Influence of Consolidation and Forming Parameters in the Molding of Continuous Fibre Reinforced Thermoplastic Composites

by

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Abstract

Continuous fibre reinforced thermoplastic (CFRTP) composites offer many advantages over thermoset composites and metallic materials, especially their resistance to corrosion, their recycling possibilities and their high specific stiffness. The shaping of these materials into complex forms however requires a good knowledge of the combined behaviour of the molten thermoplastic matrix and of the fibres because of the high intra and interlaminar shear deformations involved during the forming process.

In this paper, the influence of laminate consolidation parameters on the microstructure and mechanical properties of the laminate are first presented. Next, the deformation mechanisms induced in the laminate in typical forming conditions are presented and discussed in regard to their influence on the physical and aesthetic properties of the moulded part. Numerical moulding predictions obtained from a commercial code are finally presented.

1.0 Introduction

CFRTPs offer many advantages over thermoset composites for automotive body panels due to their short processing cycle time, their potential for recycling and their improved mechanical and physical properties [1]. Efforts are currently devoted to the development of processing techniques allowing large volume production of CFRTP parts, especially in the automotive industry. In this respect, the processes used for the moulding of CFRTP parts can be seen as an intermediate between the sheet metal stamping process and the thermoplastic polymer thermoforming process. Indeed, as in sheet metal stamping, large displacements, controlled by a clamping system (or blank holder), must be allowed to the unstretchable fibres of the laminate. In addition, during the forming process the deformation of the laminate by fibre re-orientations and interlaminar ply slippage creates high viscoelastic deformations in the thermoplastic matrix, similar to that encountered in the thermoforming of thermoplastic polymer sheets.

The thermoforming/stamping of CFRTP composite materials is a process in which a stacking of composite sheets, preheated to the melting temperature of the polymer matrix, is installed between two rigid mould halves defining the geometry of the part to be formed and stamped to the desired shape by closing the mould. Figure 1 shows the major steps involved in the process. The consolidation and the final consolidation stages are very important because they are determinant in the final mechanical properties of the part. Because thermoplastic materials have specific thermophysical and thermomechanical behaviour when cooled from their melting temperature, a good understanding of the interaction between the fibres and the matrix during consolidation and the influence of consolidation time, pressure and temperature are of prime importance in the process. During transfer from the oven over the mold halves (stage 2) and during the forming stage (stage 3), the temperature of the laminate drops at a relatively fast cooling rate depending on the ambient air and mold temperatures and mold thermal conductivity. Such cooling will affect the microstructure of the matrix which in turn will affect the properties of the molded part. During the forming stage, the laminate deforms to adjust to the geometry of the mold. Many laminate deformation mechanisms are involved in this stage and contribute to ensure the laminate conformation. Their contributions depend mainly on the mold geometry, the orientation of each ply of the laminate and the architecture of the fabrics used as constitutive plies in the laminate.

To avoid relying on costly and inefficient “trial and error” practices as it is often the case in the development of new processing technologies, and considering the complexity of the thermoforming/stamping process of CFRTP parts, many research works are devoted to the development of numerical tools to predict the laminate behaviour during the forming process and the mechanical behaviour of moulded parts [2-6]. In parallel to these developments, many research activities are dedicated to the understanding of the macro- and micro-mechanical behaviour of composite materials during moulding [7-10], which is determinant in the development of efficient forming tools for CFRTP materials.

In this paper, the influence of laminate consolidation parameters on the microstructure and mechanical properties of the laminate are first presented. Next, the deformation mechanisms induced in the laminate during the thermoforming-stamping process are presented and discussed in regard to their influence on the physical and aesthetic properties of the moulded part. Numerical moulding predictions obtained from a commercial code are finally presented.

2.0 Influence of the fabric consolidation parameters on the mechanical properties of CFRTP laminates

The quality of consolidation of the thermoplastic fabric composite is a critical parameter governing the final properties of the parts obtained by the thermoforming-stamping technology. In fact, good consolidation means full impregnation of the fibers by the thermoplastic matrix. The impregnation involved the wetting of the fibers by the molten polymer matrix, the establishment of the fiber/matrix interaction and can also lead to the creation of particular matrix morphology in the bulk and in the interfacial area. As schematically shown in Figure 2, impregnation in commingled fabric composite is favored by the homogeneous blend of the glass and polymer fibers. Figures 3 to 6 show the effect of the consolidation pressure, temperature and time on the composite and matrix microstructure and the resultant mechanical properties. As expected, the mechanisms responsible for the consolidation of the thermoplastic commingled fabric are time, temperature and pressure dependent. Increasing consolidation pressure and temperature results in lower times required to obtain almost void free composites (Figure 3). Figure 4 shows that optimal short beam shear (SBS) strength, related to the interfacial strength in the composite, can be obtained in less than 1 minute at temperature of 200°C. At 160°C, optimal interfacial strength can also be obtained but the time required to reach this performance is very long, even at high pressure.

While optimal interfacial properties can be obtained at a low consolidation temperature of 160°C, the composite show very low tensile strength at this temperature, even if a high consolidation pressure is maintained over a long period of time (Figure 5). The low value of tensile strength can be explained by the change of the matrix morphology (Figure 6), known to play an important role in the performance of a thermoplastic composite. It is well known that the development of the crystalline structure in PP composite is related to its thermal history. Spherulitical structure in PP is obtained only when the PP is heated at temperatures higher than its thermodynamic melting point of approximately 170°C. In such conditions, crystallization operates via a homogeneous nucleation mechanism and large spherulites are formed. When the consolidation temperature is lower than 170°C, crystalline entities remain in the melt and crystallization operates via a heterogeneous nucleation mechanism; in this case the crystalline structure is not well defined. It seems that a spherulitical structure is essential to obtain the optimum mechanical performance in PP composites.

In order to evaluate the importance of the quality of the consolidation of a preform on the subsequent mechanical properties of a molded part, preforms obtained under different consolidation conditions were next used to mold small plaques by the thermoforming-stamping process. Consolidation conditions of the preforms and the thermoforming-stamping molding conditions are shown in Table 1 with the measured modulus of elasticity (E_T), tensile strength (σ_T), short beam shear strength and void content of each preform and stamped plaque. Comparing the properties of the stamped parts with those of the well consolidated preforms 1, 4 and 5, it is observed that tensile and interlaminar shear strength close to the optimum values can be obtained for a stamping temperature of 180°C, a mold temperature of 23°C and a stamping pressure as low as 14 psi. In addition the preforms maintained their 2% void content. In case of preform 2, consolidated at 160^{o}C and characterized by 5% of void content, the results show that when molding at the same temperature and pressure than preforms 1, 4 and 5, much lower mechanical properties are obtained even if the mold temperature was maintained at 100^{o}C. A deconsolidation of the preform when molding at a lower pressure (14 psi) than the consolidation pressure (100 psi) was observed. The 5% void content increased to 25% in the part due to the expansion of the entrapped air. For preform 2, the best performances were obtained for a stamping temperature of 200°C, mold temperature of 100°C and a stamping pressure of 50 psi. Even under these conditions however, it is noted that the properties never reached the properties of the well consolidated preforms 1, 4 and 5. These results show how important it is to start from a well-consolidated preform to optimize the mechanical properties in the part molded subsequently. This is even more important if complex 3-dimensional part geometries are molded because in such cases the risks of inducing laminate deconsolidation and part defects during molding increase with the number of deformation mechanisms necessary to insure a good laminate conformation as will be shown below.

Due to thickness variations of the laminate induced during forming, the size and geometry of each mold halves must be such that, once the mold is closed, the cavity thickness must perfectly match the final thickness distribution of the part to ensure a uniform consolidation pressure over the part area. This aspect is even more critical when deep parts with small draft angles are stamped because in such cases, the increased shear deformations of the laminate are combined to lower consolidation pressures over the side walls of the part (the component of the press closing force normal to the side walls being much lower in such cases). Keeping in mind the importance of a good consolidation on part properties discussed above, the next section will show how the laminate deformation mechanisms observed during the forming stage increase the complexity of the thermoforming-stamping process by showing how they influence the overall part quality.

3.0 Influence of the laminate deformation mechanisms on the quality of molded parts

During the forming of a part, the laminate is forced to pass from a relatively flat, undeformed geometry at the exit of the oven, to the cavity geometry, which can be relatively large and complex with large and small corners radius, small draft angles and a large depth to width (or length) ratio. Many laminate deformation mechanisms are involved during the forming phase as shown in Figure 7. The intraply (trellis) shear is certainly the dominant one. Figure 8 shows a schematic and a photograph of the conformation at the corner of a typical box, for a woven fabric initially oriented at 0^o with the mould sides. It is shown that high intraply shear of the fabric is needed at the corners to insure a proper conformation of the fabric at this location. This deformation mode is dominant in the forming of CFRTP parts because it insures laminate conformation over complex 3-D geometries. Indeed, at 2-D forming sites (around straight edges or straight cylindrical regions), the angle between the fibres does not change when formed over the edge and in this case, the interply shear mechanism is dominant. In 3-D forming sites (at corners) however, the fabric will shear and the angle between the fibres before and after forming over the corner will be different. This behaviour of the fabric remains true whatever the geometry of the part and the orientation of the fabric with respect to the mould before forming [6].

Many other deformation mechanisms are present during forming of a part, even if they seem less dominant. Interply rotation is similar to interply slippage except that it is observed by rotation of the plies against each other. It is especially obtained with laminates made of unidirectional plies. Straightening of the fibres is a characteristic of woven fabrics for which a tensile load on the fibres in one direction will straighten these fibres and increase the yarns waviness in the other direction. Yarn buckling arises when local longitudinal compression of the fibres is observed, especially in regions where the membrane tensile load on the laminate induced by the clamping system is insufficient to counterbalance in-plane compressive loads that arise during forming. This can also be observed by locally curved fibers in laminates made of unidirectional plies (Figure 9A). Yarn slippage is mainly obtained in 3-D forming sites with fibres submitted to tensile loads. It corresponds to slippage of rovings at crossover points and it combines to the trellis effect in the reorientation of the fibres in 3-D forming sites (Figure 8). Resin flow occurs in resin rich zones, which develops especially along the edges of the part where high pressure gradients develop during the conformation of the laminate. It combines with resin percolation through the fibres and fibre compaction (transverse squeeze flow) which precede the formation of resin rich zones (Figure 9B).

It is important to keep in mind these laminate deformation modes arising during part forming because many defects observed in moulded parts are closely related to these modes. Laminate wrinkling for example is caused by an excessive intraply shear of the fabric, which reaches an angle lower than what is called the locking angle (angle at which roving rotation in the fabric becomes no longer possible) and resulting in local out-of-plane buckling (or wrinkling) of the fabric. Wrinkling can also be caused by local yarn buckling in the fabric due to in-plane compression loads. These two types of defects, sometimes named corner wrinkles and carpet wrinkles, are among the most frequent and obvious defects in moulded parts. The other types of defect are heterogeneity in fibres distribution, flexural wrinkles, surface roughness, part porosity, fibre print-through, thickness variations, part distortions, fibre damage and delamination.

Non-homogenous fibre distribution is directly related to resin percolation through the fibre reinforcements. This arises where high pressure gradients are induced in the laminate, especially along edges and corners of the mould due to high local compression stresses (Figure 9B), and results in a separation of the laminate constituents to form resin and fibres rich zones. Flexural wrinkles are associated with interply slip movements of the fabric at 2-D deformation sites. In these regions, viscous interlaminar shear movements induce in-plane compression stresses in the inner plies of the laminate, analog to compression loads in a beam submitted to a flexural load, resulting in local buckling (or wrinkling) of the fibres [11]. This kind of defect is particularly observed when conforming sharp edges with a thick laminate at high forming rates. Surface roughness is associated with the quality of the surface finish of the part and it is caused by a premature cool-down of the matrix during the forming of the part, creating matrix shear and cracking. It can also be caused by local air entrapment in mats or at roving crossover points of a fabric (Figure 10), or simply by the surface quality of the tools used to mould the part. Fibre print-through is related to non-homogenous fibre distribution, especially at crossover points of the rovings in the woven fabric. The important shrinkage of the resin-rich zones during cooling creates small depressions over the surface of the part. These depressions are very difficult to avoid, even when a surface coating is applied on the laminate surface or in the mould before moulding (Figure 11). Thickness variations are closely related to the deformation mechanisms of the laminate. In areas of the part where intraply shear occurred, the part is thicker because this shear is accompanied by an out-of-plane expansion of the rovings in the laminate. Thickness reductions will however occur along edges and corners of the part due to important compaction of the fibres and resin flow associated with the high pressure gradients in these regions (Figure 9B). Part distortions are mainly attributed to the difference in in-plane and out-of-plane coefficient of thermal expansion of a composite laminate [12]. Residual stresses induced by mould halves made with materials having different thermal conductivities or preheated to different temperatures can also be responsible of this kind of defect, which is traduced by small curvatures of regions of the part that should be flat after moulding. Fibres damage occurs when high tensile loads are applied on the fibres. This usually occurs on deep parts molded with small draft angles, small corners radii with a mold preheated to a low temperature [9]. Finally, delamination can be observed in unpressurized regions, especially at the sheet periphery where the laminate is not pressurized and consolidated during mould closure.

As shown above, a considerable number of parameters have to be taken into account to optimize the thermoforming-stamping process for CFRTP composites, especially during the consolidation and forming phases. To avoid relying on the expensive trial and error technique for the development of efficient tooling equipments, numerical models of the process must be developed. These models must take into account the thermophysical properties of the melted matrix in the laminate and the deformation mechanisms of the laminate observed during the forming phase. Figure 12 shows preliminary results for the fibre orientation predictions obtained from a commercial finite element analysis (FEA) simulation program. The model corresponds to a two plies laminate of a woven fabric having the fibres oriented at ±45° with respect to the sides of the mould. By comparing with the photograph of the part in Figure 12, it is shown that the program can predict the orientation of the fibres and the regions where the laminate exhibited high shear deformations. It gives also indications concerning the location of wrinkles formation by predicting the locations for which there is insufficient control on the laminate deformation.

4.0 Conclusions

CFRTP parts are becoming popular in automotive and aerospace applications due to their short processing cycle time, their potential for recycling and their improved mechanical and physical properties. However, to obtain good laminate mechanical properties and high quality parts, many parameters have to be kept in mind during the design of tooling. The laminate consolidation must be completed and to achieve this, a good knowledge of the parameters influencing the matrix microstructure, such as the optimum consolidation temperature, pressure and time as well as the cooling rate have to be taken into account. Good knowledge of the laminate deformation mechanisms involved during moulding is also necessary to avoid deconsolidating the laminate or creating macroscopic defects in the molded part, especially when the matched-die process is used. Indeed, because these mechanisms influence directly the final thickness distribution of the part at the end of the forming stage, good prediction of the thickness distribution dictates how the mould must be machined to ensure a good laminate consolidation over the part area and a high quality surface finish.

The use of efficient numerical modelling tools is necessary to reduce the development time of the molding equipments and ensure their efficiency in the molding of acceptable part quality. By predicting the fibre orientation for each ply of the laminate after molding, these tools are also very useful to predict the mechanical properties and the structural behaviour of molded parts.

5.0 References

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6.0 Figures

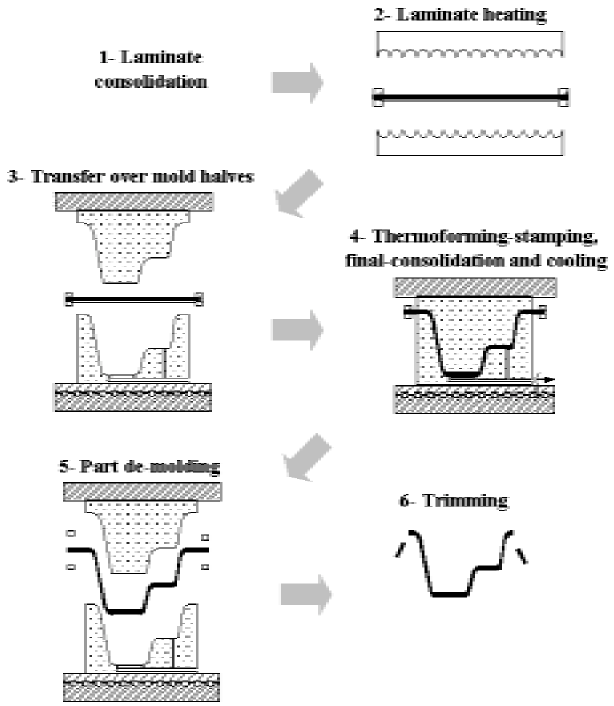


Figure 1. Major steps involved in the thermoforming-stamping process of CFRTP composites.

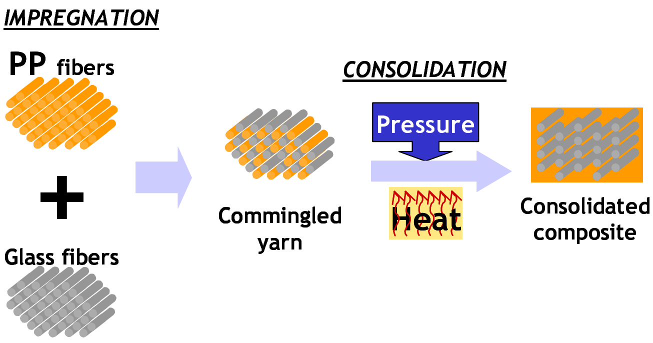
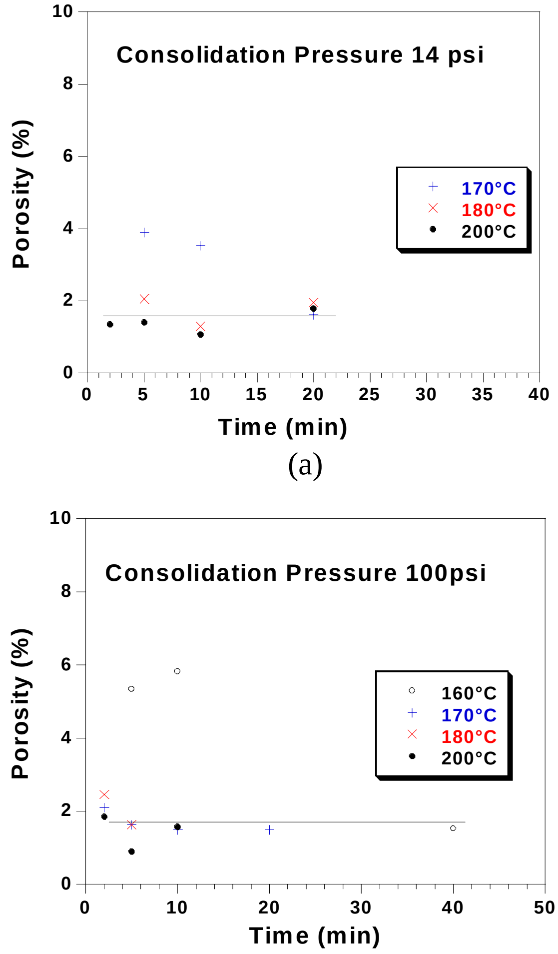


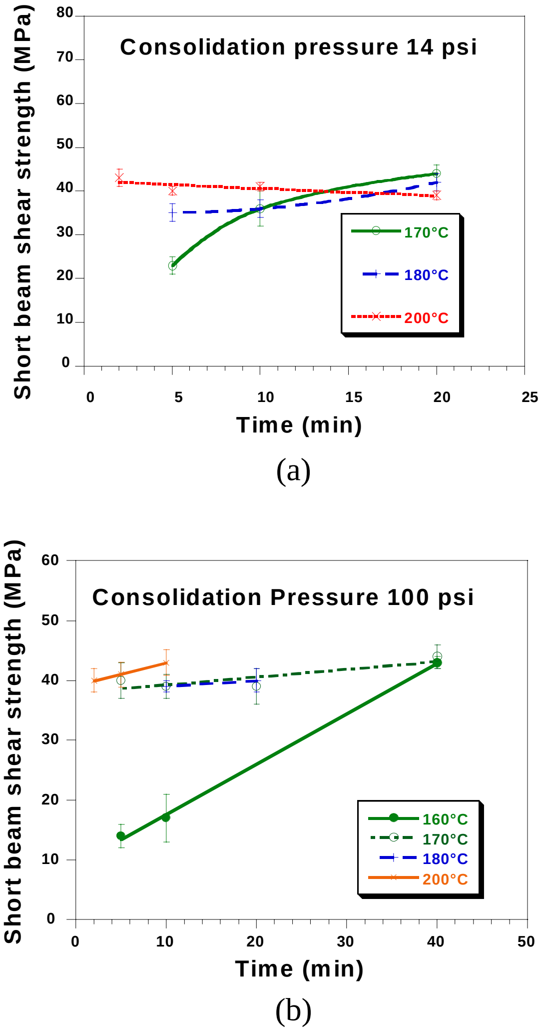
Figure 2. Schematic of the consolidation process of a commingled thermoplastic fabric.



(a)

(b)

Figure 3. Effect of the consolidation temperature and time on the level of porosity in the composite for consolidation pressures of (a) 14 psi and (b) 100 psi.



(a)

(b)

Figure 4. Effect of the consolidation temperature and time on the SBS strength of the composite for consolidation pressures of 14 psi and 100 psi.

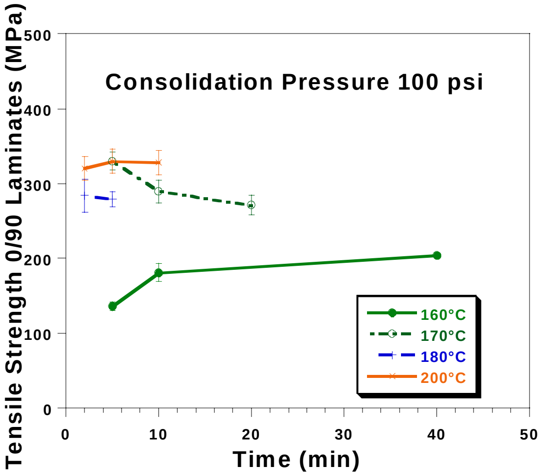


Figure 5. Effect of the consolidation temperature and time on the tensile strength of the composite for a consolidation pressure of 100 psi.

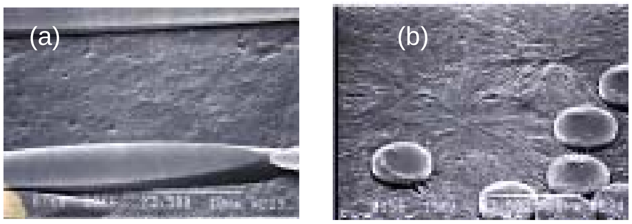


Figure 6. Etched surfaces of glass fiber PP composites consolidated at (a) 160°C and (b) 200°C.

Table 1. Influence of the consolidation conditions and stamping conditions on the mechanical properties of the preform and molded part respectively.

Preform	**Consolidation conditions**	**E_T 0/90 (GPa)**	**σ_T 0/90 (Mpa)**	**SBS (Mpa)**	**Void content (%)**
1	200°C, 5 min, 100 psi	17	280	40	2
2	160°C, 10 min, 100 psi	12	180	17	5
3	160°C, 40 min, 100 psi	17	200	40	2
4	170°C, 2 min, 100 psi	17	320	40	2
5	250°C, 40 min, 100 psi	17	310	40	2
Stamped preform	**Stamping conditions**				
1, 4, 5	T = 180°C, P = 14 psi, Tmold = 23°C	---	270	36	2
2	T= 180°C, P = 14 psi, Tmold = 100°C	---	100	6	25
2	T = 200°C, P = 50 psi, Tmold = 100°C	---	210	23	4

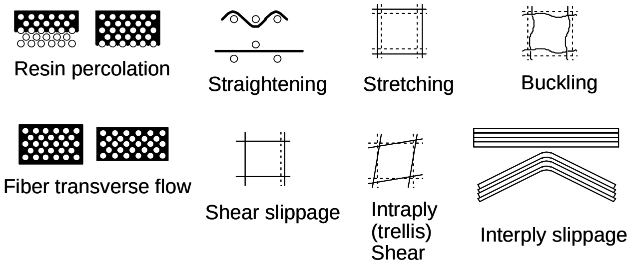


Figure 7. Major laminate deformation mechanisms occuring during the forming stage.

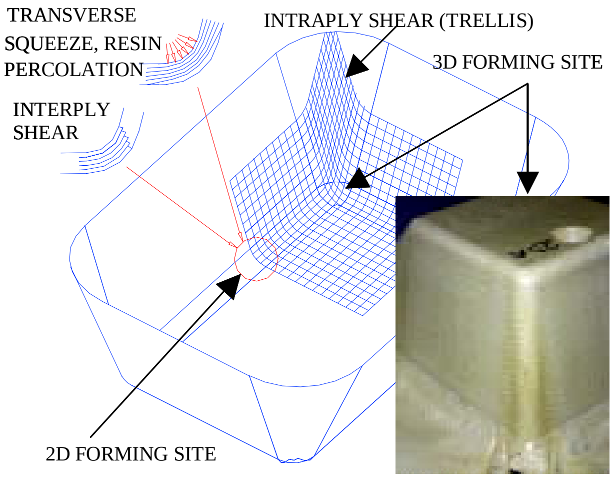


Figure 8. Schematic of the conformation of a fabric (only one quarter is shown in the figure) in the corners and along edges of a part.

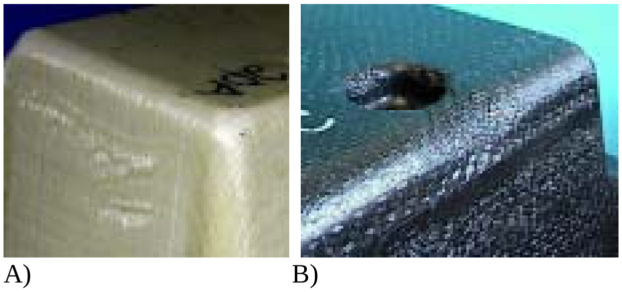


Figure 9. A) Fibre compression and buckling and B) Fibre compaction and resin percolation along edges and corners.

Figure 10. Surface porosity on parts molded with commingled PP/glass mats (left) and twill 2x2 fabrics (right)

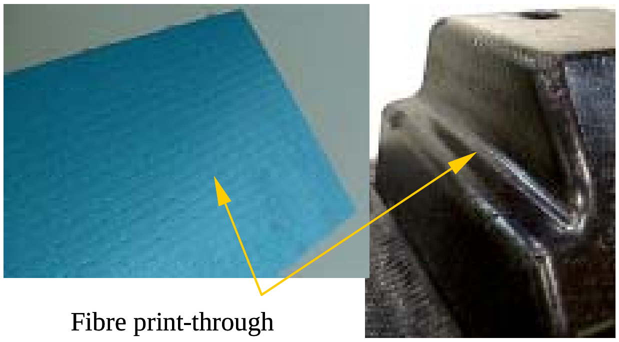


Figure 11. Fibre print-through over a flat part (left) and along the edges of a part (right).

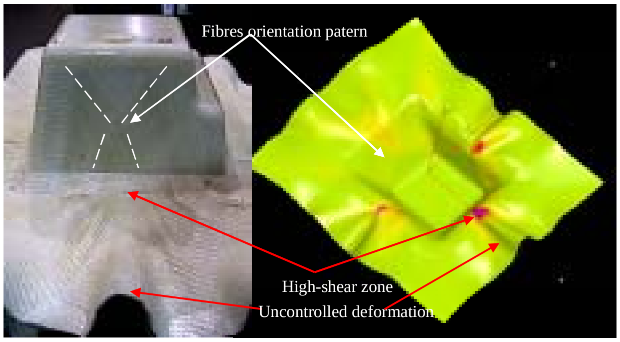


Figure 12. Fibre orientation and laminate deformation predictions from a commercial FEA program and comparison with a moulded part.

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