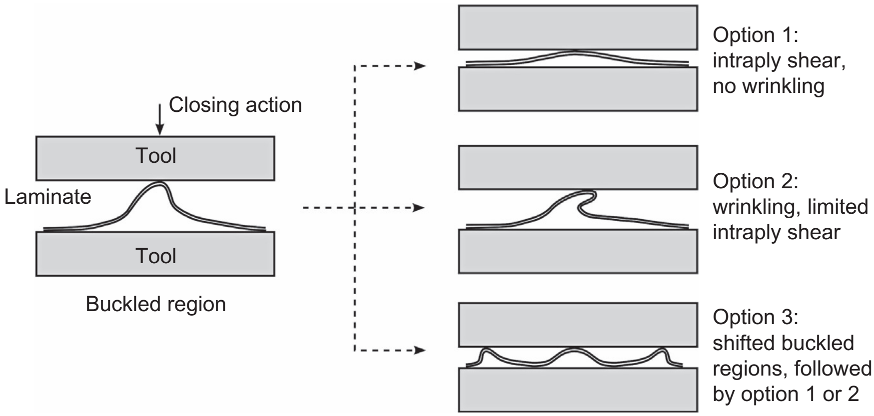


Figure 6.9 Laminate deformations when double curvature leads to excess material during forming.
Reproduced from Haanappel (2013).

Table 6.2 Material parameters employed in the parameter sensitivity study, indicated with small (–1), medium (0), and large (1)

Deformation mechanism	Material parameter	Levels		
		Small (–1)	Medium (0)	Large (1)
Shear (χ_1)	$\eta_L = \eta_T$ (Pa s)	3×10^4	3×10^5	3×10^6
Bending (χ_2)	E_1 (MPa)	25	250	2500
	E_2 (MPa)	12.5	125	1250
	G_{12} (MPa)	10	100	1000
Friction (χ_3)	η (Pa s)	70	700	7000

Table 6.2 presents the material property data employed in the simulations for the longitudinal and transverse viscosities, the elastic bending parameters, and the Newtonian viscosity employed in the friction model, respectively. The values 1, 0, and 1 represent the small, medium, and large values, respectively. Figure 6.10 illustrates the design space for this sensitivity study, employing a face-centred cubic design augmented with four additional design points. The results are represented in Figure 6.11, showing the deformed laminate shapes at a remaining closure travel of 10 mm for all design points in the parameter space.

By means of visual observation, a crude classification is obtained using the symbols χ_1, χ_2, and χ_3 for (1) intraply shear, (2) bending, and (3) friction, respectively:

I. Long straight wrinkles that originate from one side of each gripper only are observed for simulations $(\chi_1, \chi_2, \chi_3) = (-1, -1, -1)$, $(0, -1, 0)$, and $(0, -1, -1)$.

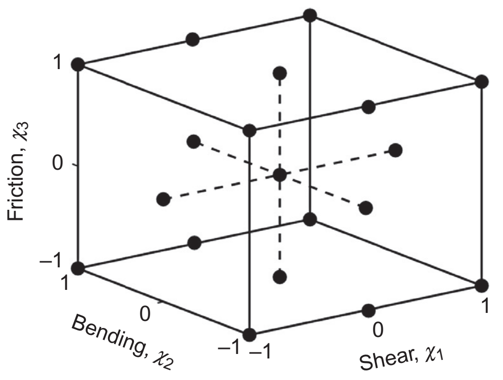


Figure 6.10 Design space for the sensitivity study. Each point represents a simulation for a certain combination of material parameters.
Reproduced from Haanappel (2013).

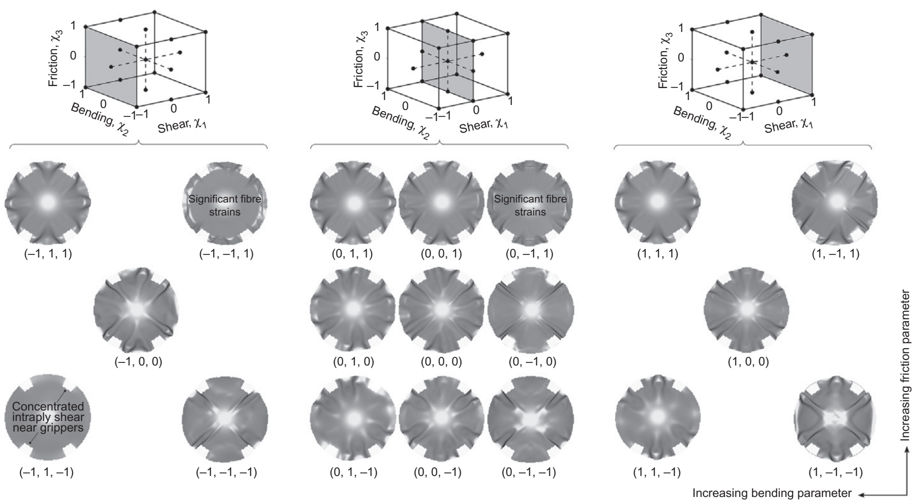


Figure 6.11 Simulation results for the finite element simulations of the quasi-isotropic laminate, showing the deformed shape at a remaining closure travel of 10 mm.
Reproduced from Haanappel (2013).

II. Uniformly distributed wrinkles that run straight are observed for nearly all the simulations in the top row of Figure 6.11. The material parameter combinations read (−1, 1, 1), (0, 1, 1), (0, 0, 1), (1, 1, 1), and (1, −1, 1).

III. No wrinkling is visible for (−1, 1, −1), whereas wrinkling is concentrated near the rim of the dome for (−1, −1, 1) and (0, −1, 1). These predictions are accompanied by obscure in-plane deformations. Concentrated intraply shearing was observed near the grippers for (−1, 1, −1). Fibre stretching was observed for simulations (−1, −1, 1) and (0, −1, 1).

IV. Uniformly distributed, but more curved wrinkles are observed for (0, 1, 0), (0, 0, 0), (0, 1, −1), (0, 0, −1), (1, 0, 0), and (1, 1, −1).

Figure 6.12 Rendered image of the coordinate measurement results (with an in-plane resolution 1 mm × 1 mm) of a press formed shallow dome at a remaining closure travel of 10 mm. Reproduced from Haanappel (2013).

Figure 6.12 shows a rendered image of the experimental result for this laminate. The fourth category (IV) matches best with this experimental result, in which curved wrinkles are present as well, although the number of wrinkles was less than predicted. The sensitivity study shows that alternative material parameter combinations can result in predictions quite similar to the base simulation (0, 0, 0). However, other material parameter combinations result in very different wrinkle distributions. These effects highlight the importance of obtaining a reliable material parameter input as determined from characterisation experiments.

Analysing these results in a systematic way we observe the following logic. When an initially flat laminate is formed to a doubly curved surface, its plies must deform in-plane, with or without interply slippage. If only two unique fibre orientations are present in the laminate, then the in-plane deformations of the laminate can be achieved by intraply shear only or by a combination of interply slip and strain transverse to the fibres. Trellis shear without interply slippage is likely to occur in UD laminates when the frictional rigidity is higher than the intraply shear rigidity. If more than two fibre orientations are present in the laminate (which is the case for a QI layup), then the in-plane deformations of the plies must be accompanied by interply slippage to prevent wrinkling from occurring (due to the inextensibility constraints in the fibre directions). The bending mechanism, finally, may involve the laminate as a whole, but may also lead to delamination and bending of separate ply groups. As a general statement we can conclude that *the formability of fibre-reinforced laminates is determined by a delicate balance between the available deformation mechanisms*; *that is*, *intraply shear*, *interply slippage*, *and ply/laminate bending*.

This was further illustrated by a series of forming trials, where different reinforcements (fabric and UD) and different matrices (PPS, PEEK, and PEI) were used to manufacture stiffener ribs with primarily quasi-isotropic layups, as reported by Sachs (2014). Figure 6.13 shows the different amounts of processing-induced defects for

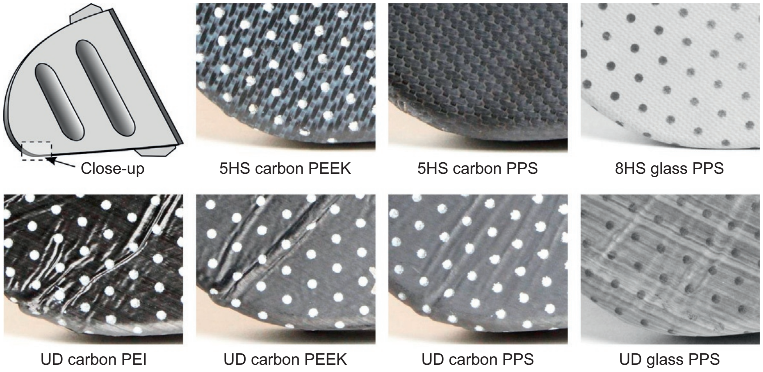


Figure 6.13 Quasi-isotropic laminates of different thermoplastic composite materials pressed to stiffening ribs showing different formability in areas with double curvature
Reproduced from Sachs (2014).

these materials in a region with large double curvature. Haanappel (2013) showed that this stiffener rib can be formed without wrinkles when using UD carbon/PEEK laminate with a cross-ply layup. For a QI layup, however, the UD laminates show significantly more wrinkling than the fabric-reinforced laminates. The differences can be caused by various factors: a higher bending rigidity of the fabric laminates, a higher intraply shear rigidity of the UD plies, higher interply friction between the UD plies, or a combination of these. This example illustrates that accurate process and material analysis are required to achieve predictable thermoformed composite laminate quality.

Although the previous analyses, assuming isothermal conditions in the simulations, already provide very useful information on the process and its effects on the laminate formability, the actual process is essentially nonisothermal, which further complicates the phenomena and their analysis. Temperature gradients develop in the laminates when these leave the heating stage and, most significantly, when contact with the tooling is established. The latter results in rapid cooling of the laminate surface, whereas the inner plies are affected only in a later stage of the process, as polymer composites have a relatively low through-thickness heat conductivity. This progresses with a certain delay through the inner plies. Again, simulations can be used to illustrate the phenomena, in this case using a square $[0/90]_s$ carbon/PEKK laminate, which is pressed in the shallow hemisphere tools. Three different closing times were used (10, 2, and 1 s), combined with three different tool temperatures (150, 200, and 250 °C). Figure 6.14 shows the temperatures at the bottom and the top surface, contacting the positive and negative side of the tool, respectively, just before the mould is completely closed. The results clearly show a varying temperature distribution over the laminate and its dependence on the tool-ply contact development on either side of the laminate. The delicate balance between intraply shear, interply slippage, and ply/laminate bending is now seen to be a function of the local temperature distribution as well.

The superficial cooling directly affects the tool-ply friction, whereas the more gradual cooling through the thickness (in a slightly later stage) will affect the local

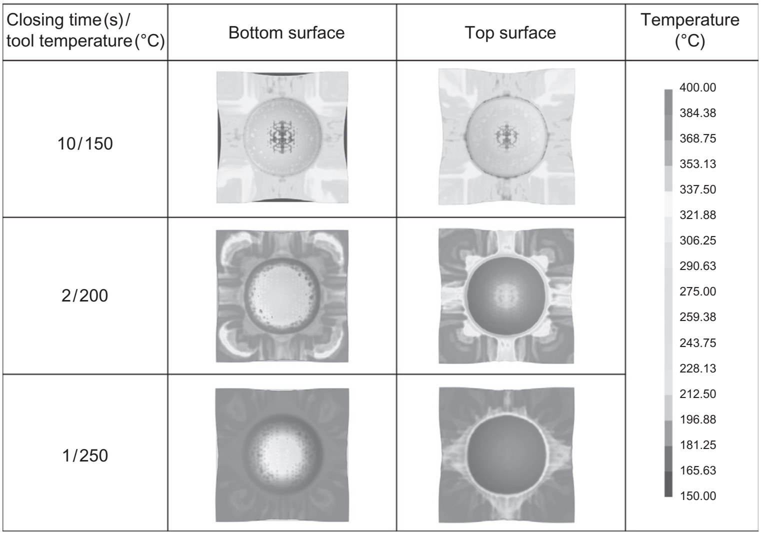


Figure 6.14 Predicted laminate surface temperatures (just before full mould closure) using a full thermomechanical process simulation model, for different mould closing times and tool temperatures.

resistances against intraply shear, bending, and ply–ply slippage. Moreover, this is seen to influence the wrinkling behaviour at intermediate forming stages, which affects the laminate–tool contact development and, in turn, the three-dimensional temperature evolution. Obviously, this will affect the ply deformations and, for instance, the fibre stresses, as illustrated in Figure 6.15 for the bottom, centre, and top plies, respectively. The deformation rate clearly affects the stress levels according to these model predictions. In addition, we observe that there is a shift in the occurring deformation mechanisms, namely more tool/ply slippage for lower tool temperatures and forming rates. The results indicate that the resulting residual stresses in the press formed part will be highly sensitive to the process settings, such that deformations during part release (warpage, spring-back, spring-in) will also be affected significantly.

6.4 The next steps

So far, we have only considered simple shapes with a uniform layup, where the blanks were cut from larger preconsolidated laminates. This leads to significant amounts of cutting scrap for most product geometries. Using modern tape or fibre placement techniques, it is possible to produce so-called tailored blanks that, in the first place, significantly reduce the amount of cutting scrap but, secondly, also provide the ability to apply product-specific fibre orientations (Skinner and Cramer, 2006). Obviously, the

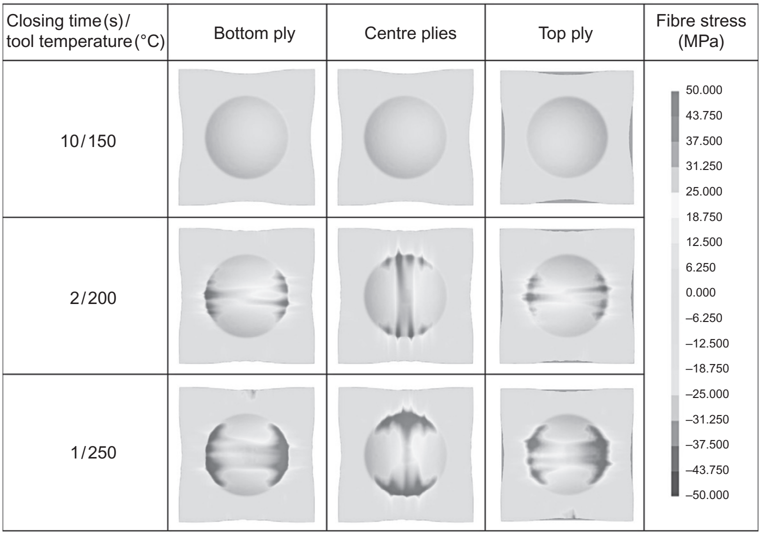


Figure 6.15 Predicted fibre stresses (just before full mould closure) using a full thermomechanical process simulation model, for different mould closing times and tool temperatures.

amount of waste can be reduced by using narrower tape, but in consequence the tape placement process will take more time. An optimum tape width for a given part can be determined by employing relatively simple cost models.

Not only the fibre directions can be tailored in this approach, but also the thickness and even the prepreg materials can be varied and optimised. Although these basic ideas are fairly straightforward, the actual implementation is by no means trivial. First of all, the quality of the blank is likely to affect the quality of the final product. If good preconsolidation quality of the blank is required to achieve the desired final product quality, then the preconsolidation process of a blank with nonuniform thickness will require a tailored pressing tool, for each individual product series, according to the preform thickness distribution. Alternatively, the tape placement process itself could feature "*in situ* consolidation" quality, which may require a slower deposition process. In either case, the press forming tooling for the specific product will need to match the thickness variations of the blank, which then also needs to be positioned very accurately during the forming process. The coming years will teach us in what respect these technology developments will find their place in actual industrial manufacturing processes.

Apart from more optimised and more complicated processes, also more robust product development processes and manufacturing chains are likely to be realised in the years ahead. Thermoplastic composites have the potential for large series production of lightweight structural parts, saving weight and energy in future applications. The required robustness involves the whole chain of materials, design methods, and production systems. Variabilities in each of the sub steps and their consequences in the following steps of the process chain need to be quantified and captured in reliable predictive models in order to achieve predictable product development times and predictable and reproducible good part quality, rather than maximum performance for only few of the parts manufactured.

Humans have used metals in their tools and products for centuries, starting well before the Industrial Revolution. From this point of view, continuous fibre-reinforced thermoplastics are indeed a very young family of engineering materials. However, overseeing the current worldwide developments in composites technology, this young family is likely to catch up rapidly with more conventional materials.

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