The Optimisation of the Non-Isothermal Press-Forming process for Fibre Reinforced Thermoplastics

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ABSTRACT

The pressforming of thermoplastic materials, involves converting laminates in flat sheet form, which are assembled from individual plies of woven prepreg fabric or unidirectional plies into a 3 dimensional component using suitable tools. By means of a fast response heating source, such as quartz infra-red emitters, this method can result in very short cycle times. A right angle and a cylindrical dish mould are employed for the experimental study of the pressforming process of the following thermoplastics, Glass fibre reinforced PA12 (G101 & G201), Carbon fibre reinforced PEI (CETEX) and Carbon fibre reinforced PEEK (APC-2). Preconsolidated laminates were heated above the melting temperature of their polymer matrix, then transferred to the moulding tools. The optimal processing conditions were established for each of the four materials, with particular interest in the effect of the initial shape of the flat pre-formed laminate, tension on the laminate during forming, the forming pressure, rate of forming and the mould temperatures. The resulting cycle times, including heat-up and pressing range, from 5 minutes for G101 to 7 minutes for APC-2.

This paper addresses not only optimisation of such a forming process, thereby demonstrating it's attractiveness to industrial applications, but also examines how the presence of continuous inextensible reinforcing fibres constrain the deformation mechanisms thereby giving rise to buckling and wrinkling of the formed part. Buckling in parts of simple deformation , i.e. 90° bend, was seen to be a surface ply phenomena, while buckling in the more complex cylindrical dish part had a through the thickness effect. In each case the degree of buckling was considerably reduced or eliminated by means of optimising the preform shape and introducing a suitable clamping system. The clamping system produced a tensile force to counteract the compressive forces which result in fibre buckling. Fibre movement within the thermoplastics were analysed by means of X-ray detection of tracer fibres embedded in the composites and the methods used to determine final part quality were surface appearance, photomicrography through the part thickness and ultrasonic C-Scan.

1. Introduction

One of the principle advantages of thermoplastic composite materials is that they can be processed by a wide range of manufacturing techniques. Of all the techniques available to the manufacturers, thermoforming is the one that shows most promise. Thermoforming refers to the processes for the conversion of 2-dimensional laminates into 3 dimensional shaped parts and its potential advantages have been well documented by several authors[1,2].

The principles behind the thermoforming of the fibre reinforced thermoplastic composites can be outlined as followed,

-Upon heating, the viscosity of the thermoplastic resin in the composite decreases.
-The laminate is transferred to the tool
-Pressure is applied to the laminate, it drapes around the mould to conform to the shape and consolidation begins.
-On cooling the resin gels, holding the fibres in place and part geometry is set.
-After cooling below the glass transition temperature, the part is removed.

One of the major advantages offered by thermoplastic composites is that they allow for the rapid transformation of flat composite laminates into 3-dimensional finished parts and are therefore conducive to thermoforming techniques. Many thermoforming methods exist, the most common of which are matched die, rubber pad and diaphragm forming. The former two methods can be executed using a press and can be therefore generalised as pressforming.
The principle advantage that pressforming has over other techniques of thermoforming is the part cycle time, and combined with a high speed heating source, it can be quite appealing to the industrial sector. The time required for the rapid pressing of the thermoplastic to a formed piece is dependent on two factors, the first is the rate at which the thermoplastic resin can be heated to its processing temperature, the second is the rate at which the material is cooled once forming has been completed[3]. Other important factors in the pressforming process are the type of tooling used, the forming pressure and the forming rate. The forming rate must be at a speed that interply and intraply slip processes will occur. If the piece is formed too quickly sufficient slip may not occur and surface plies on the inside radii of a bend may buckle. Fibre buckling is one of the most common defects in the thermoforming of composites. It can have a significant effect on the mechanical performance of the composite structures, leading to possible void formation during solidification, reducing strength and causing cracks and delaminations. In the case of fibre reinforced composite materials, particularly those that are highly anisotropic, compressive strength is less than tensile strength. Carbon fibres are an example of such an highly anisotropic material, with high modulus and tensile strength, but when placed in compression, by the very fact that the fibre are so slender, they have a reduced compressive strength and make them more prone to microbuckling under compression.

2. Experimental

Test Rig

The core of the pressforming rig consisted of an hydraulic actuator with complimenting control hardware mounted on a four post arrangement straining frame unit(Figure 1.). Cooling channels were machined into the support column to assist cooling of the dies using compressed air. To aid in the fastest possible heat up times for the tools, they were designed with the thermal mass to be as low as possible. The tools, matched metal dies, were of two forms, a 90° bend and a cylindrical dish shape. Incorporated into both halves of the tools were cartridge heaters and cooling channels. So that the complexity of the heater control could be reduced, the heater banks were divided into control zones. The principle behind the zoning was that groups of heaters could be regulated using the one controller. Since the laminates to be processed were of uniform thickness, only two control zones were necessary, one to minimise overheating in the centre of the laminate during heat-up while the second outer zone ensured sufficient heating in the outer areas of the laminate(Figure 2.). A suitable PID control program was developed to ensure an even temperature distribution was maintained on the laminate to be heated. The control for all the variables of the non-isothermal pressforming rig was incorporated into one turbo-basic control program so as to enable ease of operation and data recording. Once the laminate had reached its processing temperature it would be transferred to the pressing area by means of a pneumatic transfer mechanism.

Materials

Analysis was carried out on four principle fibre reinforced composite materials, namely:

- 1/7 satin weave glass fibre/nylon matrix(trade name Hulls Vestopreg G101).
- 1/3 crowfoot weave, glass fibre/nylon matrix(trade name Hulls Vestopreg G201).
- Plain weave Carbon Fibre/Poly Ether Imide(PEI) (Trade name Cetex)
- Unidirectional Carbon Fibre/Poly Ether Ether Ketone(PEEK)(Trade name APC-2)

The materials were supplied in sheet form and were required to be laid up to the required height and fibre orientation prior to pre-consolidation. Pre-consolidation of a laminate panel was carried out in an autoclave, the thickness of which was to be 2mm.

3. Results

Infra red heating of laminates

As laminate heating cycle was the most important parameter in the reduction of the overall pressforming cycle time, it was the prime area for optimisation. Previous research[4] has demonstrated that the radiative heating achieved by means of infra-red heaters is the most rapid and economical heating mechanism available for the heating of thermoplastic composites to their processing temperature. Initial experiments on G101 demonstrated how the heater to composite distance effected the heat-up characteristics of the laminate. The heat-up results for four differing heater to composite distances are shown in Figure 3.. with the reference temperature being that of the ply closest to the heaters. A 400W heater bank placed 220 mm from the laminate did not have sufficient power to bring the laminate to its processing temperature while on the other extreme, having the heaters positioned close to the laminate(60mm), the heat up rate was so quick that the controller could not compensate for the initial overshoot of the laminate surface temperature. Similar results were seen for the other four materials.

As the thickness of the thermoplastic panels which were to be pressformed did not exceed 2mm and the materials high emmisitivity, it was initially considered that single sided heating would be sufficient for heat-up. For the analysis of both cases the heaters were located 100mm from the laminate with thermocouples located beneath the top and bottom plies of the laminate. The heat-up characteristics displayed by the double sided heating system were far superior to those exhibited by single sided upward facing heaters. The difference was seen to be most extreme in the case of the APC-2 material. Figure 4. shows that there existed a temperature difference of up to 150°C between the top and bottom panel surfaces. This was found to be unacceptable forming conditions and the only solution was to employ double sided heating. Figure 5. illustrates the improved temperature distribution and heat up times that are achieved from the implementation of double sided heating. It was found that the glass fibre/nylon materials could be brought to their processing temperature in approximately 2 minutes, CETEX in 3.5 minutes and APC-2 in 5 minutes. With fast heating times and a very short pressing time, the only other parameter governing the cycle time was the cooling rate while the part was contained between the mould halves. To maintain its shape conformity, the part was to be removed after it had cooled below the glass transition temperature. This was achieved in less than 2 minutes with the aid of an internal cooling system contained in the moulds. The resulting cycle times ranged from 5 minutes for the G101 and G201 materials to 7 minutes for APC-2.

Pressforming Results
With the heating cycles for each of the materials optimised, the next step was to optimise the pressing cycle. After each part was manufactured a visual inspection was formed by examining the characteristics of the part surface. The fibre positioning in and around the bend regions were of particular concern, as little fibre misorientation was expected in the flat portion of the sample. In cases were the fibre misorientations were hard to visualise, a grid was imprinted on the top and bottom surfaces of the laminate blank prior to forming. The degree of resin percolation could also be judged by the surface finish of the final part. Parts which were formed under insufficient forming pressure would display a rough surface finish. The internal quality of the formed parts was evaluated by means of optical micrography and ultra-sonic inspection (C-scanning). Such inspection techniques were concerned with the occurrence of voids, fibre buckling or fibre cracking through the part thickness. C-Scanning was employed for the non-destructive testing of fabricated panels prior to forming. While successful inspection was carried out for CETEX and APC-2, problems were experienced with the glass fibre composites. Glass causes the sound waves to diffract and reflect making the penetration of sound waves, which is necessary for C-Scanning, impossible. With regard to the inspection of formed parts, the shape complexity proved to be a problem in the ultra-sonic inspection of cylindrical dish parts. Added to its shape, the part also experienced distortion due to the thermal stresses which occur on cooling, otherwise known as spring forward[5]. Figure 6. illustrates the spring forward experienced by the cylindrical dish part. The non level surface prevented accurate C-scanning from taking place.

The Forming Parameters of 90° bend and Cylindrical dish parts

Effect of Forming Pressure
The starting point for the forming pressure was that of the materials suppliers recommended value[6,7,8]. Due to the geometric complexity of the part, larger optimal forming pressure values were obtained for cylindrical dish when compared to that of the 90° bend. In the case of the latter forming resembles that of a simple point loading deformation, but in the case of the cylindrical dish part the load is applied across a larger area. Because the male punch has to fit into the female die, a resistance to forming develops at the edges of the female mould once draping begins. Figure 7. demonstrates how this resistance to forming was developed. Extra pressure was required to overcome the resistance to movement of the plies just above the female die.

Effect of Mould Temperature
Cylindrical dish parts formed at tool temperatures approaching the melting temperature of the matrix displayed large areas of resin migration to the external bend region The quality of parts formed using moulds below the materials glass transition temperature were also not impressive. Once the laminate had been transferred from the heating cabinet it began to experience a drop in temperature. The cool mould caused matrix solidification prior to complete part drape. Increasing the forming rate ensured that the thermoforming of the laminate occurred at a higher temperature. This improved part quality but it was still deemed unacceptable. Successful forming occurred for mould temperatures above that of the glass

transition temperature, yet considerably below the matrix melt temperature. Table 1 outlines the acceptable mould temperature and forming pressure ranges for all four materials.

Table 1. Forming Conditions for Part Pressforming.

Material	Mould Temperature(°C)
G101/G201	130-160
CETEX	230-280
APC-2	230-300

Effect of Shape Complexity

The manufacture of cylindrical dish parts involved more complex deformation mechanisms than those of the 90° bend parts. A grid imprinted on both sides of the preformed laminate was used to demonstrate the draping behaviour. The grids displayed the large compressive strain that the inner fibres experience and the large tensile force on the exterior surface. In the case of the weave materials, the imprinted grid indicated clearly the areas of the surface, be it interior or exterior, which undergo the most deformation and could be used as a guide in the minimisation of it. The deformation occurred in two forms, the simple plain bending of the fibres and, secondly, fibre deformation in the form of the changing cross-over angle in the weaves due to a stretching effect, otherwise known as the trellis effect. At the 0° and 90° regions(Figure 8.), the fibres conform readily to the shape of the mould, as it resembles simple bending along the fibre axis and no cross-over angle distortion occurs. For the first 30° of each side of the principle fibre axes, the fibre crossover angle begins to gradually change in order to correspond to part geometry. At this stage the deformation is part simple bending and part fibre rotation. It is in the 30° to 60° area that most of the fibre deformation occurs. The ease of formability of the surrounding area has left this region(particularly in the dish interior) with more mould surface area than there was laminate area to drape on. The laminate would compensate by compressing and shearing, thereby increasing the fibre crossover angle, leading to further fibre buckling. Figure 9. illustrates how the fibre deformations are more extreme at 45°to the fibre angle direction.

Effect of Forming Rate

90° bend parts from the four materials were formed at three differing forming rates, 10mm/sec, 50mm/sec and 100mm/sec. On visual inspection the APC-2 parts exhibited buckling in the interior region of the bend. This was to be expected since it is in this region that the highest compressive stresses are experienced during forming. The parts in which surface fibre buckling was at a minimum were the quasi-isotropic and $[0,90]_{4S}$ lay-ups at 10mm/sec. It was apparent that the forming rate was low enough to allow sufficient interply slip, thereby relieving most of the compressive stresses that were built up as the part deformed. The forming rate in all other cases appeared to be too high for complete interply slipping of plies. The fibre buckling that occurred at the inner bend region took the form of in-plane buckling[9]. Micrographic inspection revealed that the buckling occurred on the top surface ply and neither buckling nor fibre damage were evident in the preceding plies. Examination of the ends of the part revealed that the top ply did not slip as much as the other plies in the lay-up(Figure 10.). One possible explanation for the occurrence of buckling in these parts is the resistance between the mould and the laminate. On initial contact with the male punch, the laminate deforms, but on its contact with the edge of the female die, a frictional force is induced. This friction results in a tensile force being created on the bottom plies. The effect of this tensile force is transferred through the plies by virtue of a resin rich layer of reasonably low viscosity. At the top ply there existed a contact resistance with the male punch which resisted the interply slip. Unable to slip, the fibres counteract the compressive stress by buckling.

The influence of the lay-up was of greater concern with the unidirectional APC-2 material. It has been seen that this material was more prone to buckling. Parts of differing lay-ups were formed using the 90° bend tool at a forming rate of 50mm/sec. Once formed the parts were examined visually and microscopically for buckling in the bend region. An obvious trend was noted regarding the quality of the part surface, all the parts with the outer fibres oriented perpendicular to the bend region exhibited out of plane buckling at the inner bend region, while the parts comprising of the outer plies parallel to the bend region exhibited none. The fibres parallel to the line of deformation were free to move or possibly roll in accordance with the deformation. In this case the friction between the tooling and the composite was considerably less than that of having fibres perpendicular to the line of deformation. The resin acts as a lubrication for the sliding motion of the fibres and material is being continuously sheared with the tool and replacement polymer material can come from beneath the composite surface. While the ply experienced the compressive and tensile stresses associated with the deformation, the surface fibres did not. Added to this, the fact that micrographic inspection displayed no buckling in the intermediate plies, weight was added to the idea that buckling was a surface ply orientation phenomena.

In glass fibre materials(G101 and G201) the buckling was not as evident and could be attributed to the weave nature of the fibres. The buckling in the fabrics was affected by the fibre straightening effect. Due to the crimped nature of the fabric, the tows can increase in length, allowing the individual fibres to stretch[11]. On deformation, the tensile force created causes the bottom plies to stretch. The weave nature of the fibres allowed for a certain amount of interaction between the plies and this stretching effect is transferred through the thickness. In this way, the degree of compressive stresses created on the top surface was reduced. As one would expect, the fibre straightening depends on the type of weave, with maximum stretching occurring in a plain fibre weave, thereby offering an explanation for the lack of buckling in the CETEX material.

Buckling in the cylindrical dish parts occurred in the interior side wall regions. The buckling characteristics for three different forming rates(10mm/sec, 50mm/sec and 100mm/sec) were compared by means of a grid imprinted on the surface of the dish.

As it was considered that the degree of buckling in the $[0,90]_{2S}$ lay-up was influenced by the fact that the fibres were only in two directions, a laminate consisting of layers oriented at 45°, i.e. $[0,45,90,-45]_S$, was prepared and formed. The layers oriented at 45° were expected to distribute the buckling effect to the 0° and 90° directions. Forming was carried out at the lower forming rate of 10mm/sec. Visual examination confirmed areas of ply folding and buckling at not only the ±45° regions but also in the 0° and 90° directions (Figure 11.). While the buckling was spread out over four principle areas, it was still as extreme in the individual regions as had been in previous parts. The addition of the 45° layers did not serve to distribute the effect of buckling across the inner surface of the dish but amplified the fibre deformations. Similar observations were noted in the manufacture of spherical dish parts in an autoclave between polymeric diaphragms[12].

For the analysis of the APC-2 parts nickel tracer wire was embedded between the plies at the lay-up stage. The fibre movement was determined by X-ray analysis of the final piece. As was the trend with the 90° bend pieces, the faster forming rates resulted in more extreme fibre buckling. The X-ray analysis of the part formed at 100mm/sec, shown in Figure 12., revealed that the buckling was not limited to the surface ply, but spread to the middle plies where the tracer wires were located.

Effect of Preform Shape on Buckling

While the size of the preform blank was of no great concern for the manufacture of 90° bend parts ,it did have a great effect on the quality of the cylindrical dish parts. Parts were initially formed from a square 160mm x 160mm preform blank. It was observed that, particularly in the weave materials, most of the buckling was initiated in that region 45° either side of the fibre directions. In the design of an optimised blank shape, this was identified as an area where excess material could be removed. Besides the initial rectangular shape, two more shapes were considered, a circular shape of 165mm diameter and an optimised shape(Figure 13.). The optimised shape was developed from experimental experience of the draping process and previous research done in the field[13]. Its design not only limited the fibre lengths to the absolute minimum but also ensured the least possible amount of excess material, particularly in that 45° region, where it has been seen that the fibre rotation was hindered resulting in ply folding and fibre buckling.

The circular blank formed well, but as with the square blank, excess material was evident at the areas 45° to the fibre orientations. The optimised shape formed easily into the mould with just enough excess material remaining to aid in its removal. When compared to the over-sized parts previously formed, the extent of ply folding and fibre buckling had greatly reduced, resulting in a better quality part.

In the weave materials the reduction in the degree of fibre buckling was quantitatively measured by the reduction in the fibre cross-over angle and the amount of severe ply buckling. The optimised shape allowed for further reduction in this angle since the excess material, that had once hindered the fibre rotation causing ply folding, was now eliminated. The parts formed were not without buckling as the materials, particularly G101 and CETEX still experienced compressive stresses in the inner surface. One must remember that these were tightly woven fabrics, where the crossover angle is of principle concern in its deformation behaviour.

Effect of Clamping Force

A number of differing methods were examined with the ultimate aim of developing a suitable system for maintaining tension on the laminate while forming. The method which was deemed most suitable for the 90° bend part manufacture was that which would employ the use of extension springs attached to laminate preform (Figure 14.). The design of the clamping method employed in this case required that the initial preform laminate blank be oversized in its length. This was to ensure that the laminate clips would remain in place at all stages during the forming process, thereby maintaining the tension until the blank has completely draped into the mould.

Four principal tensile forces were examined ranging from 1.24 to 6.7N. The G201 and G101 parts were formed with great success. The lower tensile force value appeared to be sufficient in the forming of buckle free parts. The forming rates had no effect on final part quality, the parts formed at 10mm/sec were just as good as those formed at 100mm/sec. The observations from the APC-2 parts were more interesting. The lower force of 1.24N appeared to be insufficient for both forming rates, but the quality did improve with the use of the stiffer springs, showing that the forming rate still proved to be of great influence with this material. A buckle free part was formed at 2.33N at 10mm/sec but the same part at 2.33N and 100mm/sec exhibited buckling in the bend region.

The clamping method which was found to be most successful in the manufacture of cylindrical dish parts involved attaching a spring loaded collar to the male punch. As the male punch descended, the laminate experienced an applied pressure between the collar and female mould rim and when the male mould began to drape the laminate into the die, a tensile force was initiated on the laminate. This tensile force was maintained until forming was complete. The added advantage of this method is that the force was experienced in all directions which was necessary due to the complex deformation mechanics involved in forming the part. This clamping mechanism is shown in Figure 15., describing its operation. The tensile force which was applied to the laminate could be varied on the substitution of various compression springs. The experiments were carried out at the lower forming rates of 10mm/sec. The pressures applied on the laminate by the collar were in pressure ranges from 10kPa-270kPa.

As was the trend with the 90° bend clamped parts, the lower pressures were sufficient in the reduction of buckling. The parts formed with the lower clamping pressures showed a visual improvement in the fibre folding which had occurred in previous parts under the same forming conditions. The main area of concern was related to the cross-over angle and its reduction beyond its minimum limit. While the folding decreased on the application of the greater pressure, in plane buckling became more evident. The pressure applied on the laminate caused it to be stretched further than would normally have been the case, thereby reducing the cross-over angle below its buckle free limit. It was deemed that the lower pressure value was more suitable for the forming of such parts. Parts formed from the G101 and G201 materials displayed catastrophic results at pressures greater than 150kPa. The parts, on removal, displayed severe ply tearing on the female mould facing side. The excess pressure applied too great a tensile force on the laminate and being unable to fully drape into the mould the bottom plies began to tear.

The resulting fibre movements for a correctly clamped G201 part are illustrated in Figure 10.22. When compared to the previous fibre patterns achieved without clamping, one can see the improvement in the reduction of buckling. A similar improvement was noted for the APC-2 material(Figure 16.).

Problems encountered using Matched Metal Dies

With matched die tooling, the laminate thickness is required to match exactly with the designed die gap, the distance between the male and female moulds at which all points between the two are the same. For these experiments the distance was 2mm. In the forming of 90° bend parts, laminates of thicknesses less than that of the gap width experienced highly pressurised zones in the radial or bend regions, while little consolidation occurs further up in the tangential or flat region. The opposite was the case for laminate pieces thicker than the designed die gap. A more catastrophic effect was observed in the forming of extra thickness laminates with the cylindrical dish tools. As the tool was designed for a 2mm clearance any thickness above this results in the laminate jamming between the upper lip of the female die and the bottom corner of the punch. The result of this was that the mould jammed and was unable to complete the draping or forming process. Increasing the forming pressure at this stage completed the forming process but at a cost of extensive fibre damage. Most of these problems surfaced in the manufacture of APC-2 parts. The 16 ply APC-2 lay-up which had consistently formed 2mm thick right angle parts would display this locking effect. The reason for this was thought to be due to a combination of APC-2's resistance to compression because of its high fibre volume and the buckling of laminate plies. The high fibre content reduces the compressibility of the laminate and the reduces the lubrication effect which the molten matrix establishes The folding over of the plies increased the thickness of the laminate and results in the interference fit occurring between the mould halves. For further cylindrical dish parts to be formed from the carbon fibre materials the number of plies in the lay-up had to be reduced. A higher success rate of cylindrical dish manufacture was achieved but at the cost of having areas of poor consolidation. The weave nature of the G101, G201 and CETEX materials allowed for better shape conformity and draping characteristics.

Another problem pertaining to the manufacture of cylindrical dish parts was that the mould design exerted no pressure onto the side walls of the cylindrical dish part during forming, resulting in insufficient consolidation in this region.

4. Conclusions

Using the optimised non-isothermal press-forming process, parts could be formed, cooled and removed inside as little as 5 minutes, depending on the material used. The most important factors in the cycle time were found to be the preform heating time, and the cooling time between the mould halves.

The ideal mould temperature was found to be greater the glass transition temperature of the materials matrix yet much less than the resin melt temperature.

More complex shapes, such as the cylindrical dish, required a greater forming pressure to overcome the resistance to forming which develops at the edges of the female mould.

In the manufacture of both bend and dish parts, APC-2, the unidirectional fibre material was found to be more prone to buckling than the weave materials. The most influential forming parameter in the occurrence of buckling was found to be the forming rate.

In the manufacture of right angle bend parts, especially APC-2, buckling was seen to be only a characteristic of the top surface ply and did not effect the plies beneath it, and orienting the fibres parallel to the bend region eliminated all buckling. In this case, the occurrence of buckling was attributed to the frictional forces developed between the surface fibres and the tip of the metal male mould.

The cylindrical dish parts, which involved more complex deformation mechanisms, were more prone to buckling. By reducing the size of the preform laminate the buckling was considerably reduced. The buckling was also considerably reduced by applying a small tensile force to the ends of the laminate preform.

Acknowledgements
The authors would like to acknowledge BRITE/EuRaM for the provision of funding for this project and the invaluable assistance provided by the partners of Project No. BE-5092. Also the help and expertise provided by the Mechanical and Aeronautical Engineering Department is much appreciated.

References

1. Mitchell, A., "Thermoforming-Cost Effective Production of Plastic Components", Metals and Materials, December 1990.
2. Witzler, S., "Pressure Molding Methods for Thermoplastic Composites", Advanced Composites, Sept/Oct 1988.
3. Cogswell, F. N., "Thermoplastic Aromatic Polymer Composites", Chapter 4. The Microstructure of Aromatic Polymer Composites, Butterworth-Heinemann Ltd., 1992
4. Sweeney, G.J., Monaghan, P.F., Brogan, M.T. and Cassidy, S.F., "Reduction of Infra-Red Heating Cycle Time in Processing of Thermoplastic Composites", 3rd International Flow Processes in Composite Materials, U.C.G., Galway, Ireland, July 1994
5. Zahlan,N. and O'Neill, J.M.,"Design and Fabrication of Composites Components: The Spring Forward Phenomemon", Composites, Volume 20. Number 1, January 1989.
6. Vestopreg Data Sheet, Huls Aktiengesellschaft A.G., Germany, 1994.
7. Ten Cate Product Information Sheets, Ten Cate Advanced Composites, NL-7440 AA Nijveral, Netherlands, 1994
8. Fiberite Materials Handbook, ICI Fiberite, Tempe Arizona, U.S.A., 1992.
9. Williams, R.F. "Non-Isothermal Pressforming of Fibre Reinforced Thermoplastic Composites" , Chapter 4, Masters Thesis, Dept of Mechanical Engineering, University of Limerick, Ireland, 1996
10. Tabor D., "Friction, Adhesion and Boundary Lubrication of Polymers", ACS International Symposium on Polymer Wear and its Control, Plenery Lecture, Los Angeles 1974
11. Murtagh, A.M. "Characterisation of Shearing and Frictional Behaviour in Sheet Forming of Thermoplastic Composites" Ph.D. thesis, Dept of Mechanical Engineering, University of Limerick, Ireland, 1995
12. Monaghan, M.R. "Mechanical Characterisation of Polymeric Diaphragm Films" Ph.D. thesis, Dept of Mechanical Engineering, University of Limerick, Ireland, 1993.
13. Krebs,J., Friedrich,D. and Bhattacharyya,D., "3-D Thermoforming of Continuous Fibre Reinforced Thermoplastics using the Diaphragm Forming Technique" 3rd International Flow Processes in Composite Materials Conference, U.C.G, Galway, Ireland, 1994.

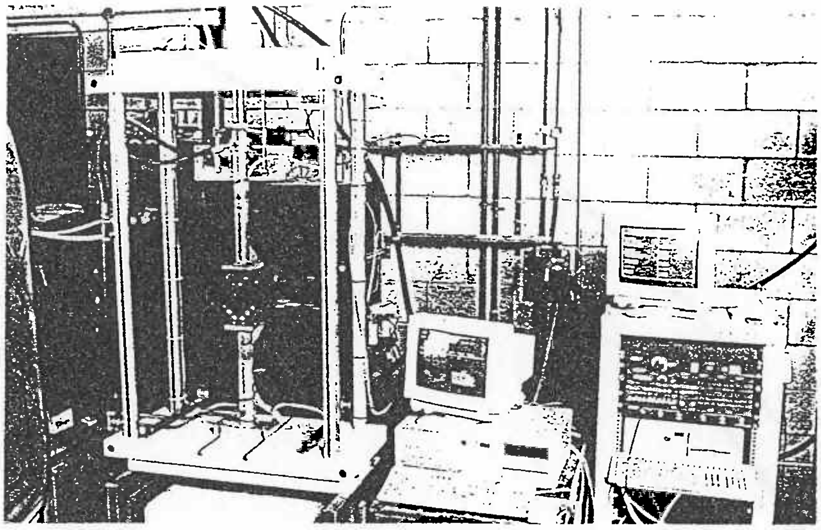

Figure 1 Non-Isothermal Pressforming Rig

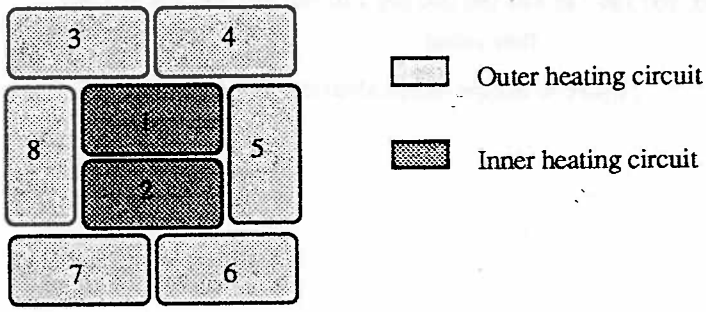

Figure 2. Arrangement of Heaters on Upward Facing Side.

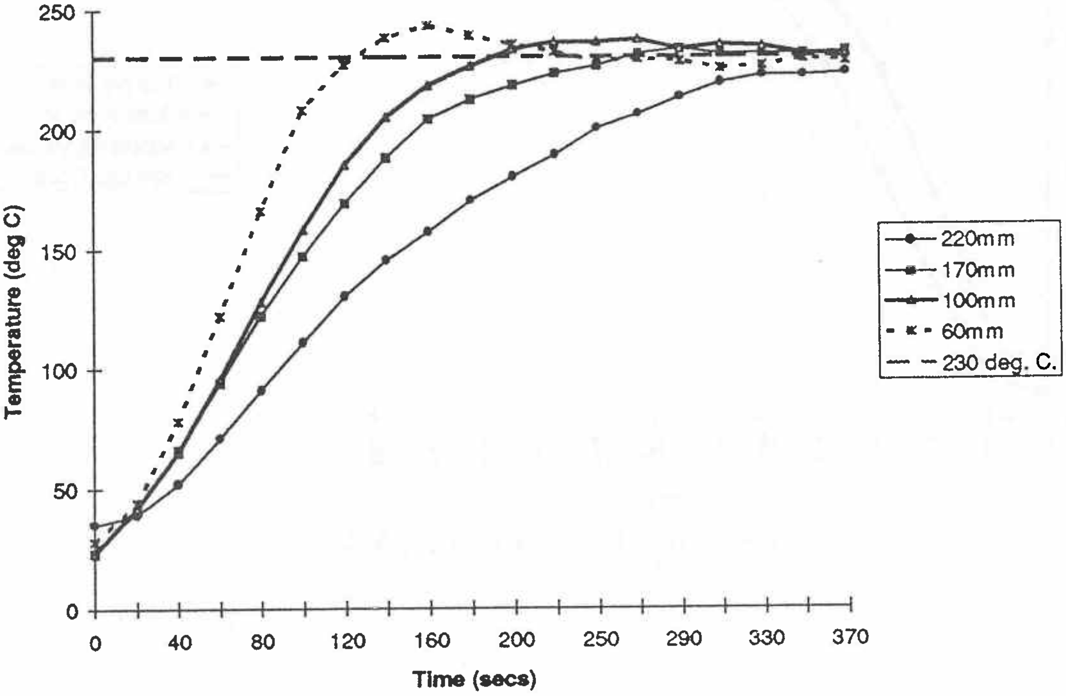

Figure 3. Heat-Up Rates at Various Heights(G101)

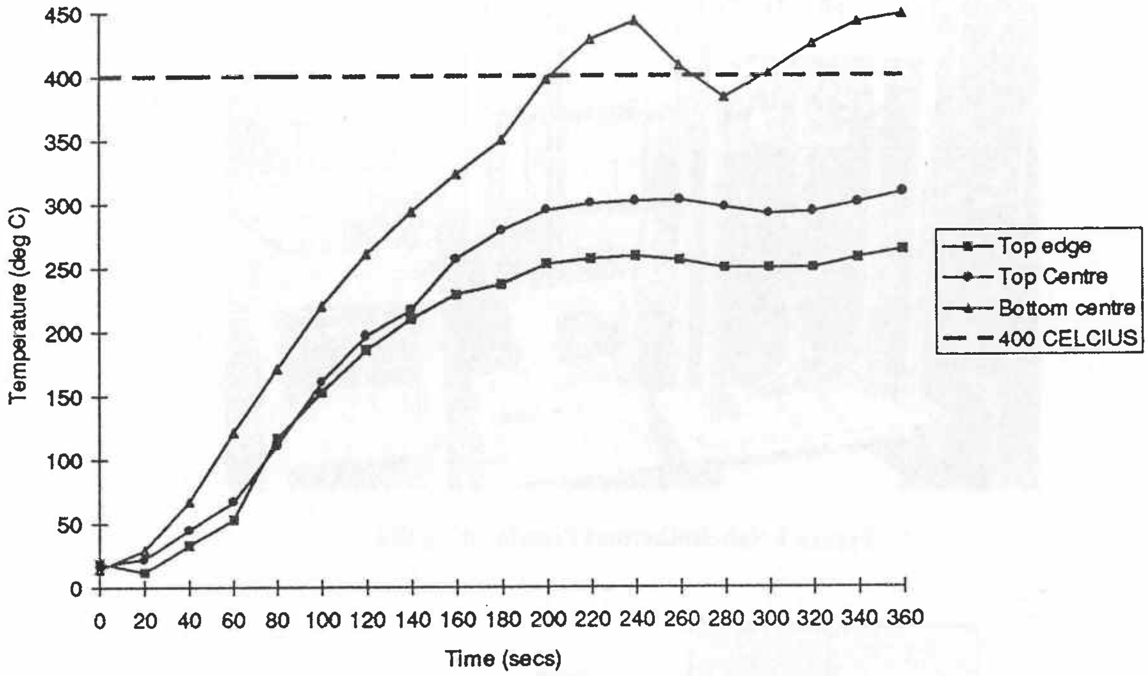

Figure 4. Single Sided Heating of APC-2

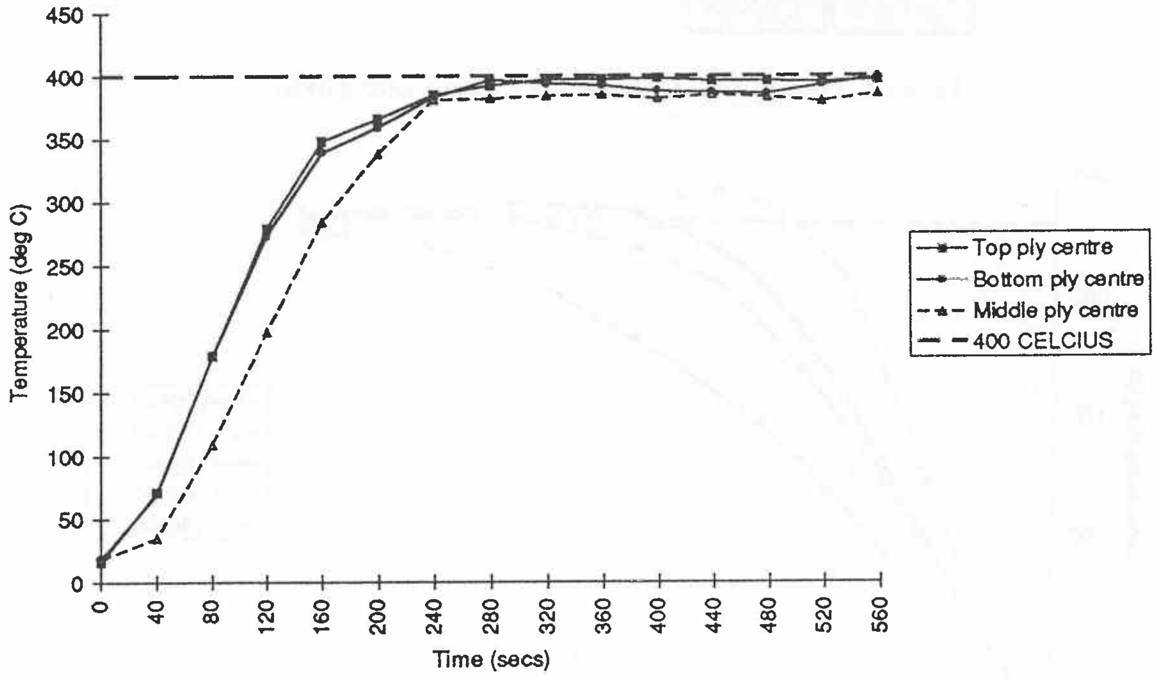

Figure 5. Double Sided Heating of APC-2

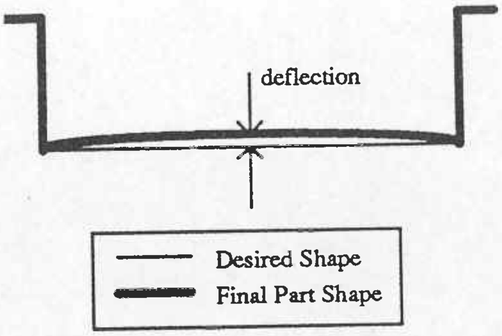

Figure 6. Spring Forward in Cylindrical Dish

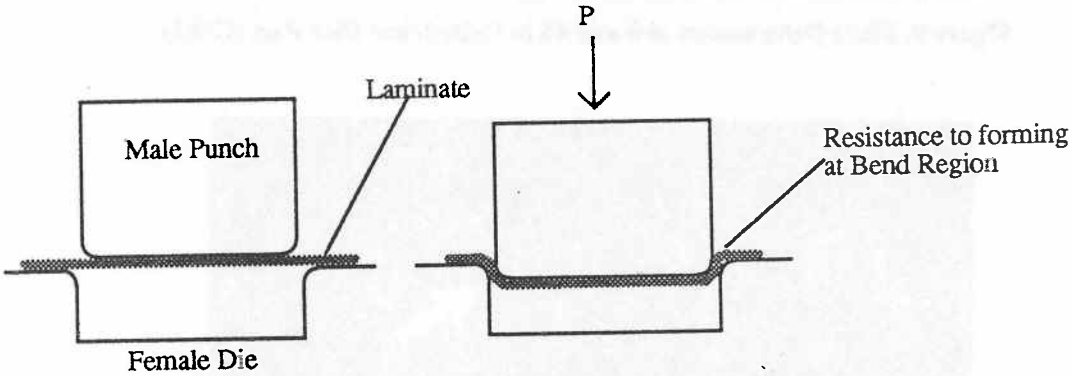

Figure 7. Resistance to draping in Cylindrical Dish Part

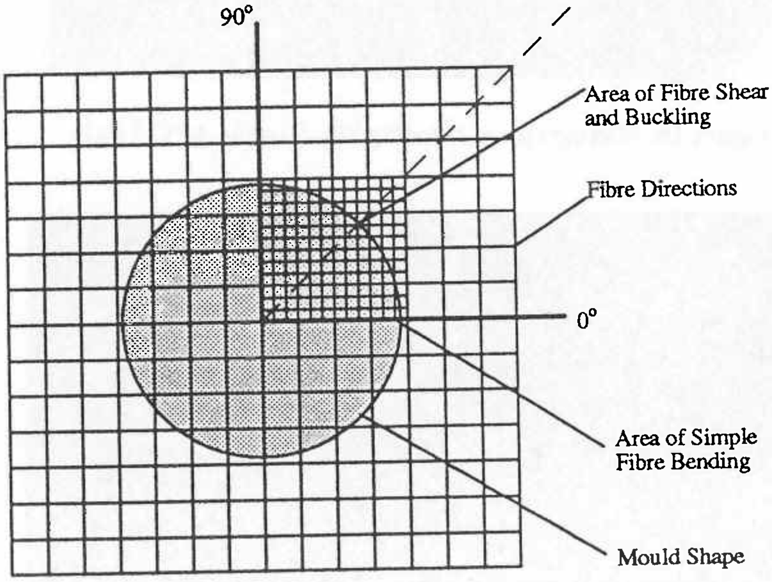

Figure 8. Deformation Areas of Fibres in Cylindrical Dish Forming

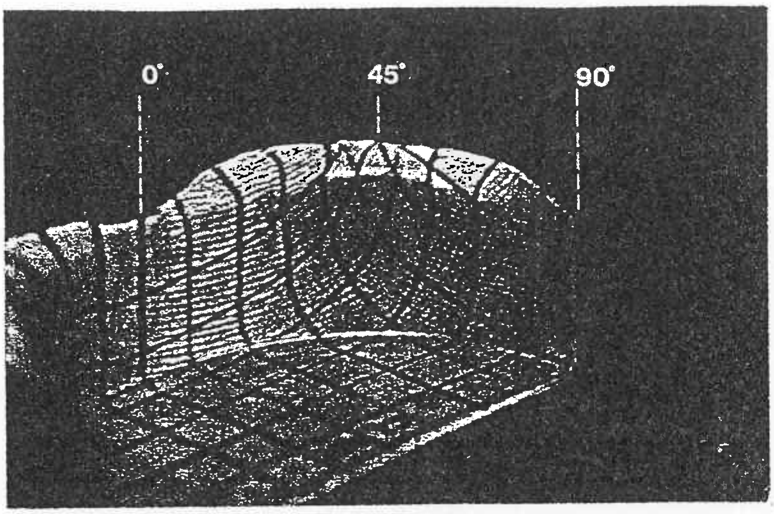

Figure 9. Fibre Deformation at 0 and 45 in Cylindrical Dish Part (G201)

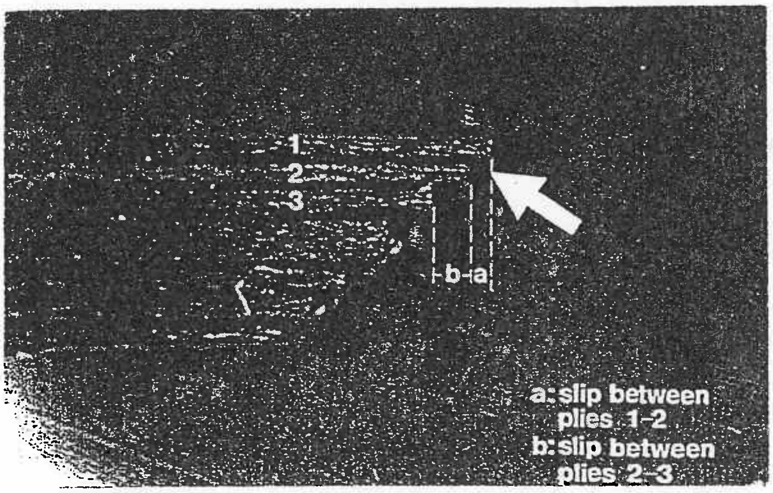

Figure 10. Micrograph of InterPly Slip Region, APC-2 part

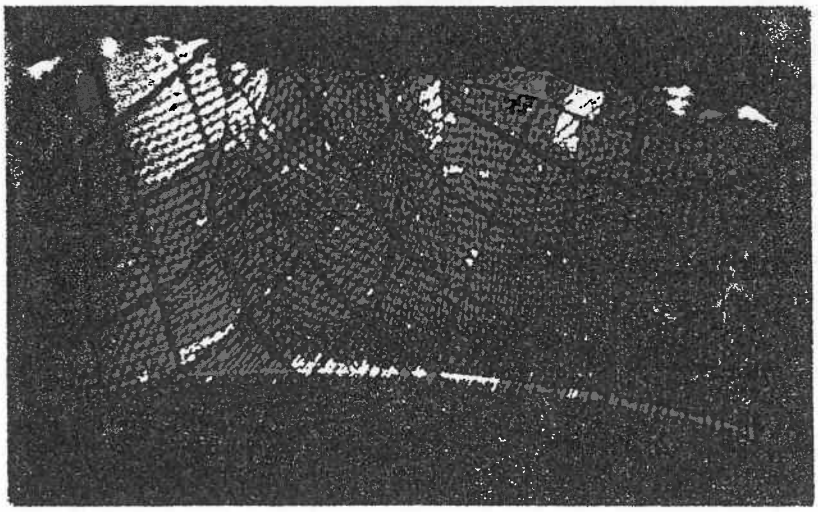

Figure 11. Buckling in [0,+45,90,-45] Cylindrical dish G101 part

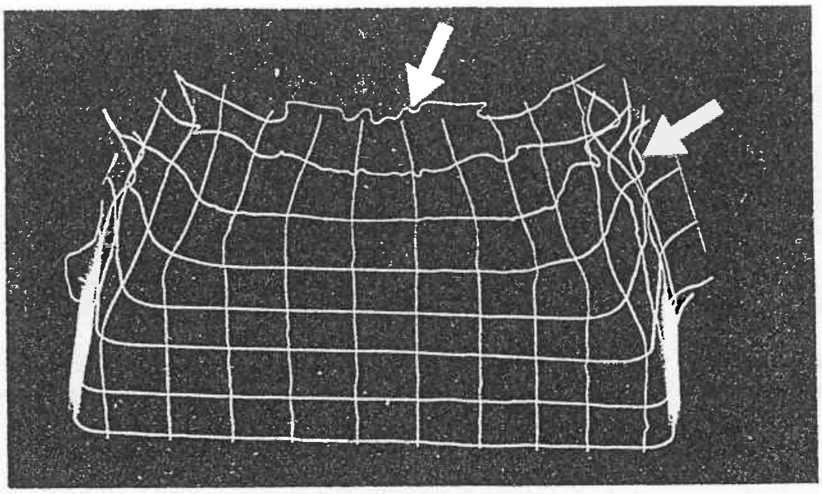

Figure 12. X-Ray of buckled region in Cylindrical Dish APC2 Part

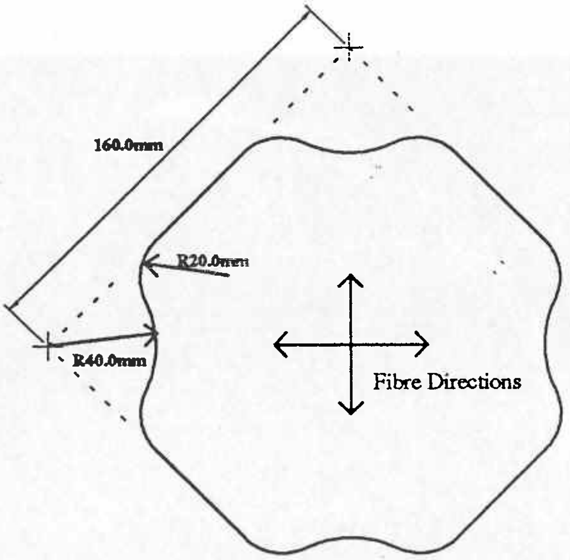

Figure 13. Optimised Blank Shape Dimensions

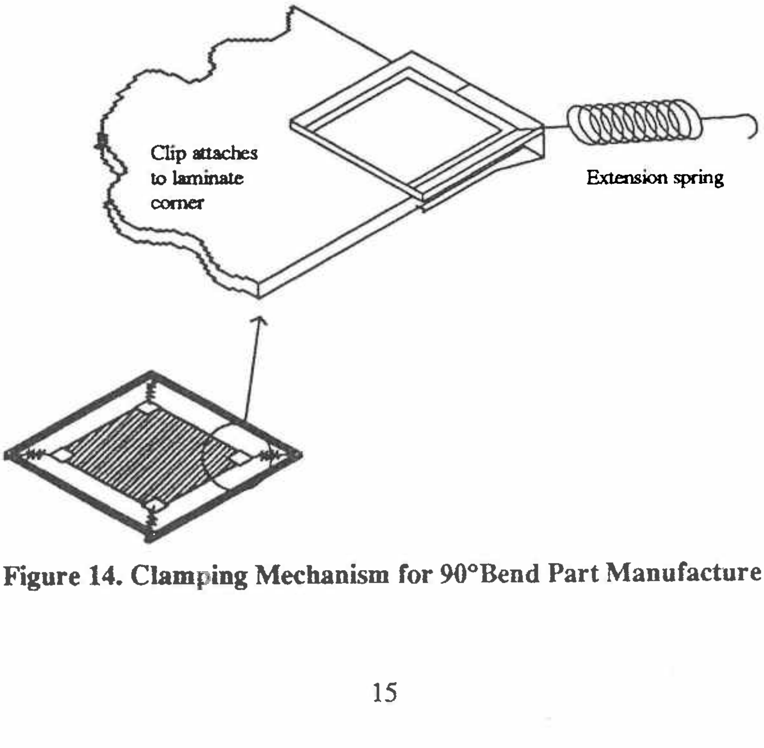

Figure 14. Clamping Mechanism for 90°Bend Part Manufacture

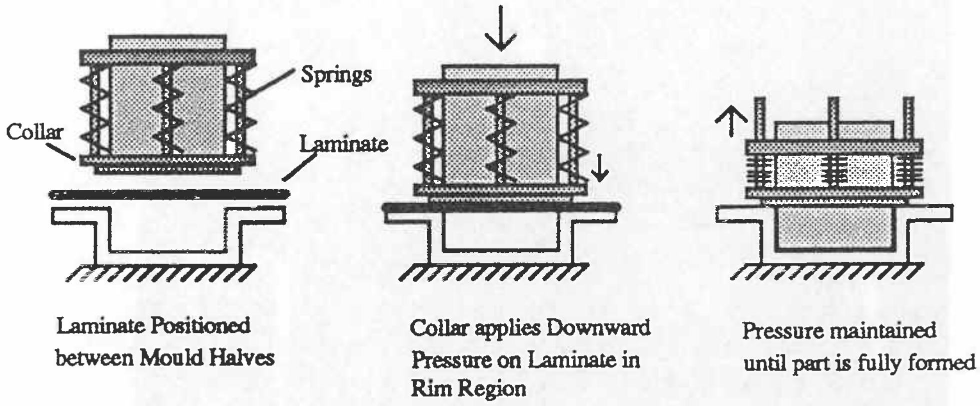

Figure 15. Operating Principle of Cylindrical Dish Clamping and Tensioning Mechanism

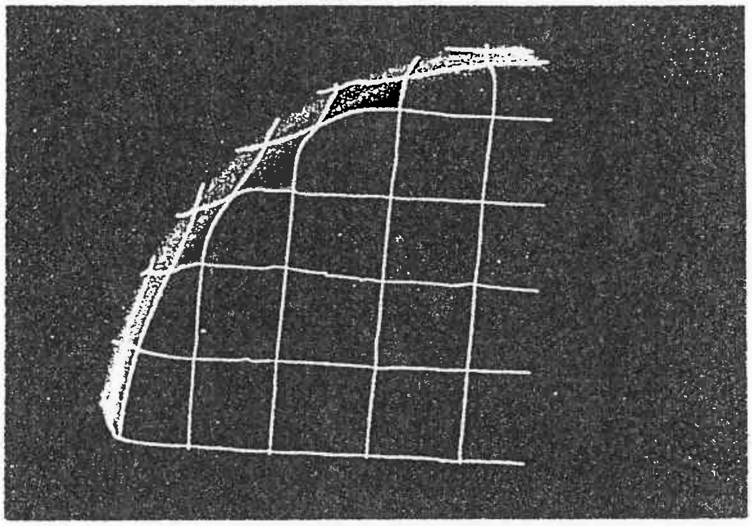

Figure 16. X-Ray of buckled region in Cylindrical Dish APC2 Part using optimsed forming conditions