

## 11.1 Introduction

This chapter gives an overview of the technologies currently used for forming thermoplastic composites (TPCs). Unlike thermosets, which undergo a chemical curing reaction for geometry stabilisation during forming, the forming process for TPCs is relatively simple and involves purely physical changes to the material. Essentially, the matrix is melted by heating, the part shape is formed and, finally, the geometry is stabilised by cooling. There are, of course, other factors to consider, such as the relatively high viscosity of the thermoplastic melt and the degree of consolidation which can be achieved within a specific processing window of time, temperature and pressure. Part quality will clearly depend on the latter. How these more fundamental issues are addressed by the forming technologies currently used by industry is the main subject of this chapter.

The specific forming technology used depends to a large extent on the TPC material form. Is it supplied as partially or fully consolidated? Is the reinforcement in a fabric or aligned form? Section 11.2 describes the various intermediate forms of TPC available and how, in many cases, matrix and reinforcement have been combined to aid the subsequent forming and consolidation processes. Before the various forming technologies are described, the basic principles of isothermal and non-isothermal forming are explained in Section 11.3. The main forming technologies are then covered in some detail in Section 11.4 including compression moulding of flow materials and more aligned structural TPCs, vacuum forming, diaphragm forming, bladder moulding and roll forming. The aim is to give an overview of each technology and address the factors which dictate its application and scope. The chapter concludes with a brief consideration of some recent developments.

## 11.2 Thermoplastic composite materials (TPCs) for forming

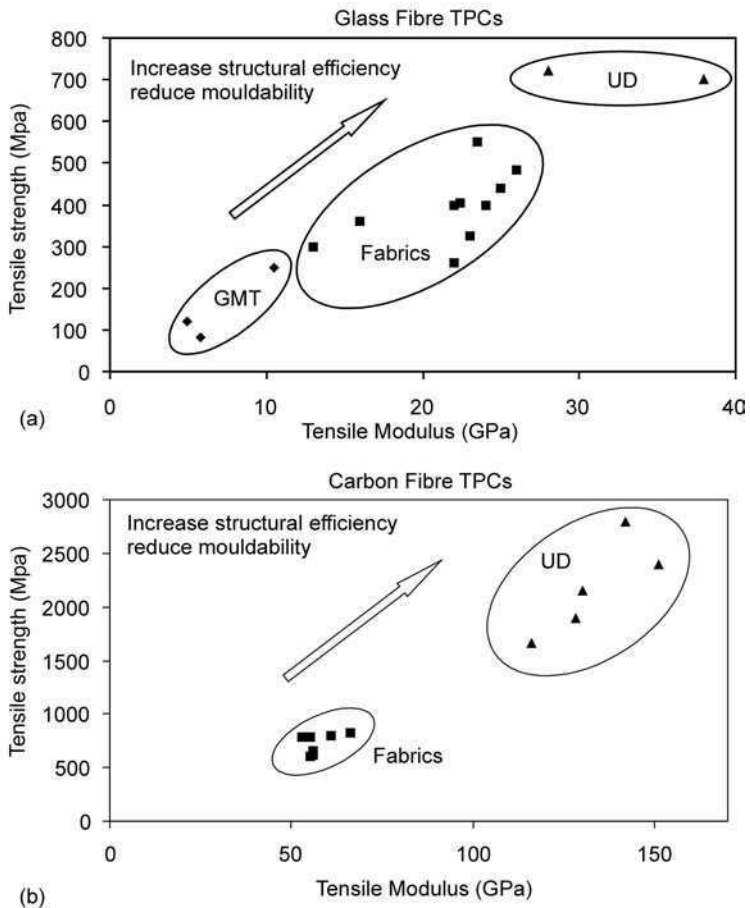
Thermoplastic composites are available commercially in a number of different intermediate forms, each of which determines the appropriate forming

technologies required for making parts from the material. The material forms can be categorised according to their reinforcement fibre architecture and their matrix distribution or level of consolidation in the intermediate form. Thus, fibre architecture can be random, a textile form or fully aligned while matrix distribution can be partially consolidated, fully consolidated, commingled or powder impregnated. Various combinations of these attributes result in the material forms available commercially. Table 11.1 illustrates the broad range, their form (fibre architecture and matrix distribution) and some key properties

*Table 11.1* Range of thermoplastic composites, their form and key mechanical properties (stiffness and strength)

Supplier	Thermoplastic composite	vf (%)	Tensile modulus (GPa)	Tensile strength (MPa)
<b>GMT</b>				
Quadrant	GMT 40wt% glass/PP random	24	5.8	81
Quadrant	GMtex 40 wt% glass/PP 1:1	24	4.9	120
Quadrant	GMtext 40 wt% glass/PP 4:1	24	10.5	248
<b>Glass fabrics</b>				
Comfil	Commingled glass/PET twill	44	22	260
St-Gobain Vetrotex	Twintex glass/PP 2:2 twill	35	13	300
Ten Cate	CETEX glass/PPS fabric	50	23	324
Plytron	Glass/PP 0:90	35	16	360
St-Gobain Vetrotex	Twintex glass/PP 4:1	35	24	400
Bond laminates	TEPEX 22 101 glass/PA66 twill	47	22	400
Bond laminates	TEPEX 22 102 glass/PA6 twill	47	22.4	404
St-Gobain Vetrotex	Twintex glass/PP 1:1	50	25	440
Ten Cate	CETEX glass/PEI fabric	50	26	484
Bond laminates	TEPEX 22 109 glass/PA46 twill	46	23.5	550
<b>Glass UD</b>				
St-Gobain Vetrotex	Glass/PP UD	50	38	700
Plytron	GN tape glass	35	28	720
<b>Carbon fabrics</b>				
Bond laminates	TEPEX 22 206 carbon/PA12 twill	50	55	610
Ten Cate	CETEX carbon/PPS fabric	50	56	617
Ten Cate	CETEX carbon/PEI fabric	50	56	656
Bond laminates	TEPEX 22 209 carbon/PA46 twill	50	55	780
Bond laminates	TEPEX 22 201 carbon/PA66 twill	48	53	785
Schappe Tech.	Stretch broken carbon/PA12	56	61	801
Hexcel	Towflex 22 carbon/nylon twill	51	66	821
<b>Carbon UD</b>				
Hexcel	Towflex 22 carbon/nylon UD	51	116	1665
Ten Cate	Carbon/PEI UD	60	128	1890
Schappe Tech.	TPFL carbon/PEEK slivers UD	52	130	2150
Cytec	APC-2 carbon/PEEK UD	63	151	2400
Gurit	SUPreM carbon/PEEK UD	60	142	2800

when formed into laminates or parts. Although not a comprehensive list, the table includes examples from most of the main suppliers and focuses on glass and carbon fibre reinforced materials. Data has been obtained from a number of sources including materials suppliers and information published by the CORONET European Network in Thermoplastic Composites.<sup>1</sup> Other reinforcements, levels of reinforcement volume fraction and a significantly wider range of resins are also available and suppliers are willing to provide data. To better understand the range of materials, strength versus stiffness data from Table 11.1 is plotted in Figs 11.1(a) and 11.1(b) for glass and carbon reinforced systems respectively. At low stiffness and strength, flow materials, e.g. glass mat thermoplastic (GMT), compete with short fibre moulding compounds (not included here) in semi-structural applications. These materials can be moulded



11.1 Mechanical properties (stiffness and strength) of thermoplastic composites: (a) glass fibre-reinforced TPCs and (b) carbon fibre-reinforced TPCs.

into very complex shapes but have limited structural performance. For structural applications, continuous fibre reinforcement is required. As shown in the figures, fabric forms of reinforcement provide a level of structural performance suitable for many engineering applications. They also retain a capability to be formed into reasonably complex shapes including double curvature and concave surfaces. For maximum structural performance, however, unidirectional (UD) forms of material are required. These are often available as fully impregnated systems with high volume fraction of reinforcement and as a result are difficult to form into anything other than simple shapes. In general, as structural efficiency of the material increases (e.g., through alignment or increase in the volume fraction of the reinforcement), the mouldability, i.e. ability to form into shape, reduces. This reduction is often accompanied by an increase in cycle time and a reduction in production volume. Comparing Fig. 11.1(a) with Fig. 11.1(b) also shows, as expected, that significantly greater structural performance can be achieved with carbon systems. This clearly comes at a cost penalty.

To facilitate a better understanding of the materials a brief description of the main material forms now follows.

### 11.2.1 Partially consolidated – random reinforcement

This form of TPC is commonly called glass mat thermoplastic or GMT for short and consists of several layers of glass fibre mat (chopped strand mat, random continuous strand mat or unidirectional mat combined with either of these two) in a thermoplastic matrix, most commonly polypropylene. The material is used widely in semi-structural automotive applications, e.g. seat backs, front ends and bumpers, and can be manufactured at very high rates using compression moulding (see Section 11.4.1) giving economic high volume production. The raw material is supplied as partially consolidated rigid sheets manufactured by one of two processes: slurry deposition (also called wet laying) or melt impregnation. Slurry deposition involves mixing discontinuous fibres and polymer powder with water to form an aqueous slurry. The solids are then filtered from a head box containing the slurry by a moving screen. A randomly dispersed mat is formed which is then dried and partially consolidated in a heated double belt press. Melt impregnation is the more common method of production and involves passing a glass fibre mat through a preheating oven and combining directly with extruded polymer sheet. Up to six layers of reinforcement, interleaved with polymer melt, may be combined to form the composite sheet. The glass mat is bonded together using thousands of felt needles. This laminate then passes through calendering rolls and a heated double belt press for consolidation. GMT is a flow material and forms by flow moulding (see Section 11.4.1). Thus, volume fractions are typically 20vf% or less and hence parts are generally used in semi-structural applications only. Key suppliers of GMT are Quadrant Plastic Composites and Azdel Inc.

### 11.2.2 Commingled fabrics

The production of commingled tows involves mixing continuous filaments of reinforcement and matrix to produce a tow bundle which can subsequently be woven into fabric possessing good drape properties. A number of techniques for commingling exist. The most common (developed by St-Gobain Vetrotex for their product Twintex – commingled glass/PP or PET) involves extruding continuous polymer fibres through a spinneret and combining with a drawn tow of glass fibres. Typical reinforcement volume fractions for commercial fabric made from this type of commingled tow is 35 vf%, although levels up to 50 vf% and higher are achievable. An alternative process (developed by Schappe Techniques) involves the stretch breaking of carbon fibre tows and their combination with discontinuous polymer fibres into a commingled yarn of discontinuous (but long) fibres. This process produces materials with volume fractions of 50–60 vf%. The fabrics produced from commingled tows/yarns can be formed at significantly reduced pressures and times, a consequence of the reduced flow distance for the resin in the commingled structure. Textile weaving techniques for producing woven fabrics from commingled yarns have had to be developed. Handling of a combination of stiff reinforcement and flexible matrix fibres in the same yarn is difficult. The sizing requirements are particularly important as damage to the reinforcement must be minimised, yet good dispersion between reinforcement and matrix must be maintained during weaving. Recent developments have resulted in the production of three-dimensional woven products from commingled yarns. Near net shape preforms can be made this way which have good interlaminar properties improving impact performance.

### 11.2.3 Powder impregnated fabrics

Powder impregnated tows are produced by impregnating the fibre bundle with fine particles of polymer using either a fluidised bed or water slurry. The process is particularly relevant to resins with high viscosity although a broad range of materials can be used, such as PEEK, PES, PPS, PEI in addition to PP and PA. Powders with diameters similar to reinforcement fibre sizes would be ideal although economics normally prevents this and powders in the range 15  $\mu\text{m}$  to 150  $\mu\text{m}$  are typical. For good dispersion of powder, pins or rollers are often used to open the fibre tow or alternatively air knives and venturis have been proposed. Both mechanical and electrostatic forces control the dispersion process. After powder dispersion, tows are usually passed directly through infra-red ovens (rapid heating) to sinter the powder to the reinforcement fibres. Advantages of powder impregnation include the fact that flow lengths are short and that flow during impregnation takes place predominantly along, rather than transverse to the fibres. This results in very much lower impregnation times. Powder

impregnated tows have to be handled carefully in subsequent textile processes such as weaving into fabric or braiding. The FIT (Fibre Impregnée de Thermo-plastique) process has been developed to keep the powder in place during such textile processes. It involves coating the powder impregnated tow with a thin outer coating of polymer to keep the powder in place. Rapid impregnation can then take place during part forming. One drawback of the FIT process, however, is the debulking which takes place during the forming process which can lead to distortion and fibre buckling. A disadvantage of the powder impregnation method is that the unidirectional prepreg very often has low transverse strength and requires a high content of polymeric binding agent which remains in the system. This, however, is not a problem for fabric forms. Typical reinforcement volume fractions for powder impregnated fabrics are 50–60 vf%.

#### 11.2.4 Solvent impregnated forms

Amorphous resins such as polyethersulphone (PES) and polyetherimide (PEI) can be dissolved in organic solvents and the solution used to form preregs in a similar way to thermosets. Because of the low viscosity of the solution, impregnation of high reinforcement volume fractions can be attained in UD or fabric form. The materials can also be formed using common thermoset forming processes. TenCate's Cetex<sup>®</sup> materials are a typical example. However, the nature of these resins is such that the final part can have poor resistance to solvent attack and during processing volatiles can be released.

#### 11.2.5 Fully consolidated – UD tape

A number of different fully consolidated thermoplastic preregs exist, the longest standing of which is Cytec's 'Aromatic Polymer Composite' (APC-2). APC-2 is a fully impregnated unidirectional carbon/PEEK tape manufactured by a modified pultrusion process. Its high structural properties have ensured its use in high performance aerospace applications. Low molecular weight (and hence low viscosity) PEEK is used to impregnate the carbon fibre tow in an extrusion die. The molecular weight is then increased as a result of a reagent previously applied to the fibre surface. Chain growth occurs initially in the fibre-matrix interphase and moves out to the remainder of the matrix. The process can operate at high speed and produce material with high volume fraction (60vf% or higher). Full impregnation allows the tapes to be fabricated into components at low pressure for a short time (typically 1 MPa for 10 mins). Sheet, or wide tape forms are also available. Because the material is fully impregnated, wide tapes do not possess the required drape properties. To overcome this limitation, narrow tapes are woven into fabric form. Alternatively, tapes can be used in other fabrication processes such as tape laying and filament winding. Similar products exist using other resins, e.g.

PEKK, PEI, PPS and with glass reinforcement, e.g. glass/PP (Plytron<sup>®</sup> is an example) and glass/PA systems.

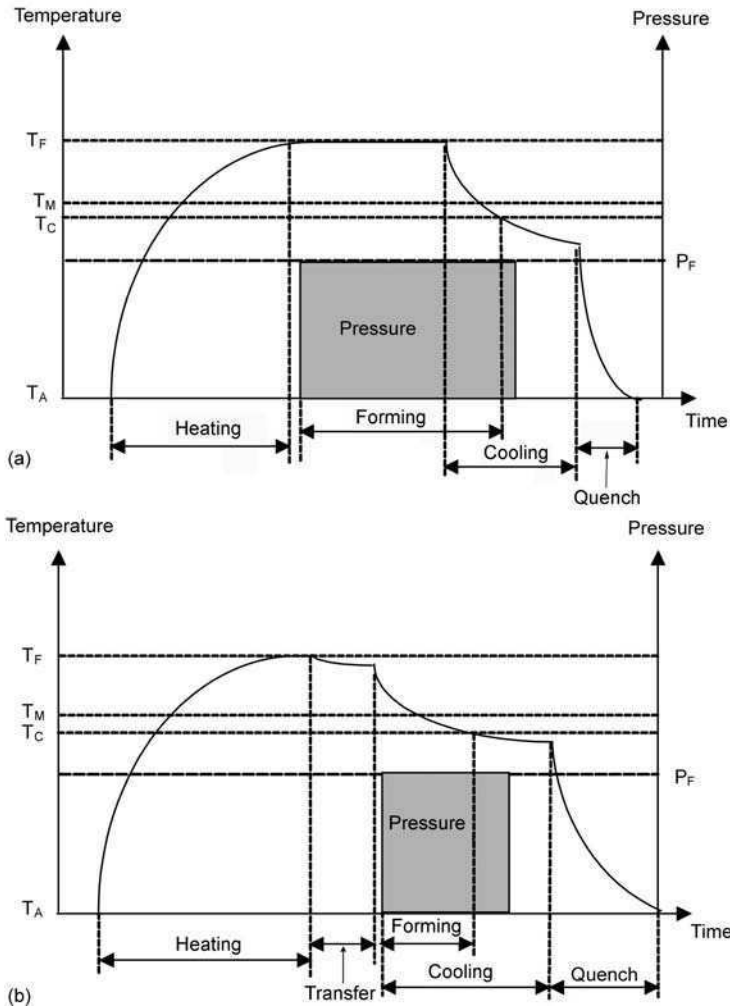
### 11.3 Basic principles of TPC forming technologies

Shape forming of TPCs is not done as an isolated process but involves a number of simultaneous and/or sequential operations including heating, forming, consolidation and cooling of the material. Although TPCs do not have to undergo a curing reaction, as do thermosets, there are specific properties of a TPC which require careful control of the process cycle during forming to achieve all of the above operations and produce a quality part. In particular, the thermoplastic matrix, at melt processing temperatures, has a high viscosity ( $\sim 10^3$  Pa s) by comparison with a thermoset ( $\sim 1$  Pa s). For forming, the material must firstly be heated above the matrix melting temperature where it will be sufficiently flexible to partially conform to a shaped mould. Sufficient pressure and time, at the melt temperature, is then needed to achieve full mould conformation, impregnation of the fibre reinforcement by the matrix and consequent full consolidation of the TPC. The required time at pressure depends on the matrix viscosity, the heating regime and the TPC material form. For the latter, as described in the previous section, a number of forms have been developed specifically to reduce the impregnation/consolidation times. Fully preconsolidated, commingled and powder impregnated forms all reduce the flow distance for the matrix allowing lower pressure processing and/or shorter cycle times.

To achieve the above, both 'isothermal' and 'non-isothermal' processes are used in practice. Figures 11.2(a) and 11.2(b) illustrate temperature-pressure-time profiles for each of these approaches.

In the isothermal process, shown in Fig. 11.2(a), the preform (and tool) are heated to above the matrix melt temperature, i.e. the forming/consolidation temperature, and pressure is applied whilst the temperature is held constant at this level. Pressure is then maintained during cooling to below the recrystallisation temperature to ensure the consolidation achieved during the isothermal part of the cycle is maintained and the resulting part has low void content ( $< 1\%$ ). Quenching (rapid cooling) can take place beyond this time to speed up the process. Whereas isothermal moulding like this can achieve high quality parts with excellent consolidation, as required by the aerospace industry, for instance, the cycle time is compromised by having to cycle the tool temperature during the process.

By contrast, a shorter cycle time can be achieved using the non-isothermal process shown in Fig. 11.2(b). Here, the preform is preheated to the forming/consolidation temperature usually separately in an oven. The preheated charge is then rapidly transferred to a forming tool located in a pressing station (e.g., press or vacuum, etc.). Pressure is then applied quickly at the same time the charge is



11.2 Temperature and pressure vs. time profiles for: (a) isothermal forming and (b) non-isothermal forming of thermoplastic composites.

cooling on contact with the tool, i.e. non-isothermal forming. Pressure can then be removed when the temperature has reduced to below the matrix recrystallisation temperature and quenching can follow if required. The non-isothermal process requires no temperature cycling of the tool and consequently heating and cooling times can be significantly shorter than the isothermal process. Process cycle times are therefore shorter. However, there is a limited time and temperature window during which forming and consolidation can take place. Consequently, the method is often applied to materials with lower reinforcement volume fraction and/or with forms requiring lower consolidation pressures and times, e.g. commingled and powder impregnated materials. The non-isothermal



process is also attractive where medium to high production volumes, i.e. short cycle times, are required, and higher void content levels are acceptable, such as in the automotive industry.

## 11.4 Forming methods

### 11.4.1 Compression moulding

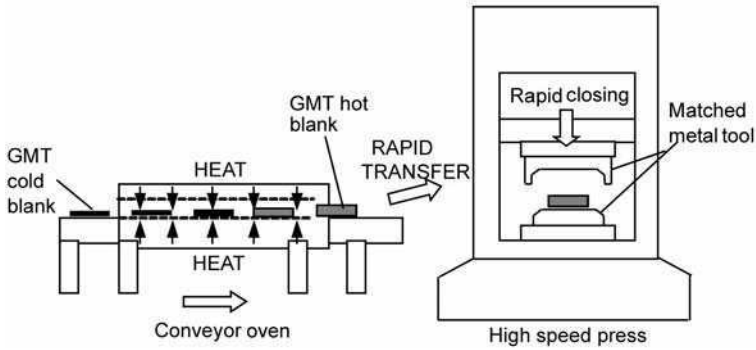
Compression moulding is used here to denote processes where the forces required to form a part are provided by a press (usually high pressure), containing a matched metal (male and female) or metal-rubber (i.e. deformable) tool. In the case of TPCs, compression moulding was originally developed for the forming of flow materials, e.g. GMT, however the process has more recently been used for both textile forms and fully aligned forms of TPC. In these cases, the process is often referred to as 'stamp forming'. The compression moulding (stamp forming) process is non-isothermal and capable of high production rates with cycle times typically under one minute. Although closely related, it is appropriate to consider the forming of flow materials and aligned materials separately.

#### *Flow moulding of GMT*

Glass mat thermoplastic (GMT) is supplied in the form of partially consolidated sheets of random glass mat and polymer (typically PP) manufactured by either a slurry deposition process or a melt impregnation process. The use of random reinforcing fibres (e.g., chopped strands or continuous swirl mat) at relatively low volume fractions (20–40 wt%) results in a material, in melt form, capable of flowing in the mould. The GMT sheet is fabricated into parts by cutting into blanks and stamping or flow moulding in a matched metal tool in a press. Net shape parts are produced. Detailed guidelines for the forming/moulding of GMT can be obtained from materials suppliers and the following overview draws on information supplied by Quadrant Plastic Composites.<sup>2</sup>

The forming process, schematically shown in Fig. 11.3, involves the following stages:

1. Several blanks are preheated in an infra-red or hot circulating air oven to the processing temperature (200–220°C for PP based GMT). Conveyor ovens are normally used for a continuous process. Blanks loft considerably during heating (two to three times original thickness) as the frozen-in forces created during GMT sheet manufacture are released. This lofting has consequences for material heating at the later stages.
2. Blanks are transferred by hand or robot to a matched metal mould, the latter being at a temperature of 20–80°C.
3. Hydraulic pressure is applied by the press. High closing speeds of 600 mm/s are necessary to retain material temperature and are followed by compression



11.3 Schematic diagram of the compression flow moulding process for GMT.

speeds of  $\sim 30$  mm/s. Full pressures of 10–20 MPa (100–200 bar) are held for less than six seconds. This allows the GMT to flow in the mould. During flow, the material is cooling against the cool mould surface (i.e. a non-isothermal process) and therefore the material has a limited flow distance to part thickness ratio.

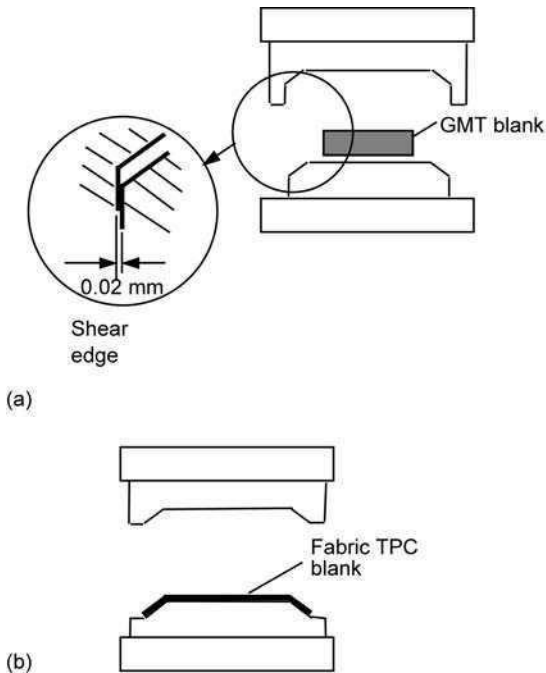
4. Cooling takes place in the mould at a typical rate of 4 to 5 seconds per mm of part wall thickness. Shrinkage is  $\sim 0.3$ – $0.5\%$ .

The whole process is high speed with cycle times of approximately 30–60 seconds. Processing times for GMT compare favourably with SMC (sheet moulding compound) which has a moulding cycle of 1.5–6 minutes. Other advantages the material possesses over SMC is that pressure is only required briefly at the bottom of the press stroke and not continually. Because the material flows, complex parts containing ribs, undercuts, inserts and varying wall thickness can all be made.

Quality of the final part depends on careful attention to a number of factors, the following in particular:

- *Blank configuration* – must be cut to the mould size and configured for part geometry; stacked in centre of mould to allow regular flow; should not be folded; overlapping to help knit weld lines; designed for flow, e.g. no bridging of ribs; no pinching by mould side walls.
- *Heating* – do not heat blank surface any greater than  $230^{\circ}\text{C}$  for PP based GMT (indicated by smoking of the material); heat blank internal temperature to between  $190^{\circ}\text{C}$  and  $215^{\circ}\text{C}$ . Transfer quickly to mould to prevent pre-cooling.
- *Pressing* – important to maintain a high compression rate (30 mm/s), otherwise incomplete parts will result.

Compression moulds used for GMT must have close tolerance telescoping shear edges (see Fig. 11.4(a)) to seal off the mould cavity at its outer shape before the GMT reaches the edges. At the same time air is allowed to escape



11.4 Schematic diagram of (a) a GMT matched metal mould with shear edge and (b) a hot stamp forming tool.

without causing flashing. Clearance of these edges should be 0.02 mm to 0.03 mm and the surfaces at these edges should be hardened (flame hardening is suitable). A heavy duty guidance system should be used to prevent wear of the sealing edges, and safety stop blocks are necessary to prevent the two halves of the mould closing on each other. The stop blocks are not used to determine part thickness but are normally set at 0.5 mm below minimum part thickness. Mould temperatures should be held constant at 40°C to 70°C using a carefully designed cooling system. The aim is to maintain a uniform temperature distribution across the mould surface.

Ejector pins should be used to eject the part evenly, in some cases from both halves of the mould. Venting is important, particularly at ribs or bosses where overheating and scorching can otherwise occur. For ease of flow and ejection the mould surface should be highly polished. GMT causes very little wear, so mould surface hardening is not necessary except near shear edges as already discussed.

Production moulds are generally made from tempered steel with a medium hardness. Apart from high volume, hardening is not necessary. Prototype tooling can be made from a variety of materials such as Kirksite or aluminium. For these, cooling channels can be omitted, as can the ejector system and mould surface polishing may not be necessary.

The forming of GMT into parts using flow moulding is a mature technology principally developed for the high rate production of semi-structural automotive parts.

### *Hot stamping of commingled fabrics and aligned prepregs*

For higher performance parts, fabric forms or fully aligned TPCs, with higher volume fractions, are used (see earlier section on 'Material forms'). Such materials can also be formed into shape using compression moulding with matched metal tooling. Shear edge tools are not necessary in this case as the materials do not flow in the mould (see Fig. 11.4(b)). Commingled and powder impregnated TPC fabrics exhibit the better draping properties, although, as for all materials, preheating to above the matrix melt temperature takes place prior to forming and consequently, even fully aligned materials are sufficiently flexible to conform to shape. Fabric forms can, however, generally be formed to more complex double curvature shapes and to greater draw depths.

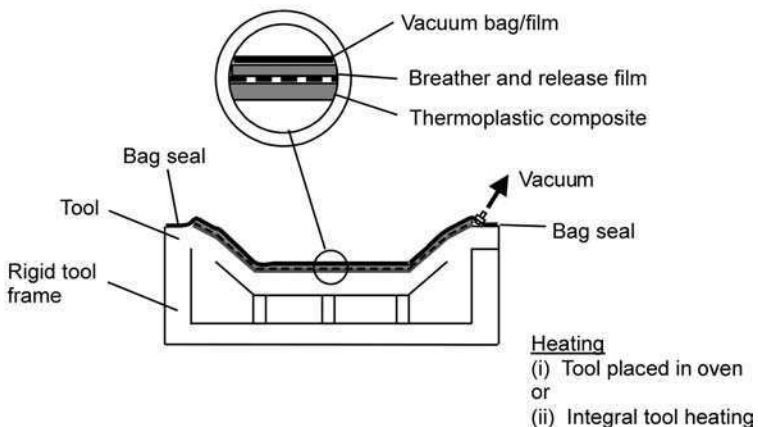
As with GMT, the intermediate material, e.g. fabric, is preheated, most commonly in an infra-red oven to melt the matrix. The material is then transferred rapidly (to minimise cool down) to a cool matched metal tool which closes quickly and forms the part into shape whilst the material cools (i.e. a non-isothermal process). Unlike GMT, the material does not flow in the mould and hence it is more of a 'hot stamping' process. As this is not a flow process and because the intermediate material already has a high degree of impregnation, forming can be undertaken at significantly lower pressures (1–2 MPa) compared to GMT moulding (10–20 MPa). Forming pressures do vary over the part depending on the local draw angle and part thickness. Horizontal surfaces, for instance, support high pressures and can achieve optimum consolidation levels with minimum void content. More vertical surfaces on the part, however, support lower pressures and can suffer from poor consolidation. Soft tooling techniques (described below) can alleviate this problem. Other factors important when forming fabrics are the maintenance of fibre direction and architecture during heating and transfer to the tool and the avoidance of wrinkling in regions of high fabric shear when forming. Both of these problems can be avoided by the use of a blank holder. The fabric is stretched under light load and held by springs biaxially in the fabric plane during heating. The blank holder thus restrains any shrinkage during heating and holds the fabric in place during transfer to the tool. During forming, the blank holder also offers a relatively low level of membrane pressure whilst the material draws in. This pressure has been shown to increase significantly the maximum attainable fabric shear angle before wrinkling occurs.

Matched metal tooling results in a pressure distribution across the part which depends on the part geometry, in particular, the draw angle and often results in variable consolidation, as discussed above. The variation in pressure across the tool can be reduced or, in some cases, eliminated by using a compliant material

for one half of the tool, e.g. the female half.<sup>3</sup> Elastomers such as silicon rubber or polyurethane are commonly used. The pressure distribution with such a tool is generally an improvement over matched metal tools and can result in near hydrostatic pressure across the tool and consequently more consistency in consolidation. Disadvantages of rubber tooling include increased cycle times due to reduced cooling rates caused by the low thermal diffusivity of the rubber and reduced production volumes achievable before tool damage and wear occurs.

### 11.4.2 Vacuum forming

Vacuum forming is a common technique for forming TPCs similar to the method used for thermosets. Useful information on the process including tooling and part design can be found in the Twintex<sup>®</sup> vacuum moulding manual supplied by St-Gobain Vetrotex.<sup>4</sup> Figure 11.5 shows the basic isothermal process. The TPC laminate is laid up on a single-sided mould (metal, metal shell or composite) and covered with a release film (i.e. peel ply) and breather cloth. The former prevents the breather cloth bonding to the laminate and the latter ensures all air is extracted under vacuum, and even distribution of pressure. A vacuum bag is then positioned over the arrangement and sealed around its edges against the mould. Typical bag materials include disposable nylon film or reusable silicon rubber. The air is pumped out until vacuum pressure up to 0.9–0.95 bar is achieved. The whole arrangement is then placed in a circulating air oven and the temperature raised to above the matrix melting temperature for forming and consolidation to take place. Consolidation time depends on part size, material thickness and degree of void content allowable in the final part. Generally 10–15 minutes consolidation time will result in void content below 2%. Longer times are necessary for better quality. It is also important that



11.5 Schematic diagram of the isothermal vacuum forming process.

sufficient heating time has been allowed to ensure the tool reaches the processing temperature and the laminate is heated through its full thickness. Large tools (for large parts) can result in significant heating times (hours) making the technique, in most cases, a low volume process. To speed up the process, shell tools with lower thermal inertia can be used but this will depend on the economics of the process. Following consolidation, the tool, etc., is removed from the oven and allowed to cool before the part can be removed. Vacuum is maintained during cooling. Again, depending on the size and construction of the tool, cooling can be a slow process. An alternative to oven heating, is to heat the tool directly using oil or electrical methods. This can, in some cases, speed up the process, but its viability depends very much on the part size and shape. More complex shaped parts prohibit uniform heating by this method.

Non-isothermal vacuum forming enables faster cycle times to be achieved. In this case the TPC laminate is preheated in an oven, transferred and laid up rapidly on a cool tool following which a vacuum is applied immediately. This can be achieved by the use of a vacuum table as shown in Fig. 11.6. The table comprises a reusable silicone rubber bag mounted in a frame capable of being closed and sealed against the table. Thus, when the preheated laminate is transferred to the tool, the bag can be closed rapidly and a vacuum pump activated to remove air and apply the vacuum. Time is critical in the non-isothermal technique with transfer time being the most important, which should be less than 20 seconds to ensure material temperature is retained. The transfer process can be improved by using transfer plates, i.e. preheated metal plates, also to assist temperature retention during transfer. Tool temperature can also be raised to slow down the cooling process, however, this will clearly affect cycle times and can result in unacceptable surface finish to the part. Non-isothermal



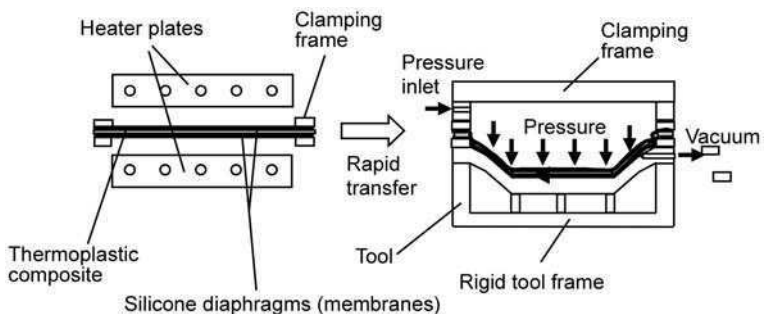
11.6 A vacuum table.

vacuum moulding is clearly a rapid process but is restricted to the size of part mouldable. Above about  $1 \text{ m}^2$  projected area, preheated charge transfer becomes problematic.

### 11.4.3 Diaphragm forming

Both single and double diaphragm forming processes are used commercially for forming TPCs.<sup>5</sup> Figure 11.7 shows a schematic representation of the double diaphragm forming process in an autoclave. The TPC laminate is placed between two flexible diaphragms (membranes) which are then clamped around their edges. The diaphragm-laminate stack is then clamped across the mould and the whole is placed in the autoclave. The space between the diaphragms is then evacuated. This serves to hold the laminate in place during heating and forming and prevents wrinkling. The autoclave temperature is then raised above the matrix melt temperature and pressure (typically up to 7 bar) is applied. The laminate itself is not edge clamped and is thus free to conform to the mould shape (along with the flexible diaphragms) by friction slip against the diaphragms and inter-laminar slip within the laminate. Relatively deep draw and complex curvatures can be achieved in diaphragm formed parts. The diaphragms must be flexible at temperature and a number of different materials are used, depending on the laminate melt temperature. Thin superplastic aluminium diaphragms and high temperature polyimide (PI) films, e.g. Upilex-R<sup>®</sup>, are commonly used for high performance laminates such as Carbon Fibre/PEEK (APC-2) while silicone rubber sheets have been used for lower performance/lower temperature materials such as Glass Fibre/PP (Twintex<sup>®</sup>). The process is isothermal and, because of mould temperature cycling, has a relatively long cycle time although this can be shortened by using shell type moulds. As a result of the high pressure and isothermal moulding, very high quality laminates with low void content can be achieved, however, this is countered by the relatively long cycle times.

To speed up the cycle time, diaphragm forming can be undertaken non-isothermally using vacuum forming and press methods. In this process, the

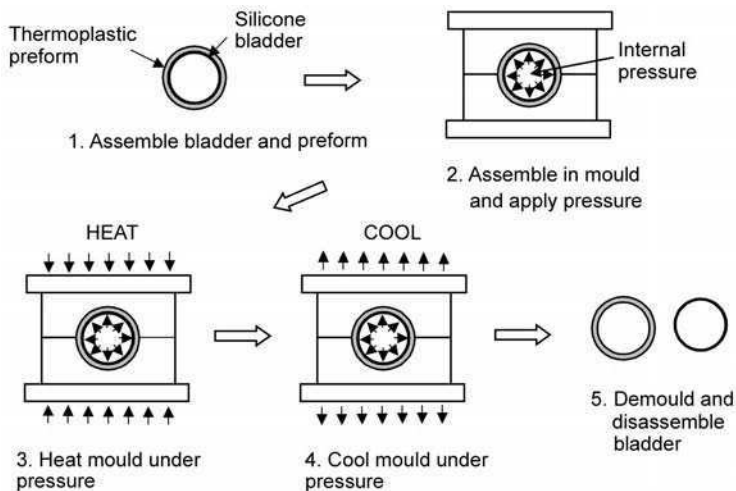


11.7 Schematic diagram of the double diaphragm forming process.

laminate contained between a double diaphragm, is preheated between heaters and rapidly transferred using a conveyor mechanism to the forming station. Pressure of 5 bar is applied above the diaphragms using inert nitrogen gas and a vacuum is applied below through the single-sided tool. This ensures rapid forming of the charge onto the cool tool surface.

#### 11.4.4 Bladder moulding

Bladder moulding is used to form hollow TPC vessels, e.g. pressure vessels, pipe sections etc. Both isothermal and non-isothermal variants of the process have been developed giving cycle times of 10–15 minutes and 2–3 minutes respectively.<sup>6</sup> The technique utilises commingled tows braided into hollow sleeves which are formed and consolidated on the internal surface of a hollow mould using a pressurised bladder. Figure 11.8 illustrates the isothermal process. Firstly, the braided TPC sleeve is assembled over a bladder. Typical bladder materials include compliant silicone rubber, capable of withstanding melt temperatures, or rigid net shape extrusion blow moulded polymer, e.g. nylon, which will soften but not melt when raised to the TPC melt temperature. Both TPC sleeve and bladder are then pinched between the two halves of a hollow mould. An initial low pressure ( $\sim 2$  bar) is applied to prevent the collapse of the bladder-sleeve arrangement during heating, following which the tool temperature is raised above the TPC matrix melt temperature. Pressure is then increased (to  $\sim 10$  bar) to ensure rapid bladder expansion and forming and consolidation of the TPC braid against the inner tool surface. Direct tool heating or oven heating methods are both used in practice. Following an appropriate consolidation time, the tool is cooled and the hollow part removed.

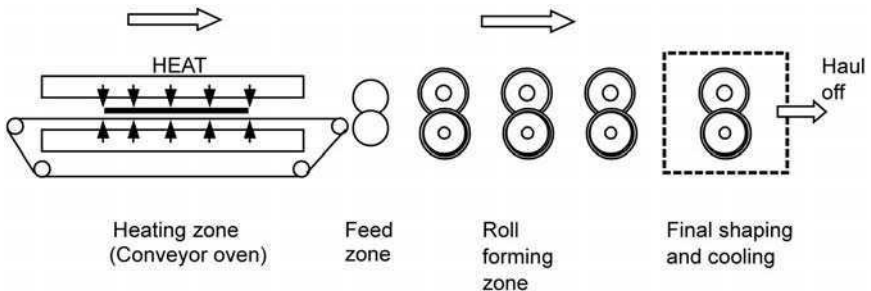


11.8 Schematic diagram of the bladder moulding process.



### 11.4.5 Roll forming

Roll forming is an established metal processing route for producing constant cross-section shaped profiles. The basic principle is to form the material progressively through a series of pairs of forming rolls until the desired cross-section is achieved. Only in the last ten years or so has the process been applied on a commercial scale to the forming of continuous fibre reinforced thermo-plastic composite sheet/strips. Figure 11.9 shows the basic stages required to roll form TPC strips as reported in an investigation of the process by Henninger<sup>7</sup> and summarised as follows. In this process, strips (800 mm × 90 mm) of glass fibre/PP and glass fibre/PA, both fully consolidated, 0/90 twill weave, are firstly fed on a conveyor belt into an infra-red heater. As the heater only heats the surface layers of the strip, it must be of sufficient length to allow time for the heat to conduct and melt the matrix through the strip thickness. Overheating of the surface must also be avoided if degradation of the matrix is not to occur. Following heating, the strip temperature is allowed to cool back towards (but above) the matrix recrystallisation temperature in a dwell zone before it is fed into the forming rolls. The entry temperature to the rolls is a critical process parameter and temperatures 10–20°C (depending on production speed) below the matrix melting temperature have been found to be optimum. Too low an inlet temperature results in high void content in the formed strips i.e. poor consolidation. Too high a temperature results in spring back or spring forward depending on throughput speed. Forming takes place in a number of stages and must be completed before the material cools to the recrystallisation temperature. Following forming to the final shape, further shape consolidation is achieved by passing through further rolls. However, to avoid spring back/forward it is important that the material cools to below the recrystallisation temperature before passing out of the final rolls. To achieve this, forced cooling may be necessary in the shape consolidation zone.

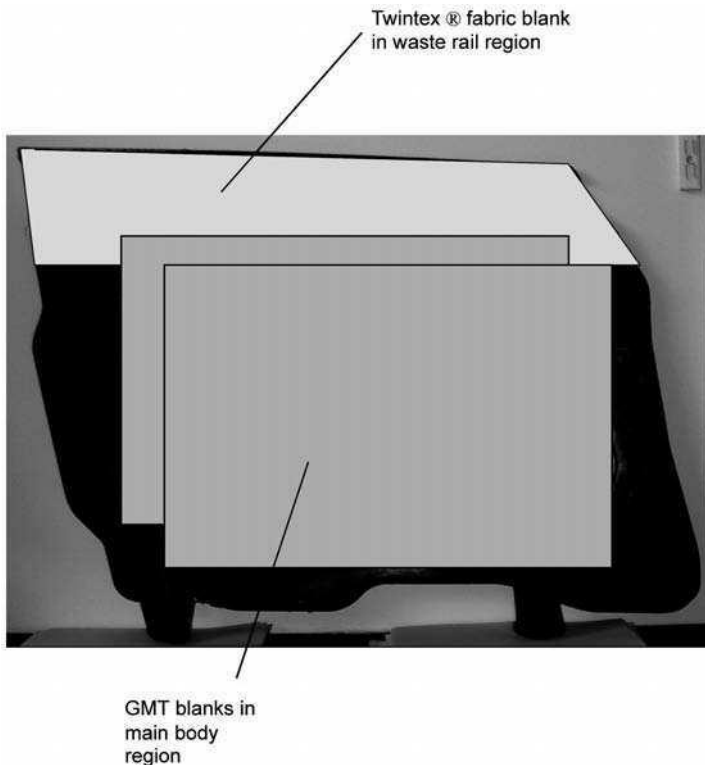


11.9 Schematic diagram of the roll forming process.

## 11.5 Some recent developments

### 11.5.1 Co-moulding

Combining material forms to achieve optimum part design and mouldability has been the subject of much activity in recent years. Wakeman *et al.*<sup>8,9</sup> report on the development of ‘over-injection moulding’ of thermoplastic composites, both UD and fabric forms. The technology involves robotic placement of UD tape or tows or the placement of pre-stamped fabrics into an injection tool. Preheating of the composite forms to just below the matrix melting temperature ensures good final consolidation and fusion with the over moulded long fibre thermoplastic (LFT) injected into the mould. The continuous TPC forms provide structural efficiency where required and the LFT enables ribs and complex part features to be moulded. Cycle times are low, in line with LFT injection moulding. Combination of GMT and fabric TPC in a compression moulding process,<sup>10</sup> to form a prototype automotive door cassette, has been shown to achieve similar results. Figure 11.10 shows the charge placement for this part resulting in a highly structural waste rail (top of the cassette) and a relatively complex shaped main



11.10 Blank configuration for a co-moulded automotive door cassette (after Wakeman *et al.*<sup>10</sup>).

body with lower mechanical properties. A similar process development, termed E-LFT (Endlessfibre reinforced Long Fibre Thermoplastic) has been reported by Ruegg *et al.*<sup>11</sup> and combines the local placement of continuous fibre TPC with LFT in a compression moulding process. Commercial material combinations, using the above principles, are now available for parts moulding, e.g. Quadrant Plastic Composites' GMText<sup>®</sup> combines two skin layers of commingled TPC, Twintex<sup>®</sup>, with an intermediate layer of GMT. The flowability of the latter aids the forming process for the former by allowing for thickness variations and evening out pressure variations across the mould.

Many of the above processes have moved into mainstream manufacture of production automotive parts at high volumes and the materials combinations and co-moulding processes are expanding the application areas for both GMT and LFT.

### 11.5.2 Sandwich moulding

TPC sandwich structures generally possess significantly higher stiffness and strength to weight ratios than monomer TPC structures and can offer lightweight solutions in many applications. The forming of flat TPC sandwich structures/panels and beams has previously entailed pre-consolidation of the TPC skin in a press forming process and subsequent reheating (often the skin surface layers only) before bonding to a thermoplastic core, typically a low density polymer foam or honeycomb. This bonding process can be achieved continuously by feeding reheated skins over a cold core in a double belt laminating process or in a batch process using compression moulding. In the latter process, tool stops are required to prevent over crushing of the core during bonding. Recent work has aimed at developing the single shot moulding of these structures, i.e. consolidation of the TPC skin at the same time as the sandwich panel is formed. By removing the skin pre-consolidation process, this will save on manufacturing time and cost. The problem is to avoid over crush of the core during the process while still attaining good skin consolidation. This requires correct choice of forming pressure relevant to the crush strength of the core material. Brooks *et al.* have demonstrated that good quality glass/PP skinned sandwich structures with PP foam cores can be made using a low cost single step vacuum forming process.<sup>12</sup> Heated transfer plates are used to retain skin temperature during transfer from the heater to the mould.

### 11.5.3 Reaction moulding

Recent material developments have resulted in a class of low molecular weight cyclic thermoplastic polyesters (CBTs) which can be melted to a very low viscosity resin in the temperature range 120–160°C.<sup>13</sup> With the addition of a catalyst, the resin polymerises into high molecular weight thermoplastic PBT.

Because of the initial low viscosity, these resins can be combined with high volume fraction fibre reinforcement in a similar way to thermoset resins. Thus, many moulding/forming processes used for thermosets are also applicable to composites manufactured with CBT resins such as resin transfer moulding and resin film infusion.<sup>14,15</sup> Cyclics offer the property advantages of TPCs with the processing advantages of thermoset composites, e.g. impregnation of high volume fraction reinforcement. However, the fact that the resins do undergo polymerisation in the mould precludes them from the very high rate (low cycle times) associated with most TPC forming processes.

## 11.6 Conclusions

Forming methods for thermoplastic composites are developing at a rapid rate. This chapter has provided an overview of the processes currently available for forming TPCs into shape in addition to some recent developments. Whereas isothermal processes can produce high quality parts, cycle times are compromised by the need to thermally cycle the tool during processing. Conversely, non-isothermal processes reduce significantly the cycle time but generally at a cost of part quality. The challenge therefore is to form high quality, structurally efficient parts at high production rates. Significant innovation in both materials forms and the forming technologies themselves in recent years are addressing this challenge and it is likely that further developments will continue into the foreseeable future.

## 11.7 References

1. CORONET European Network in Thermoplastic Composites, *www.coronet.com*.
2. 'GMT Part Design and Moulding Guidelines', Quadrant Plastic Composites, *www.quadrantplastics.com*.
3. Mallon P J and Obradaigh C M, 'Compliant Mold Techniques for Thermoplastic Composite', in *Comprehensive Composite Materials*, Ed. A Kelly and C Zweben, Volume 2, Ch. 2.26, 874–912.
4. Twintex<sup>®</sup> Vacuum Moulding Manual, St-Gobain Vetrotex, February 2005, *www.twintex.com*.
5. Pantelakis S G and Baxevani E A, 'Optimization of the diaphragm forming process with regard to product quality and cost', *Composites: Part A*, 33, 2002, 459–470.
6. Wakeman M D, Vuilliomenet P and Manson J-A E, 'Isothermal and non-isothermal bladder inflation moulding of composite pressure vessels: a process/cost study', *Proc. 24th SAMPE Europe Conference*, 1–3 April 2003, Paris, France.
7. Henninger F and Friedrich K, 'Production of textile reinforced thermoplastic profiles by roll forming', *Composites: Part A*, 35, 2004, 573–583.
8. Wakeman M D, Beyeler P, Eble E, Hagstrand P-O, Hermann T, and Manson J-A E, 'Hybrid thermoplastic composite beam structures integrating UD tows, stamped fabrics and injection/compression moulding', *ECCM-11, Proc. of 11th European Conference on Composite Materials*, 31 May–3 June, 2004, Rhodes, Greece.

9. Wakeman M D, Hagstrand P-O, Ecabert B, Eble E, and Manson J-A E, 'Robotically placed continuous fibre tow as tailored structural inserts for over injection moulding', *Proc. 25th SAMPE Europe Conference*, 30 Mar–1 April 2004, Paris, France.
10. Wakeman M D, Cain T A, Rudd C D, Brooks R and Long A C, 'Compression moulding of glass and polypropylene composites for optimised macro- and micro-mechanical properties. Part 4: Technology demonstrator – a door cassette structure', *Composites Science and Technology*, 2000, 60, 1901–1918.
11. Ruegg A, Stotzner N, Jaggi D and Ziegler S, 'E-LFT process – a new mass production process for structural lightweight', *Proc. 25th SAMPE Europe Conference*, 30 Mar–1 April 2004, Paris, France, 318–324.
12. Brooks R, Kulandaivel P and Rudd C D, 'Vacuum moulding of thermoplastic composite sandwich beams', *Proc. 25th SAMPE Europe Conference*, 30 Mar–1 April 2004, Paris, France, 494–500.
13. Brunelle D, Bradt J E, Serth-Guzzo J, Takekoshi T, Evans T L, Pearce E J and Wilson P R, 'Semicrystalline polymers via ring-opening polymerization: Preparation and polymerization of alkylene phthalate cyclic oligomers', *Macromolecules*, 31, 1998, 4782–4790.
14. Rosch M, 'Processing of advanced thermoplastic composites using a novel cyclic thermoplastic polyester one part system designed for resin transfer moulding', *Proc. 24th SAMPE Europe Conference*, 1–3 April 2003, Paris, France, 305–310.
15. Coll S M, Murtagh A M and O'braidigh C M, 'Resin film infusion of cyclic PBT composites: A fundamental study', *Proc. 24th SAMPE Europe Conference*, 1–3 April 2003, Paris, France, 311–317.