3-D THERMOFORMING OF CONTINUOUS FIBRE REINFORCED THERMOPLASTICS USING THE DIAPHRAGM FORMING TECHNIQUE

J. Krebs*, K. Friedrich**, D. Bhattacharyya***

*At present with the University of Auckland, New Zealand

**Institut für Verbundwerkstoffe GmbH, Universität Kaiserslautern, Germany

***Composites Research Group, University of Auckland, New Zealand

ABSTRACT

One of the major barriers still excisting in the development of rapid forming for advanced thermoplastic composites is the occurrence of instabilities in the composite laminate during forming. This paper describes the progressive development of a thermoforming process which ultimately enabled the production of defect-free components out of multi-ply flat sheets. By introducing a vacuum bag, a sufficient support was provided to the laminate which prevented instabilities such as in-plane wrinkling and out-of-plane buckling from occurring during forming.

Keywords: *vacuum forming; pressure forming; diaphragm; grid strain analysis; vacuum bag*

1. INTRODUCTION

With the relatively recent advent of fibre reinforced thermoplastic composites, these materials have become increasingly appealing to automotive, refrigeration and other industries which go beyond the traditional regimes of aerospace/aircraft engineering. They have started replacing many common engineering and even thermoset materials due to their superior chemical and mechanical properties in the form of corrosion resistance, higher shelf-life, strength/weight and stiffness/weight ratios and, very importantly, better toughness performance. The ability of the thermoplastic composites to be deformed and reshaped is their biggest advantage. One of the most recent additions in this group of materials is a continuous glass fibre reinforced polypropylene prepreg called Plytron® (originally developed and manufactured by ICI Ltd., England). It can be consolidated and formed according to the user's requirements. Through various processes such as thermoforming, tape laying and filament winding, the continuous fibre reinforced thermoplastic (CFRT) materials can render themselves as alternatives to traditional materials under specialised or mass manufacturing situations. Nevertheless, one of the major barriers in the development of rapid forming techniques for advanced thermoplastic composites is the occurrence of instabilities and fibre migration in the composite laminate during forming. Instability phenomena considered to be the most important are out-of-plane buckling and in-plane wrinkling, which are both irreversible and extremely damaging to the performance of the finished structure [1]. Other defects associated with forming technologies relate to diaphragm failures and tow splitting, but in many cases these problems can be avoided by efficient tool and preform design. Another drawback of using CFRT materials for the industrial use is sometimes their high cost for producing good quality intermediates, known as pre-impregnated tapes (prepregs). Therefore, an innovative fabrication technology is needed to offset these high costs and to encourage their use in all branches of modern industry. The major thrust of current research is the further development of manufacturing methods which can deliver complex-curvature shapes with acceptable microstructure and fibre distribution under competitive economic conditions. This implies that finding ways to transform multi-ply laminates into defect-free 3-D components in an efficient manner is the key factor in determining the future of CFRT materials.

The aim of this paper is to illustrate how a suitable thermoforming technique was developed in the laboratory, capable of producing defect-free components with 3-D geometry. Utilising the diaphragm forming technique thermoforming experiments were conducted in order to form hemispherical dome, rectangular container and conical cup shaped components out of multi-ply flat sheets. These shapes, in spite of their apparent simplicity, involve the deformation modes which are prevalent in much more complex shapes. The following sections describe the progressive development of the thermoforming process which ultimately enabled the production of defect-free components.

2. THERMOFORMING OF CFRT MATERIALS

2.1 General Aspects

Thermoplastic polymers can undergo a reversible phase change from solid to liquid, thereby enabling the development of shaping and joining methods analogous to those for conventional metallic materials. Because of the collimated fibre architecture, these materials exhibit *hyper-anisotropy* ratios in the melt state as high as 10^6. Thus, in the case of fibre reinforced thermoplastic sheets the potential processing advantages have led to the development of the thermoforming process and to the adoption of sheet forming techniques typical of those used with metallic materials - one of the most pervasive methods in contemporary manufacturing technology [2-4].

Unlike the monolithic metallic sheet, CFRT materials are inextensible in the fibre direction. For these material systems, the dominant mode of deformation, parallel to the fibres, during sheet forming is therefore shearing within the individual plies and between them, i.e. intra- and interply shear. Additional mechanisms that occur when forming a flat multi-ply sheet into a double curvature formed component are (a) resin percolation through and along the layers of reinforcing fibres and (b) resin flow transverse to the fibres [5, 6]. A schematic diagram of the deformation modes in the increasing order of shape complexity is shown in Figure 1.

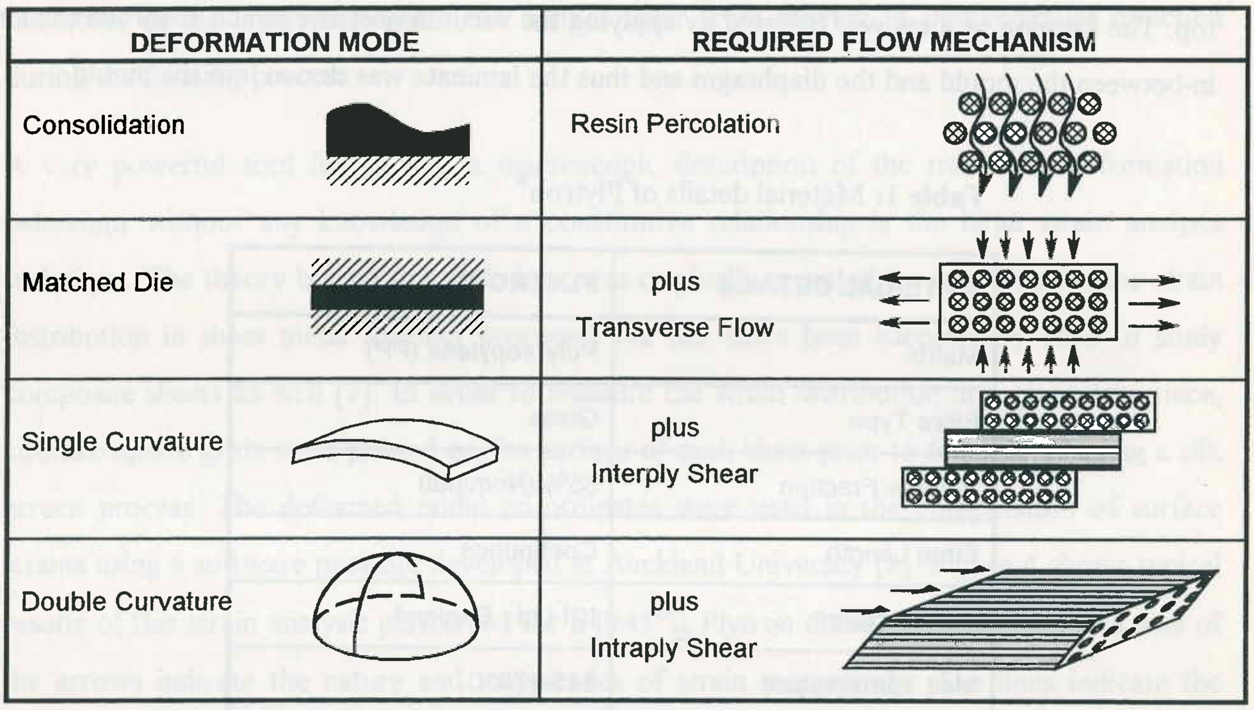

Figure 1: Deformation modes and flow mechanisms of CFRT materials.

2.1 Vacuum Forming

The first series of thermoforming experiments was implemented by utilising the vacuum forming technique. The material used for all forming experiments was Plytron which the properties are shown in Table 1. The setup, sketched in Figure 2, simply existed on a wooden unheated male mould with a circular dome shape which was connected to a vacuum pump, a base plate with vent holes in it, a silicone rubber diaphragm (0.9 mm thick) and a dead weight.

The main aim of this forming series was to gain an idea of how the Plytron material was performing under thermoforming conditions. Therefore, a number of four ply laminates with different lay-ups ($[0°]_4$, $[\pm 7.5°]_S$, $[\pm 22.5°]_S$, $[\pm 30°]_S$ and $[\pm 45°]_S$ circular blanks) were formed into circular dome parts. In order to vacuum form a part, a pre-heated flat laminate was placed onto the diaphragm of the base plate, with the mould put on top. The forming process was initiated by applying the vacuum pressure which absorbed the air in-between the mould and the diaphragm and thus the laminate was drawn into the mould.

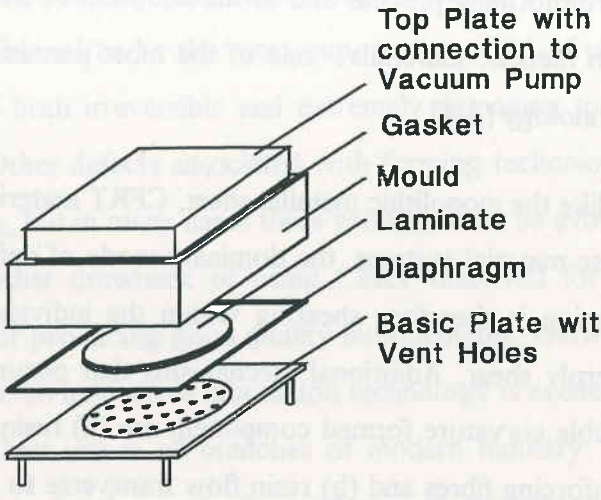

Figure 2: Sketch of vacuum forming device

Table 1: Material details of Plytron®

MATERIAL DETAILS	PLYTRON®
Matrix	Polypropylene (PP)
Fibre Type	Glass
Volume Fraction	35% (Nominal)
Fibre Length	Continuous
Manufacturer	ICI Ltd., England
Melt Temperature	145-170°C
Tape Thickness	0.48 mm (Nominal)

The results of this forming series showed that the instabilities such as in-plane-wrinkles and out-of-plane buckles only occur in certain areas of the part directly linked to the lay-up of the laminate (Figure 3). This phenomenon can be explained by looking at the deformation mechanisms involved in the forming process. When applying the vacuum pressure, the central region of the sheet is forced upwards into the mould, needing an increase in its surface area. However, since no material stretching can occur in the direction of reinforcement, the

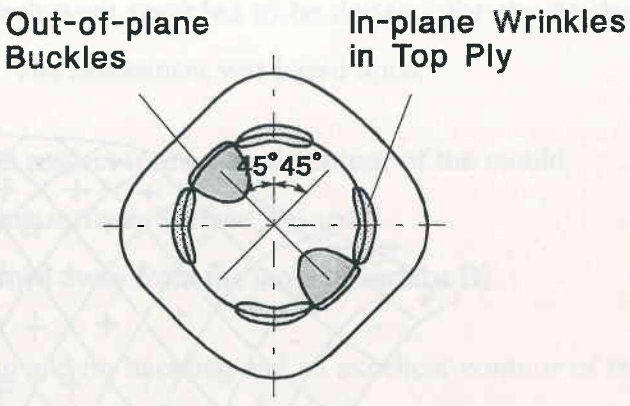

Figure 3: Sketch of in-plane wrinkles and out-of-plane buckles in a $[\pm 45°]_S$ part

inextensible fibres are forced to move towards the centre from the outer edges of the sheet. This creates tensile stresses in the fibre direction. Simultaneously, the decrease in area when moving towards the centre leads to compressive hoop stresses in the bisecting direction of the reinforcements resulting in out-of-plane buckles. The in-plane wrinkles exclusively occurred in the surface layer of the mould facing surface. As shown in Figure 3 these features were observed only in areas where the fibres of the layer underneath the surface layer were moving in perpendicular direction during the forming process.

A very powerful tool for getting a macroscopic description of the material's deformation behaviour without any knowledge of a constitutive relationship is the large strain analysis technique. The theory behind this technique was originally invented for investigating the strain distribution in sheet metal forming processes but has since been successfully used to study composite sheets as well [7]. In order to measure the strain distribution in a given test piece, circular/square grids were printed on the surface of each sheet prior to forming by using a silk screen process. The deformed nodal co-ordinates were used in the computation of surface strains using a software package developed at Auckland University [8]. Figure 4 shows typical results of this strain analysis performed for a $[\pm 45°]_S$ Plytron dome. The direction and size of the arrows indicate the nature and magnitudes of strain respectively. The lines indicate the reinforcing fibres. In this case, a quarter of the dome shaped part was sufficient to describe the strain distribution throughout the part due to its symmetrical shape. The majority of large compressive strains happened in 45° directions with respect to the fibres in the composite sheet; those were the areas where the out-plane-buckles were observed. The big arrows in the flange area indicate in-plane-wrinkles in the top layer where the layer below was moving in 90° direction. In some cases this mechanism even led to cracks along the transverse fibre direction in the flange and the bend-over region.

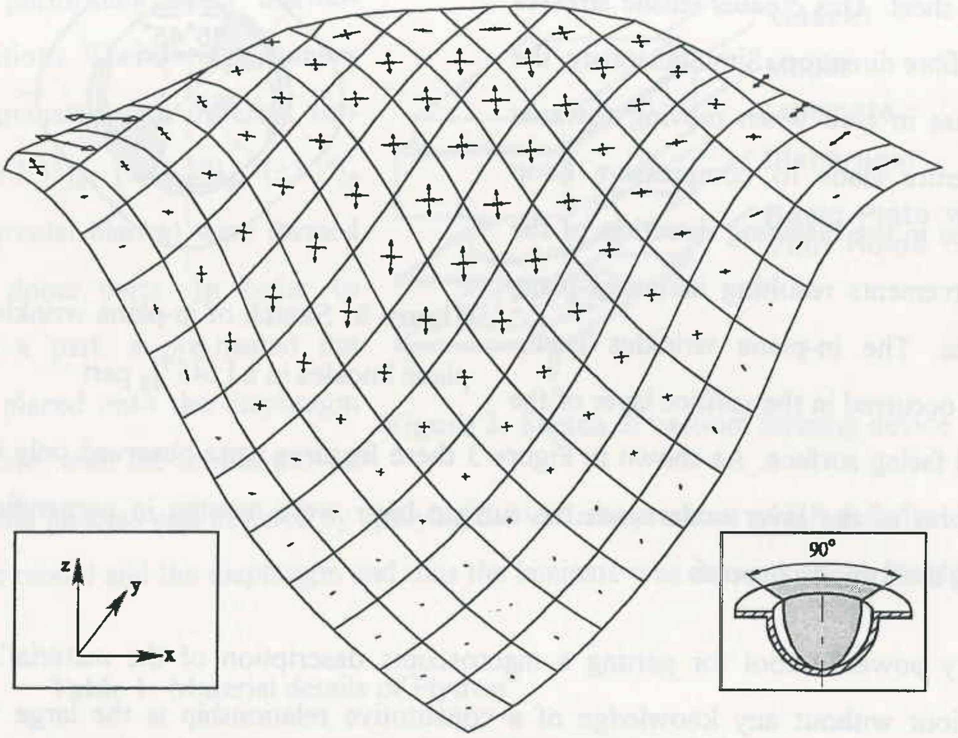

Figure 4: Arrow diagram for a [±45°]$_S$ Plytron dome

2.3 Pressure Forming

An analysis of the vacuum forming device as described earlier and the results of the first thermoforming series showed two severe drawbacks of the set-up. Hence the following modifications were made. A second silicone rubber diaphragm was introduced in order to provide better support to the laminate surface facing the mould. The thermoforming device was converted from vacuum to pressure forming since the forming load obtained through the vacuum pressure was not sufficient to draw the laminate all the way into the mould.

After gaining a basic understanding of the material behaviour under thermoforming conditions the scope of the second forming series was to optimise the parameters mainly governing the forming process. By altering the blank temperature, forming pressure and speed, laminate lay-up and forming ratio A_1/A_2 (blank area/cavity surface area) it was intended to define an optimised operation window for the Plytron material. First a standardised forming parameter set was defined and then one parameter was altered at a time. Of course, it was difficult to find a measurement capable of giving absolute values for the quality of finished components. Nevertheless, a rating scale of 1 to 10 was introduced for qualifying the results with respect to the three different criteria of assessment which were regarded to be decisive for the finished properties of the thermoformed components. The assessment was based upon

- the contour of the formed part with respect to the actual contour of the mould;
- the surface finish of the mould facing surface (Surface A); and
- the surface finish of the surface turned away from the mould (Surface B).

In this scale a 10 denotes very little wrinkling and no buckling and an excellent contour of the part with respect to the actual contour of the mould and 1 denotes the most severe cases of in-plane wrinkling and out-of-plane buckling and an unsatisfactory contour of the part.

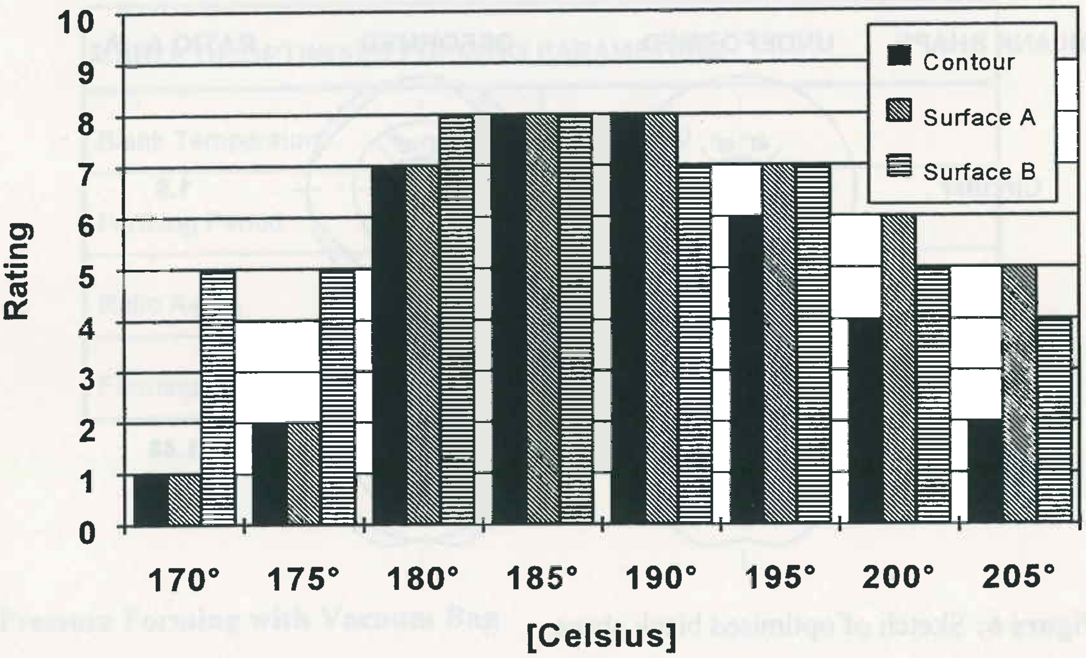

Figure 5: Results of alternation of the forming temperature

The forming temperature was altered in the range of 170-205°C. Its control was performed by embedding a thermocouple into the laminate. Figure 5 illustrates that the best forming results were achieved between 180-190°C (temperatures when initiating the forming process). There, only little in-plane wrinkling in the bend-over area was observed and hardly any out-of-plane buckling.

Below 180°C the components showed severe out-of-plane buckles in the surface facing the mould (Surface A). The contour of the parts were quite unsatisfactory with respect to the actual contour of the mould. Especially the bend-over area could not be developed in a satisfactory manner. The parts formed at 195-205°C, however, again showed increase in defects of the components finish. The low viscosity of the polypropylene matrix at these elevated temperatures enabled fibre migration resulting in unsatisfactory surface finishes.

By minimising the forming ratio A_1/A_2 down to a value of 1.48 and optimising the blank shape (Figure 6) the flange area was reduced to a minimum size and hence the compressive stresses occurring during the forming process. However, the occurrence of instabilities was still not completely eliminated.

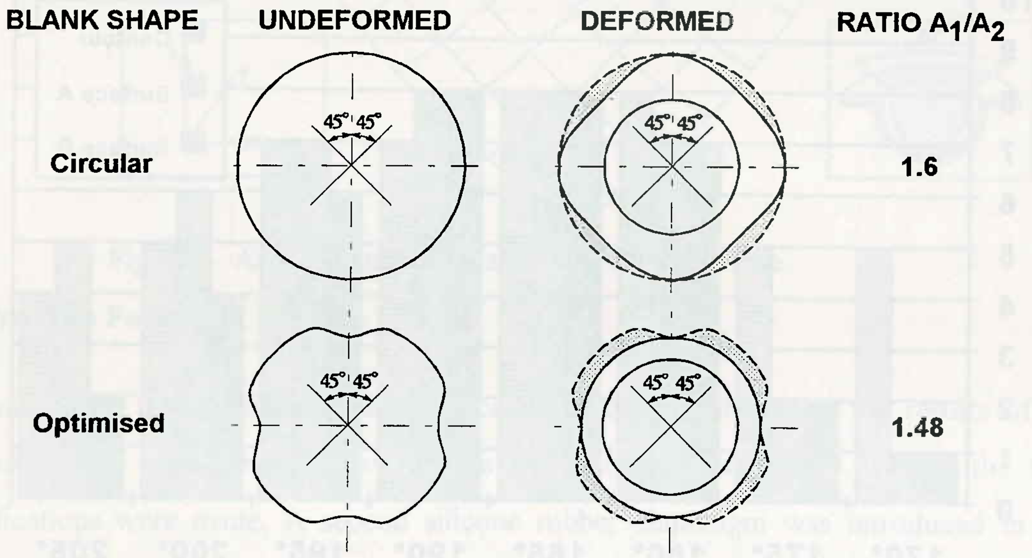

Figure 6: Sketch of optimised blank shape

The forming pressure was altered between 70 and 560 kPa. Here, the best forming results were obtained at 300 kPa; the components were completely buckle-free in both surfaces and exhibited only minor wrinkling in the bend-over area in the mould facing surface.

Due to the manual nature of the thermoforming setup it was difficult to measure the actual drawing speed of the blank when drawing it into the mould. Therefore, the main aim of this test was to investigate (a) whether the forming process could be completed while the blank was still in its molten state, or (b) if the temperature dropped below the melt temperature range while forming was carried out. The temperature was monitored during the whole process including the heating period in the oven. It was found that it did not drop below 150°C until the forming process was completed; this was considered to be still inside the melt temperature range of the Plytron material (see Table 1).

Regarding the alternation of the lay-up the main interest was to investigate how an increase in the total number of plies of the laminate influence the finish quality of the parts. By forming $[\pm 45^\circ]_{s}$, $[\pm 45^\circ]_{2s}$, and $[\pm 45^\circ]_{4s}$ sheets it was found that the lay-up had only a minor influence on the component's properties in comparison to the other parameters investigated. Even with a sixteen layer sheet it was still possible to form parts of acceptable quality. A summary of the optimised forming parameters is given in Table 2.

Table 2: Table of optimised forming parameters

TABLE OF OPTIMISED FORMING PARAMETERS	
Blank Temperature:	180-190 °C
Forming Period	90 Seconds
Ratio A_1/A_2	1.48
Forming Pressure	300 kPa

2.4 Pressure Forming with Vacuum Bag

In the course of the optimisation of the main forming parameters governing a thermoforming process, the properties of the finished components were continually improved. The combination of all separately optimised forming parameters led to forming results which were of a much better quality than the ones obtained in the preliminary forming experiments. However, since no absolutely defect free components could still be thermoformed by using the forming device introduced at the beginning of this chapter, another modification of the setup had to be implemented. A careful examination of the parts formed at different stages of this project showed that instabilities such as in-plane wrinkles and out-of-plane buckles did not represent the major hindrance in quality. However, little gaps between adjacent fibre bundles in the surface facing the mould did affect the product quality significantly. By introducing a

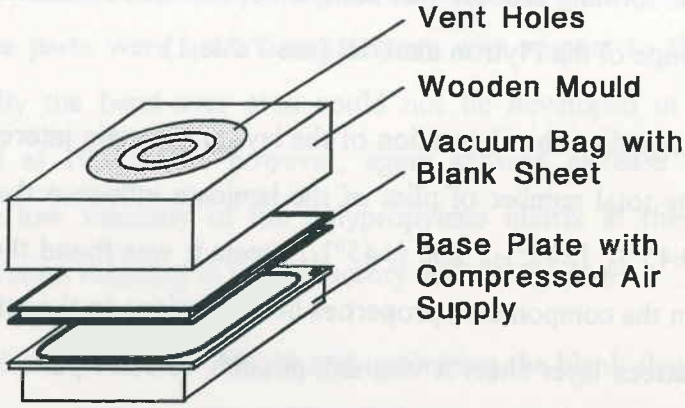

Figure 7: Sketch of forming device with vacuum bag

second diaphragm when converting the forming process from vacuum to high pressure forming the surface finish was remarkably improved. Though a diaphragm basically acted as a supporting jacket for the blank sheet, it became obvious that the key to improving the thermoforming device had to be found in a more efficient way of supporting the composite surfaces. Therefore, in order to enforce the supporting effect of the diaphragms, a vacuum frame was introduced holding the laminate in a vacuum between the two diaphragms during forming and added to the forming device, Figure 7. An analysis of the thermoforming forming process and the finished parts led to the following conclusions:

1. During the actual forming process, when the blank is at its molten state, there is nil or only minor slip possible between the matrix rich layer of the blank and the diaphragms. However, the composite and the diaphragms deform differently. When forming, both of them are drawn into the cavity of the mould but the diaphragms stretch when it is necessary whereas the fibres, due to their inextensibility, have to migrate with respect to one another and the diaphragms. This results in a clamping effect that keeps the laminate in tension during the forming process, thus eliminating the defects discussed.

2. The support of the diaphragms also prevents the material from buckling, wrinkling, or developing gaps in the surface. The large strain analysis method underlined that by optimising the forming parameters and by providing an optimal support to the blank lead to lower strain and thus to lower values of tensile and compressive stresses in the finished component.

This way, a significantly improved method to produce almost defect-free parts from a CFRT material using essentially diaphragm forming technique was developed. A selection of different components and shapes formed by employing this technique are shown in Figure 8 which reconfirms the potential of such materials in mass manufacturing conditions.

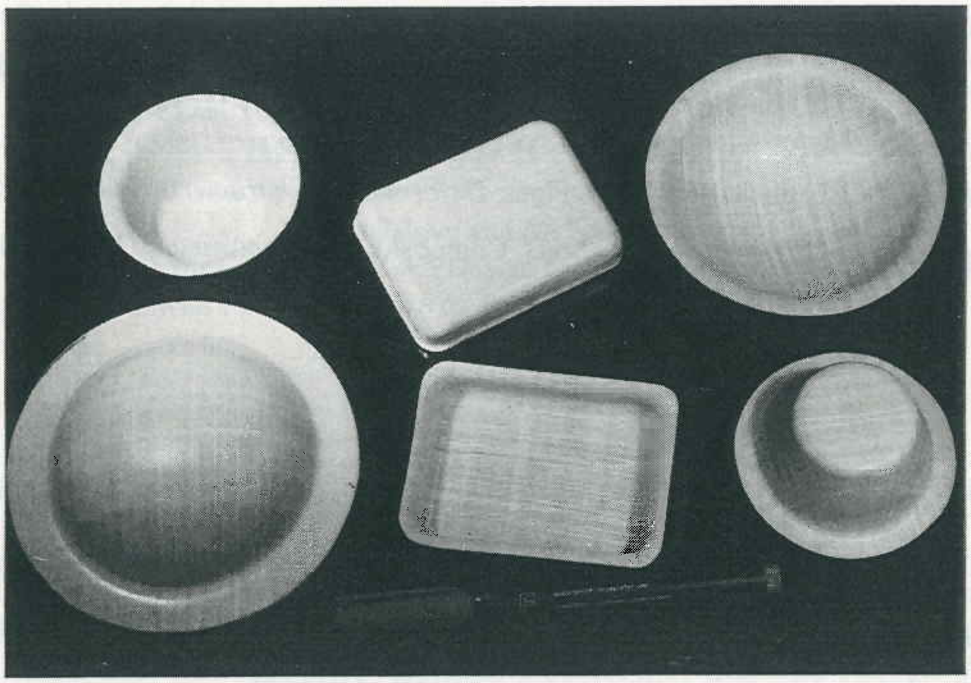

Figure 8: Selection of thermoformed components

REFERENCES

[1] C. M. O'Brádaigh, *Analysis and Experiments in Diaphragm Forming of Continuous Fiber Reinforced Thermoplastics*, Dissertation, University of Delaware, USA, Center for Composite Materials, (1990)

[2] T. A. Martin, *Forming Fibre Reinforced Thermoplastic Composites*, Ph.D. Thesis, University of Auckland, (1993)

[3] C. R. T. Burt, *Forming of Fibre Reinforced Thermoplastic Composites*, M.E. Thesis, University of Auckland, (1992)

[4] S. J. Mander, D. Bhattacharyya, R. Downs-Honey, *Recent Trends in Fibre Reinforced Thermoplastic (FRTP) Composites and Their Applications*, IPENZ Conference, Nelson-Marlborough, (1994) 54-55

[5] F. N. Cogswell, D. C. Leach, *Processing Science of Fibre Reinforced Thermoplastic Composites*, SAMPE Journal, 24/3 (1988) 11-14

[6] R. Scherer, K. Friedrich, *Inter- and intraply-slip flow processes during thermoforming of CF/PP-laminates*, Composites Manufacturing, 2/2 (1991) 92-96

[7] T. A. Martin, D. Bhattacharyya, R. B. Pipes, *Computer-Aided Grid Strain Analysis in Fibre Reinforced Thermoplastic Sheet Forming*, Computer Aided Design in Composite Material Technology III, Computational Mechanics Publications, London, New York, ISBN 1-85166-781-4, 143-162

[8] T. A. Martin, D. Bhattacharyya, R. B. Pipes, *Deformation Characteristics and Formability of Fibre-Reinforced Thermoplastic Sheets*, Composite Manufacturing, 3/3 (1992) 165-172

ACKNOWLEDGEMENTS

The authors thank ICI Ltd., England, especially G. Cuff, for the free supply of Plytron prepreg material, and also the technical staff of the Strength of Materials Laboratory at Auckland University for their assistance in setting up experimental equipment.

Paper submitted for publication on International Conference "Flow Processes in Composite Materials '94", July 7-9, 1994, Galway, Ireland