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3-D Stamp Forming of Thermoplastic Matrix Composites

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Abstract. In this investigation a mould with hemispherical cavity and 80 kN hydraulic press, allowing variable stamping speeds, are employed for experimentally studying of the 3-D stamp forming process of continuous fiber reinforced thermoplastic laminates. In particular, glass fiber (GF) reinforced polyetherimide (PEI) woven fabric made of sheath surrounded, polymer powder impregnated fiber bundles manufactured by Enichem, Italy, is used. Pre-consolidated laminates are heated by contact heating in an external heater up to about 120°C above the glass transition temperature (T_g) of the polymer matrix; they are then stamp formed in a cold matched metal tool. Typical cycle times (including preheating time of the preconsolidated laminates) are in the range of 3 min. Useful processing conditions, such as stamping temperature, stamping velocity and hold-down pressure required for stamp forming of this composite are determined. In addition the effect of die geometries (deformation radian) and original laminate dimensions are studied. The results describe the correlations between processing parameters and fiber buckling. Finally the thickness distribution in stamped parts are investigated in relation to different directions of fiber orientation.

1. Introduction

Polymeric composites reinforced with continuous fibers possess low weight along with high specific strength, stiffness and environmental resistance [1]. Therefore, they are increasingly used for structural parts in aircraft and space applications, in the automobile industry, and for sporting goods [2]. Usually the composites contain thermosetting matrices such as epoxy, phenolic, or unsaturated polyester resins. Reinforcing materials are usually glass, carbon, and aramid fibers. New developments have also focused at the use of thermoplastic matrices, because of their advantageous mechanical properties, especially improved toughness. In addition, they show advantages in processing; special emphasis is set in the development of thermoplastic composites with polypropylene, polyetheretherketone, polyamide, or polyetherimide matrices [3]. The primary property of thermoplastics is a linear structure of molecular chains. This means that, below the melting temperature they have their relevant mechanical properties; above the melting point, however, they

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become soft and are easy to process. The existence of a melting point opens the possibility of producing intermediate forms of thermoplastic composite materials, that can be processed or post-formed at a later data. However, some important processing issues have to be resolved before this can become a valuable economical process. This includes fiber placement control, low cycle times for molding and wrinkle-free complex shape forming. Inhibition to the industrial application of advanced thermoplastic composites is mainly a lack of fully-developed manufacturing techniques. The principal constraint imposed on the forming of continuous fiber composites is that the fibers can neither lengthen nor shorten. The fibers are too stiff to lengthen without breaking, and when shorting is attempted, the fibers tend to kink and then break [4].

The processes which are currently being developed for continuous fiber reinforced thermoplastic composites are thermoforming, tape laying and filament winding [5]. Stamp forming of continuous fiber reinforced thermoplastic composites is a new technique which has yet to be developed. This paper presents, on the basis of previous works [6, 7, 8], an experimental investigation of three dimensional stamp forming of thermoplastic composites consisting of continuous glass fibers (CF) in an amorphous polyetherimide (PEI) matrix. A hemispherical matched metal mould and an 80 kN hydraulic press, allowing various stamping speeds, are employed for the experiments. The aims of this work were to establish a useful processing technique and to control those parameters which lead to the production of good quality composite parts.

2. Experimental

2.1. MATERIALS

The material used in this study was continuous glass fiber (GF) reinforced polyetherimide (PEI) woven fabric made of polymer sheath surrounded, polymer powder impregnated fiber bundles manufactured by Enichem, Italy. The "fabric" had a thickness of about 0.8–0.9 mm and a weave construction of 8-H stain; its matrix was the General Electric Ultem grade 1010 PEI with a glass transition temperature of 210°C. By burning off the matrix in a high temperature oven (about 700°C for one hour), the fiber volume fraction V_f could be determined as 39.3% for this composite preform material.

2.2. MANUFACTURING OF PRE-CONSOLIDATED FLAT LAMINATES

The preparation of pre-consolidated flat laminates involved the following steps:

(a) placing a mould (300×300 mm^2) filled with eight layers of fabric material in a heated press, holding a temperature of 330 ± 1°C;
(b) preheating for 15 min, then applying a pressure of 2.0 MPa over a period of 20 min;
(c) cooling of the mould down to room temperature under pressure within 10 min.

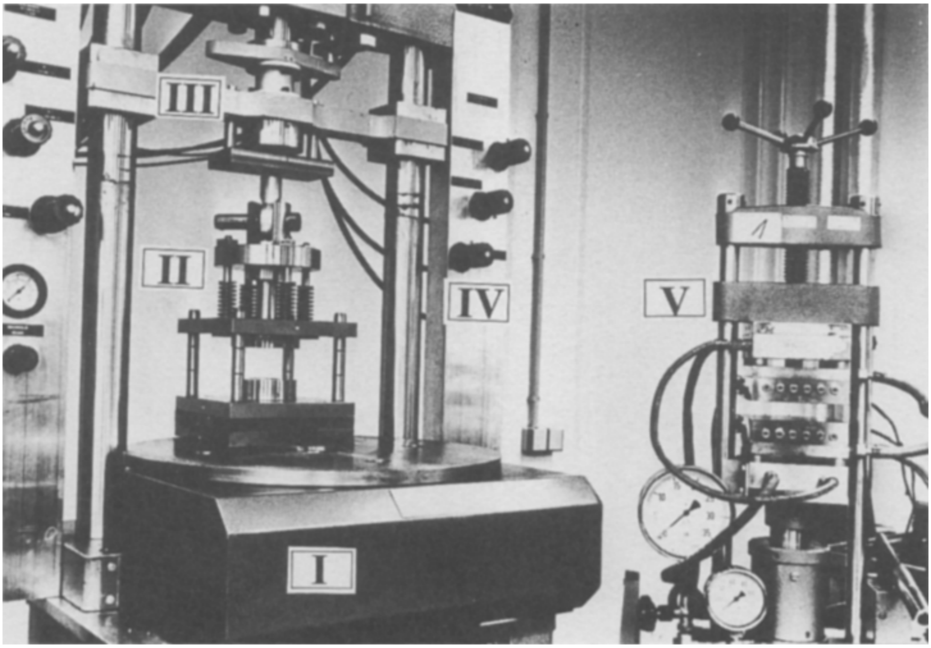


Fig. 1. Forming press and die set-up for 3-D stamp forming

2.3. EQUIPMENT

For easy release from the mould, steel foils were placed between the mould surfaces and the fabric laminate, which also resulted in smooth surfaces of the consolidated laminate plate. The latter had a thickness of 2.3–2.4 mm. Flat circular plates for stamp forming were cut out of the pre-consolidated plates by using a diamond saw. In order to measure the temperature profile of the laminate during stamp forming, various laminate samples that contained NiCr-Ni thermocouples embedded between the two middle layers were prepared. A photograph of the forming system is shown in Figure 1, in which (II) is the 3-D mould. The latter was connected via a pressure transducer (III) with the hydraulic press (I) (HY-Power OP 2MI-TR8-115/30, Italy).This press can build up a maximum load of 80 kN in compression stroke; further, it allows opening and closing velocities of 70 to 250 mm s^{-1} and a compression stroke rate between 2 and 15 mm s^{-1} respectively. Both velocities can be arbitrarily chosen by adjusting the valves (IV). The entire stroke is 115 mm, in which 30 mm is the compression stroke. Required stamping pressures can be roughly controlled by adjusting the compressed air pressure. An advantage of

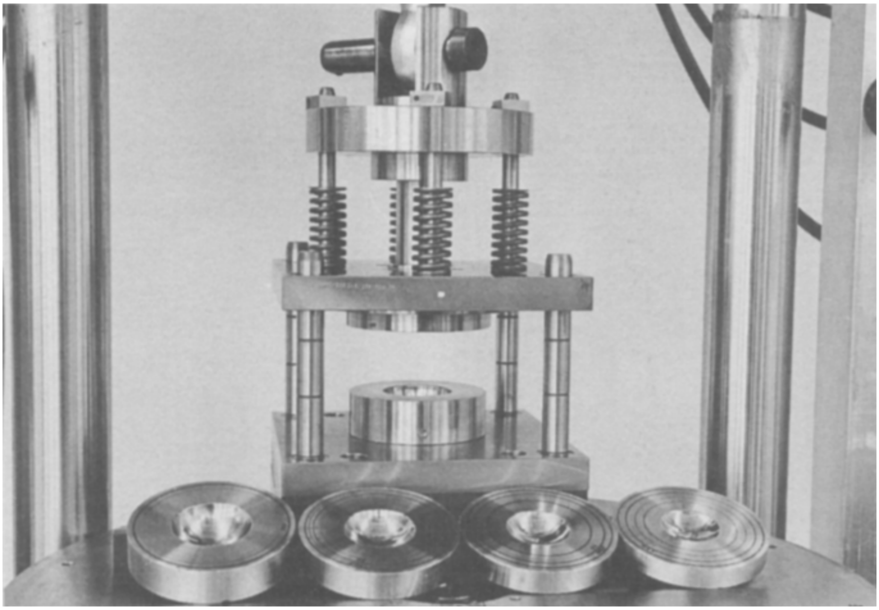


Fig. 2. Hemisphere mould

a hydraulic press lies in the fact that there is no “swing-over effect” any more, e.g. when the desired pressure is reached, the cross-head movement of the press will be immediately stopped and at this point the desired pressure will be automatically controlled by the press. Before the forming process, the sheet stock or pre-consolidated laminate is warmed up by conduction heating between two hot platens in an external heat press (*V*).

Figure 2 shows the 3-D mould system. The male half of the mould consists of a central forming stamper capable of vertically moving through a mid-plate guide system. The female half is a single piece containing a hemisphere or a segment of a half-sphere. The mould was so designed that when the mould closes, the holder moves always first down to clamp the hot laminate before it is deformed by the stamper; this helps to provide some clamping forces. Once this occurs, the male part of the tool (stamper) moves downwards in order to deform the laminate into the female cavity. The clamping force provided by the holder can be varied by adjusting either the number of springs, their elastic factor or simply the weight, which can be placed on the holder. It should be noted that during the actual forming process the flat laminate between the holder and the flange of the female mould is performing a continuous sliding movement into the mould cavity. Therefore, the

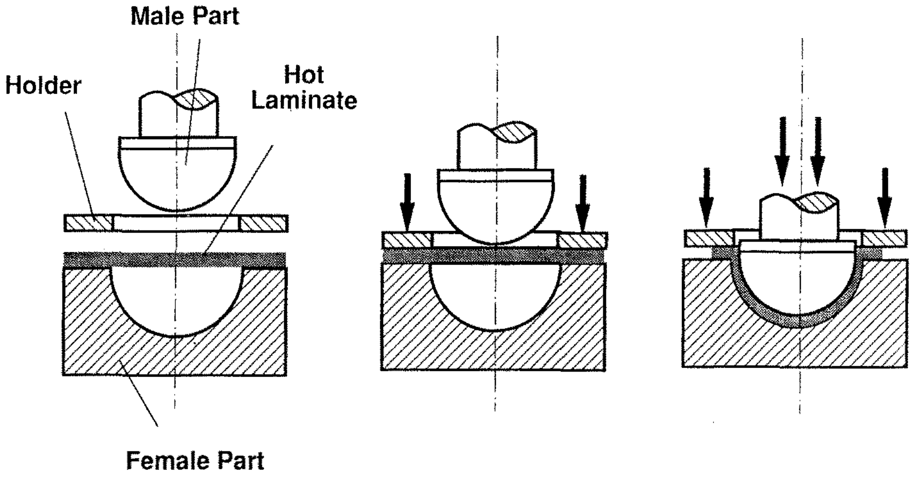
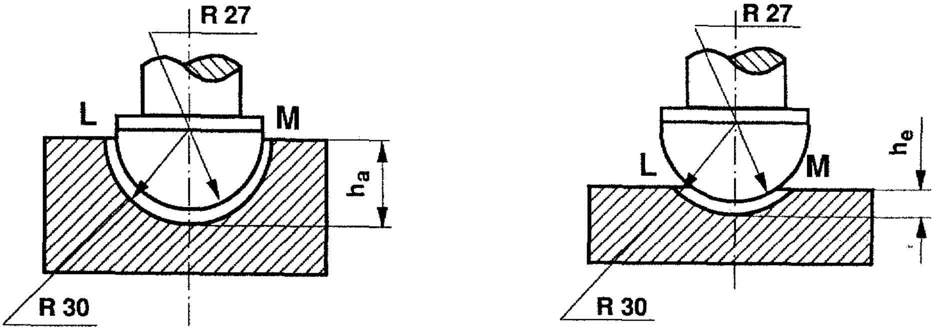


Fig. 3. Working principle of hemisphere mould

actual surface area of the laminate which is held down by the holder varies with the forming process. Thus it is very difficult to determine the actual hold-down pressure at every stage during forming. For better clarity, the initial hold-down pressure, as calculated by dividing the hold-down load through the initial surface area under the holder, will be used as hold-down pressure in the following text. The working principle of the mould is schematically shown in Figure 3. Five pairs of matched metal moulds have been used in this study; their geometrical details are shown in Figure 4. The hemisphere stamper has a radius of 27 mm and all the female moulds have a radius of 30 mm, so that there exists a uniform gap of 3 mm between the male and female part. The unique difference among these female moulds is the depth of cavity, which leads to the production of a full hemisphere out of mould A and a segment of sphere out of other moulds B, C, D and E. In order to characterize the geometrical feature of these forming tools, a concept of deformation radian (α) has been defined, which equals to the arc length of the corresponding female mould ($(\overset{\frown}{LM})$) divided by the radius of this sphere ($R = 30$ mm), i.e. $\alpha = (\overset{\frown}{LM})\ /R$. This indicates a degree of forming difficulty for a flat laminate to be formed into a hemispherical cavity. The deformation radians of these female moulds are also shown in Figure 4.

3. Processing Procedure

The basic principle of stamping with continuous fiber reinforced thermoplastic composites is to allow the preconsolidated laminate to deform in such a manner that interply slippage, interply rotation and intraply shearing can account for the gradual change in shape before cooling of the hot preformed laminate [9]. The



Deformation Radian $\alpha = \dfrac{\overset{\frown}{LM}}{R\ (= 30)}$

Female Part	A	B	C	D	E
h_i [mm]	30	20	15	12	10
α	3.14	2.46	2.09	1.86	1.68

Fig. 4. Geometries of three dimensional moulds used

typical forming procedure involves (a) heating the pre-consolidated laminate to a temperature 110–120°C above the glass transition temperature of the PEI matrix (i.e. up to 330°C) in an external hot press, then (b) quickly transferring it into the dies, which are kept at room temperature. At the high temperature of 330°C, the laminates are flexible and can be deconsolidated or easily distorted, and they tend to stick to the contact surface. This makes handling very difficult. Therefore, the flat circular plate, similar to 2-D stamp forming [6, 7], has to be heated between two polymeric films for easy transferring; the films must be deformed together with the laminate during the stamp forming process. These films result also in a good surface quality of the stamped samples. It should be noted that any undesired deformations of these films, for example, wrinkling and tearing can have an adverse effect on the quality of the formed part. This demands that the film to be used must possess a super-elastic property at the processing temperature of the PEI polymer matrix, i.e., undergo a large elongation at a temperature as high as 330°C, but not melt, wrinkle or tear at this temperature. From the literature reference [10] and the results of a series of experiments with different kinds of polymer films, UPILEX-R-25 polyimide film has been chosen to be used in this 3-D stamp forming. The foil has a thickness of 25 μm and allows an elongation of 210% at 250°C.

The laminate will be heated under this condition for about 1.5 min without any external pressure. Then, the sheet is transferred between the two dies of the forming system where the sheet is stamped to conform to the die geometry. Transfer times are of the order of a few seconds to prevent significant cooling. Because the heated laminate is exposed to a lower environmental temperature before tool contact and deformation take place, the use of high closing speeds plays an important role in successful stamp forming. During the stamping, the sheet is pressed for about 40 s and cooled by the cold tool under pressure down to a temperature below the glass transition temperature of the polymer matrix. In the following removal from the forming system, the parts have a temperature of about 40–60°C.

4. Results and Discussions

4.1. STAMPING TEMPERATURE

A major problem of stamp forming is to determine the temperature range in which the laminate can be successfully stamped into a useful part. Due to the complexity of deformation of a flat laminate during 3-D deformation it is very difficult to evaluate the suitable stamping temperature in relation to the formed part quality. Therefore a 2-D stamp forming process, e.g. forming a right angle bend sample, has been used at first to study the influence of stamping temperature on part quality. In two-dimensional forming, the interply shear is one of the important flow processes, in which the individual plies, acting as plates, shear relative to one another to prevent the kinking of the plies on the inside of the bend [11]. This interply shear is a consequence of a pressure and hence velocity gradient which is set up through the thickness of plies and along the length of a ply during molding [12]. However, if the stamping velocity is too slow, the actual temperature of the laminate falls below a temperature level necessary to allow interply slipping. In this case, the shear stress acting on the plies does not exceed the yield shear stress of the matrix material; this may finally result in buckling of the fibers at the inside of the bend, and eventually in fiber breakage events at the outside of the bend region. [6,7].

In this investigation a series of trials were made in which the compression velocity of the press was 4.2 mm/s and the closing velocity was varied between 70–230 mm/s. Stamping temperature as a function of processing time was monitored by using laminates embedded with NiCr-Ni thermocouples; this is illustrated in Figure 5. As taken out of the heating device the hot laminate had a temperature of 330°C. The upper linear bound with the black circles indicates the cooling rate of laminates in air, representing the condition where the heated laminate is not yet in contact with the cold parts of the tool. The temperature at which the cooling of the laminate starts to drop down more rapidly (due to the contact of the tool parts and the laminate during closing) is defined as the stamping temperature. Its value is the higher the faster the stamping velocity is. It can be seen from this figure that the stamping temperature of these laminates, though under different closing velocities,

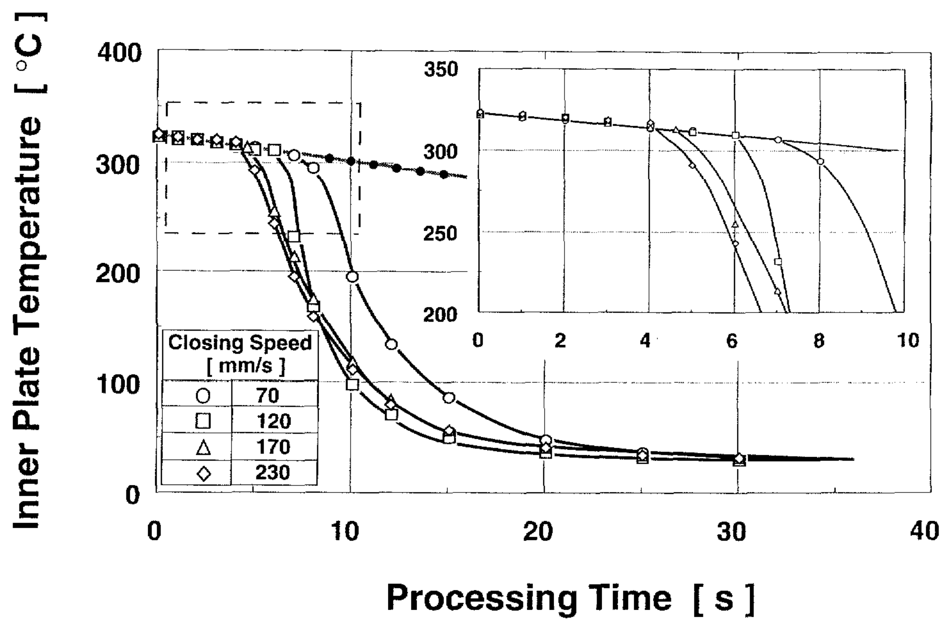


Fig. 5. Temperature profile of hot GF/PEI FIT laminate during stamp forming

could be maintained above 290°C. Micrographs of polished cross-sections of the bend regions of the angle samples give clear evidence of the good quality, e.g. without any fiber kinks, and the step-form of individual fabric plies can also be seen on bend ends. It implied that under these conditions the achieved stamping temperatures were high enough to maintain the melting state of the PEI matrix, which allowed sufficient interply slip, interply rotation and intraply slip in the laminates.

Based on the experimental results of 2-D stamp forming, the following processing conditions have been used in the 3-D stamp forming:

Heating temperature:	330°C
Closing velocity:	230 mm s^{-1}
Compression velocity:	4.2 mm s^{-1}

4.2. DEFORMATION MECHANISMS

In order to understand the forming mechanisms, it is desirable to examine the progressive stages of a 3-D stamp forming operation at first. Figure 6(a) illustrates schematically a step by step deformation of a flat circular laminate as it is moved into the cavity of a hemispheric die. Segment A represents a segment of a circular laminate before forming and section 1, 2, 3, 4 and 5 lies in one plane. Segment

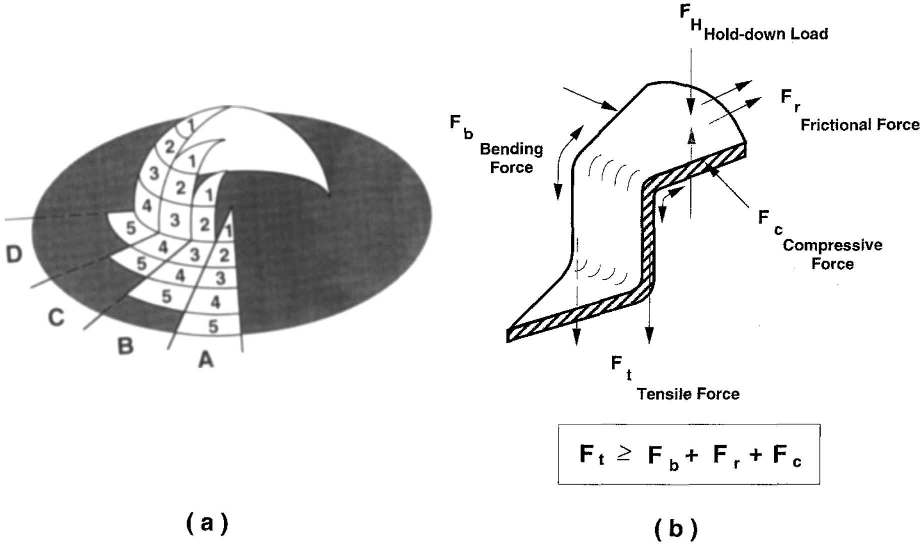


Fig. 6. Step-by-step deformation of flat laminate during 3-D stamp forming

B can be visualized as part of a hemisphere, in which 1 and 2 consist of the wall of the hemisphere while 3, 4 and 5 are still a part of the flat laminate. Segments C and D show the progressive deformation processes as the flat laminate moves continuously into the hemisphere cavity.

The important implication of this figure is the fact that the width of the arc of sections in the flat laminate becomes progressively narrower as the section is deformed into the cavity. It can be easily understood that the 3-D forming operation leads to a decrease in laminate surface area and the principle mode of deformation is compression. This indicates, therefore, the existence of compressive forces, F_c (Figure 6b), perpendicular to the radius of the circular laminate. In general, if the compressive forces generated during forming exceed the critical buckling stress, this results in fiber wrinkling and distortion around the periphery of the cavity and in the flange areas. The wrinkling problem is expected to be worse in the case of absence a hold-down pressure on the flange area. This action of hold-down can give rise to a frictional force, F_r, which opposes the flow of material into the cavity. It is well known that an important mode in achieving a three dimensional forming is called intraply shear or Trellis effect [4, 13]. During forming, the frictional forces can be generated in the reinforcing fabric in all directions other than the principal fiber directions (warp and weft). These frictional forces can introduce stretching

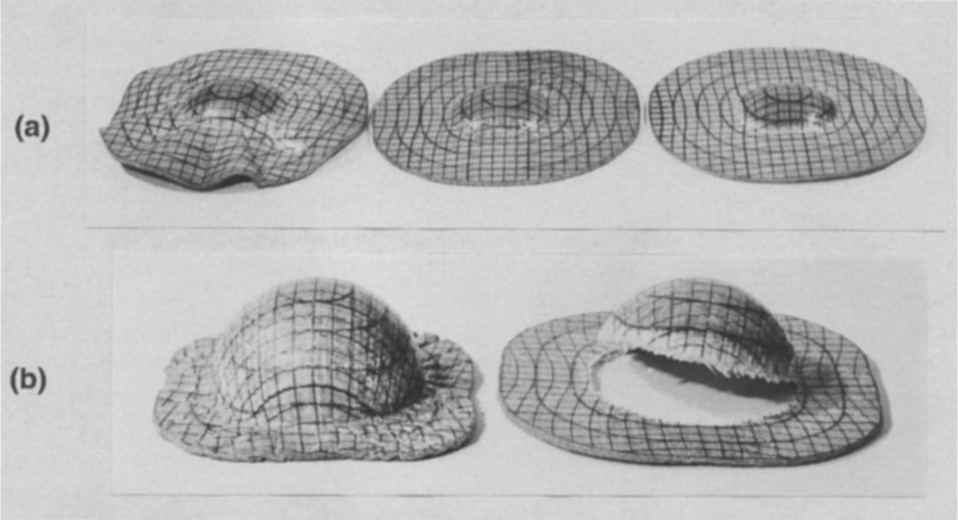


Fig. 7. Stamped 3-D parts with different hold-down pressures: (a) with mould E, a stamping pressure of 10 MPa and hold-down pressures of zero (left), 0.3 MPa (middle) and 0.9 MPa (right) (b) with mould A, a stamping pressure of 15 MPa and hold-down pressures of 0.5 MPa (left) and 1.22 MPa (right)

and shearing forces in the plane of the laminate and result in intraply shear within the laminate. The intraply shear continues until either the fiber direction coincides with the load direction or the cross-over angle between warp and weft fiber bundles reaches its minium allowable value. These effects increase the critical buckling stress of the laminate, and therefore help to prevent fiber wrinkling during forming. Each section also undergoes a bending deformation, e.g. a bending force F_b, as it moves from the flange into the cavity. The necessary condition for the successful transfer of the flat laminate into the cavity is that the tensile force exerted by the stamper exceeds or equals the sum of all other forces, as shown schematically in Figure 6b:

$$F_t \geq F_b + F_r + F_c \tag{1}$$

where

F_t: Tensile force
F_b: Bending force
F_r: Frictional force
F_c: Compressive force.

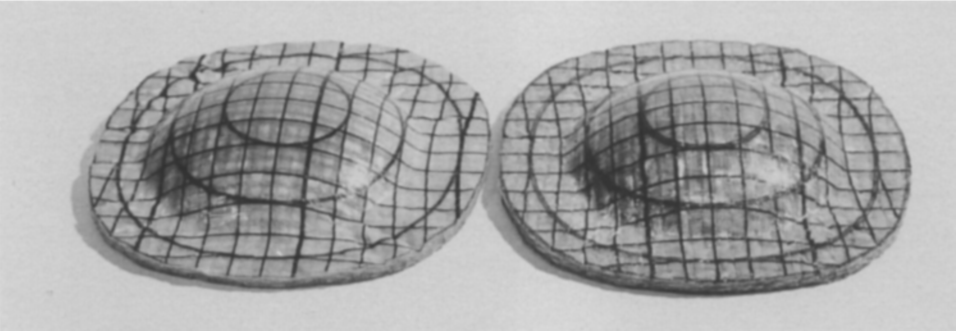


Fig. 8. Effect of hold-down pressure (0.1 MPa for left sample and 0.3 MPa for right sample) on formed part quality

4.3. EFFECT OF HOLD-DOWN PRESSURE ON PART SHAPE

As an example, Figure 7 shows a variety of stamped parts formed under different hold-down pressures; samples in (a) were formed by using mould E, those in (b) by using mould A. Without any hold-down pressure, the compression force exceeds easily the critical buckling stress of the laminate and results in severe buckling of the laminate within the flange area (left sample in Figure 7(a)). Depending on the resistance created by compression and friction, the tensile force of the stamper may simply press the laminate into the cavity, resulting in a formed hemispheric part (middle sample in (a) and left sample in (b)). If it is, however, large enough to exceed the ultimate strength of the laminate, e.g. in the case of too high hold-down pressure, this may result in punching the formed cap apart from the flat flange (right samples in (a) and (b)). The hold-down pressure, therefore, is a limiting factor in stamp forming. Forming conditions must be such that the load due to punch stress of the laminate is always larger than that due to the shear yield stress at the interface to the holder, so that the flat laminate is able to slide under the holder into the hemisphere cavity.

Figure 8 shows two samples formed by mould E. The stamping pressure was 10 MPa for both samples, while the hold-down pressure was 0.1 MPa for the left one and 0.3 MPa for the right. It is clear that the sample on the left side has experienced much more buckling than the right one. It means that the frictional force created by the hold-down pressure is not yet enough to allow the entire intraply shear of the laminate to take place during forming. If the hold-down pressure is increased to 0.3 MPa, however, there is little buckling visible in the flange area and its edges.

4.4. EFFECT OF LAMINATE DIMENSIONS ON PART SHAPE

Pre-consolidated plates with different initial diameter were stamp formed to investigate the influence of laminate dimension on the shape of a formed part. Figure 9 shows the formed hemisphere parts with mould E (a) and mould C (b), where r is

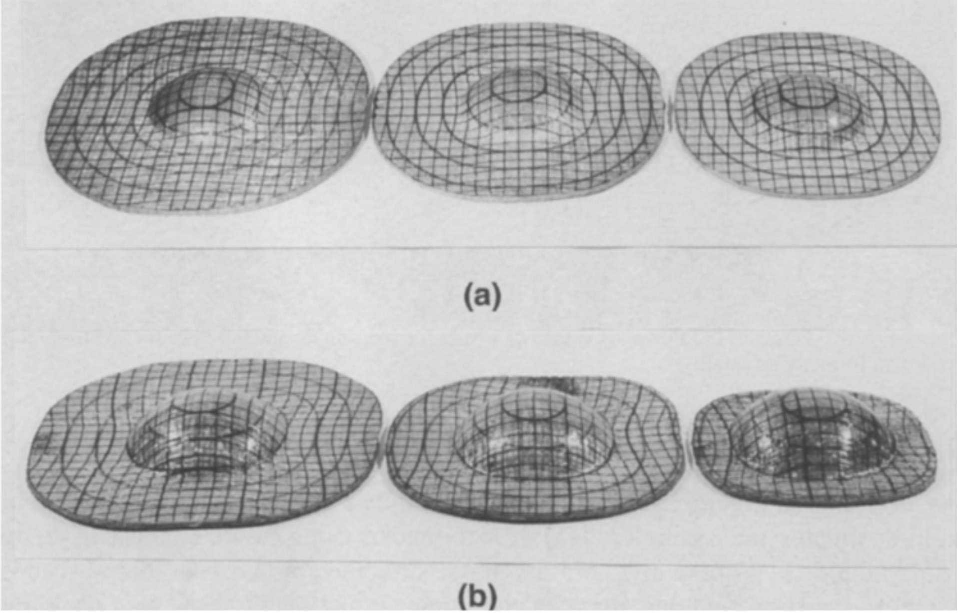


Fig. 9. Effect of laminate dimensions on part shape (a) with mould E, $r = 6.0$ (left), $r = 5.0$ (middle), $r = 4.0$ (right (b) with mould C, $r = 4.0$ (left), $r = 3.0$ (middle), $r = 2.0$ (right)

the ratio of initial area of the flat laminate (A_1) to the formed sphere surface area (A_2), e.g. $r = A_1/A_2$. All samples were stamped by a stamping pressure of 10 MPa and a hold-down pressure of 0.3 MPa. It can be seen, in general, that the samples made from mould E (a) showed no buckling within the flange area, though the ratio of r increased from 4 to 6, while the samples made from mould C exhibited some buckling, that increased with an increasing value of r. This phenomenon is thought to be due to the bigger deformation radian ($\alpha = 2.09$) that exists for mould C in comparison to that of mould E ($\alpha = 1.68$). It implies that the deformation radian might have a significant influence on buckling. One can therefore conclude that for a big deformation radian, buckling can be caused by the excess material which remains outside the formed area; the latter can be related to the ratio ($r = A_1/A_2$) of initial area of flat laminate to the formed sphere surface area.

It was found that most buckling in the flange area takes place under an angle of ± 45° to the fiber direction, as illustrated in Figure 10. The same observation was also reported by Pipes *et al.* [10, 14]. This is due to the compressive forces, which exert on the ±45° plane to the reinforcing fibers. As stamping pressure is applied on the flat laminate, the central region of the laminate is forced downwards into the cavity. Since not material stretching can occur in the direction of fibers, the inextensible fibers are forced to move inwards from the outer edges of the laminate. This inward displacement of entire fibers is primarily resisted by intraply

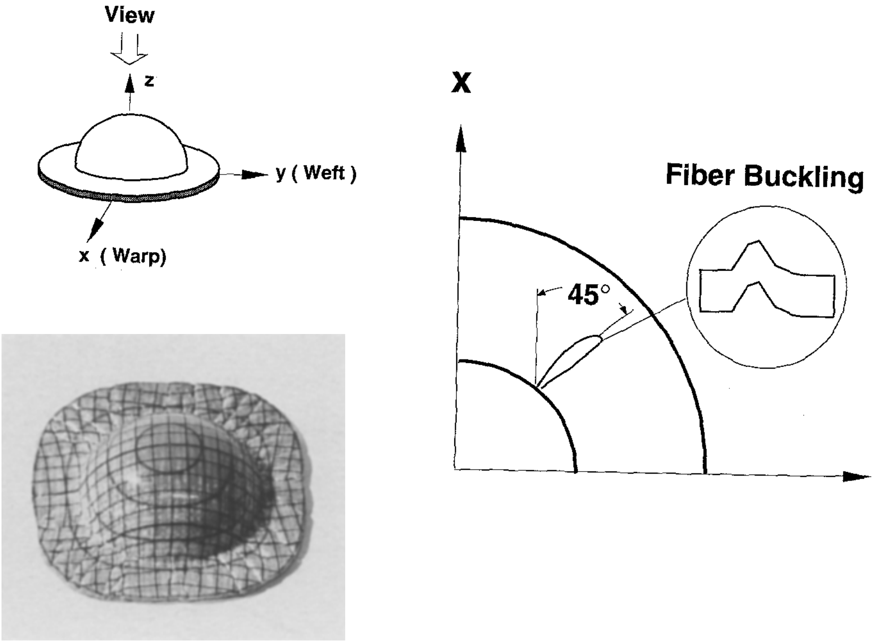


Fig. 10. Illustration of fiber buckling in 3-D stamp forming

shear forces, which can be resolved into symmetric forces at ±45° to the fibers, resulting in buckling phenomena in this direction [14].

4.5. EFFECT OF DEFORMATION RADIAN ON PART SHAPE

The influence of deformation radian on the buckling phenomenon is demonstrated in Figure 11. All samples are stamped by a stamping pressure of 10 MPa, a hold-down pressure of 0.3 MPa and a surface ratio of $r = 2$. From right bottom to left top, the samples were formed with mould E, D, C, B and A respectively. It is clearly to see that at a low value of deformation radian, for example $\alpha = 1.68$ (for mould E), there are very little bucklings visible in the flange area. As the deformation radian increases (from mould D to mould A), the severity of buckling seriously increases; for mould A, where the deformation radian $\alpha = 3.14$, the buckling of the flange area is so serious that the flange area is no more a plane, instead the buckled laminate portions overlap each other. As has been stated before, an increase in the deformation radian will mean a greater displacement of the inextensible fibers to be formed into the mould, and thus greater compressive stresses arise. It implies

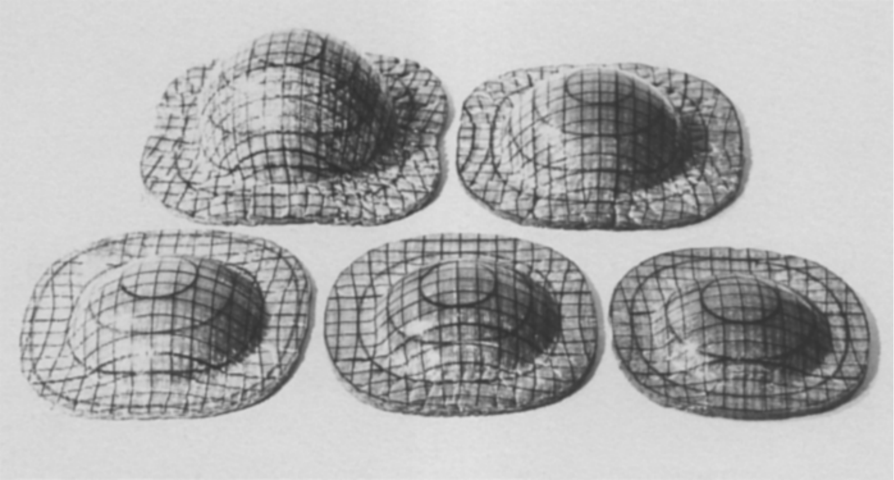


Fig. 11. Effect of mould geometry on part shape. Samples are formed with mould *E*, *D*, *C*, *B* and *A* (from right bottom to left top)

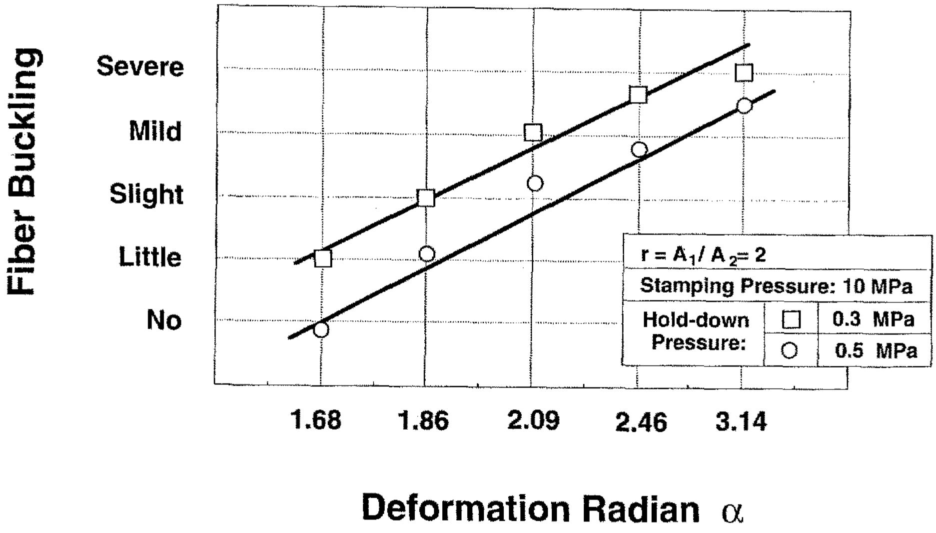


Fig. 12. Qualitative representation of severity of fiber buckling versus deformation radian and hold-down pressure

that a larger hold-down pressure is needed in order to form a sample in case of a larger deformation radian. Samples stamped under a hold-down pressure of 0.5 MPa showed appreciably decreasing buckling phenomena in the flange area.

The severity of the buckling was rated qualitatively on a scale of no buckling to severe buckling for two series of samples stamped by hold-down pressures

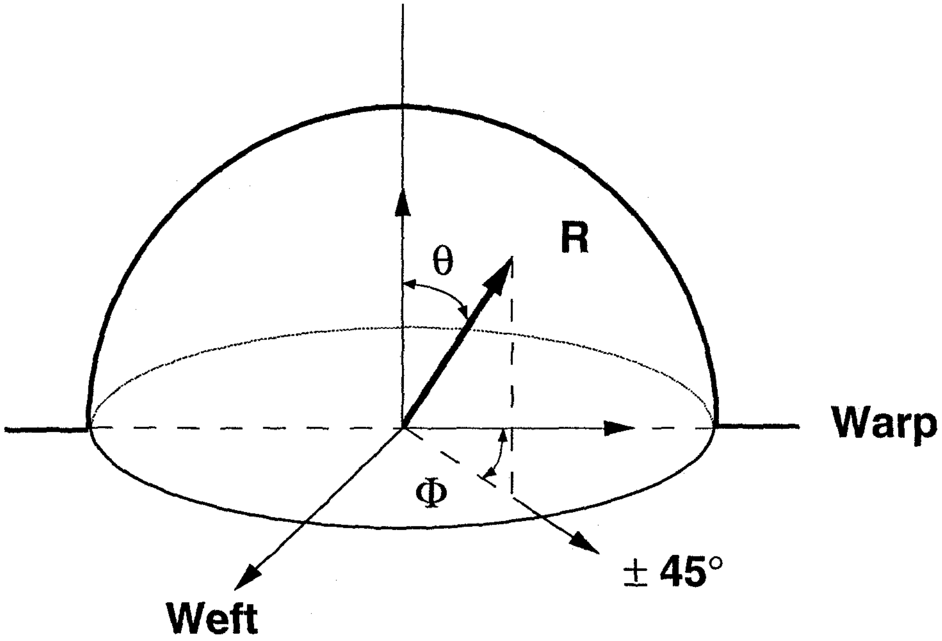


Fig. 13. Thickness measurement in hemisphere co-ordinate system

of 0.3 and 0.5 MPa respectively. Figure 12 shows the results of this study; it illustrates that increased buckling is found at larger deformation radians. It should be noted that because of the restrictions of materials available, stamp forming with all five moulds and at higher hold-down pressures have not been carried out. But from the results shown in Figure 12, it is easy to come to the conclusion that higher hold-down pressures can effectively prevent buckling created by large deformation radians.

4.6. THICKNESS DISTRIBUTION

To investigate the thickness distribution of the formed part, variations in thickness of the formed hemispherical parts were measured in three directions, i.e. in warp, weft and ± 45° to the fiber direction (Figure 13).

Figure 14 shows the thickness distribution in relation to angle θ; the sample was formed by mould B, a stamping pressure of 10 MPa and a hold-down pressure of 0.3MPa. The normalized part thickness $[= (d - d_0)/d_0]$, which is equal to the thickness change ($\Delta d = d - d_0$) divided by the original laminate thickness d_0, is demarcated as a function of the measuring angle θ. The part has a thickness variation between +12% and -8% which is symmetric about the central line through the apex of this part. The thinnest section occurs at the apex of the hemisphere; this is due to a localized higher pressure, as the male and female die contact first at this

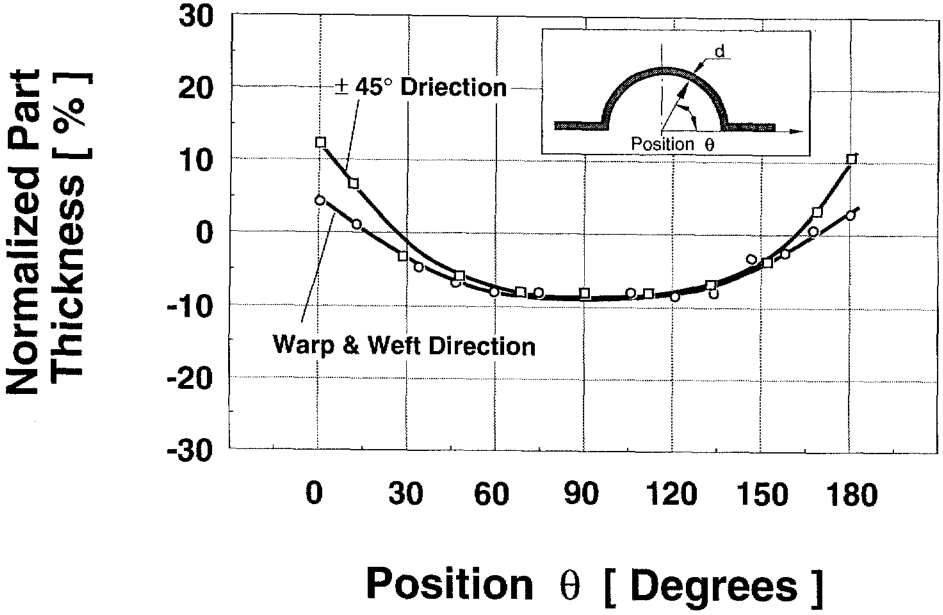


Fig. 14. Thickness distribution of stamped spherical segment in relation to fiber direction

point. The result is that the molten matrix and even fiber bundles flow away from this range. This effect forms a pressure gradient along the spherical surface from the apex to the edge of the hemisphere, leading to the transverse matrix and fiber flow towards the lower pressure regions, and a consequent increase in thickness at the edge region occurs. Because of the symmetric construction nature of a woven fabric, it is no surprise to find that the thickness distributions in both warp and weft directions are the same. It is of interest to note, however, that the laminate thickness in ±45° direction is a little bit thicker than that in both warp and weft directions. As the flat laminate is forced into the cavity, the intraply shear or the rotation between warp and weft fiber bundles takes place and allows the laminate to gradually change in shape. This results in a decrease of the angle between warp and weft fiber bundles and therefore a close accumulation of fiber bundles in ±45° directions, thus leading to a thicker laminate in ±45° relative to other directions [8]. This phenomenon may be best understood when looking at fiber arrangements in the corresponding regions after forming. Figure 15 shows the sectional photos of a hemisphere taken from the ±45° and the warp direction respectively. The samples were heated in an oven at a temperature of 700°C to burn away the PEI matrix. Considerable intraply shear and narrowing of angle between warp and weft have occurred in the ±45° sample.

Figure 16 shows the influence of stamping pressure on the thickness distribution in the fiber direction. As expected, the thickness reduction increases with an

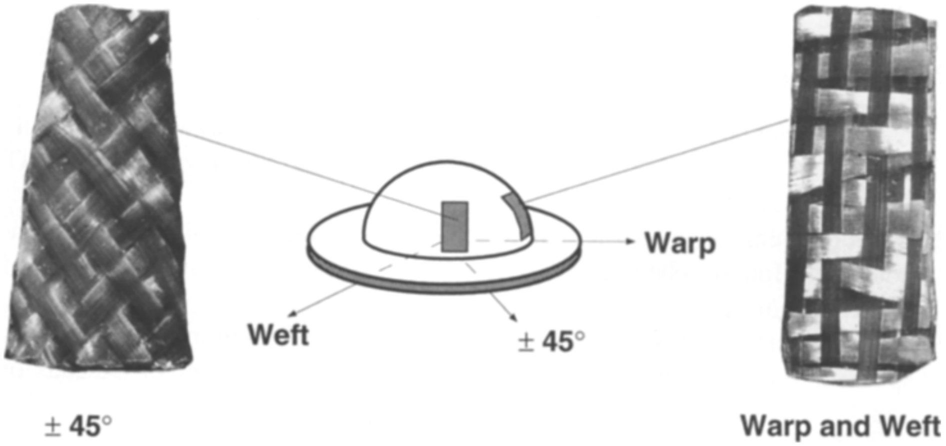


Fig. 15. Fiber arrangements after stamp forming

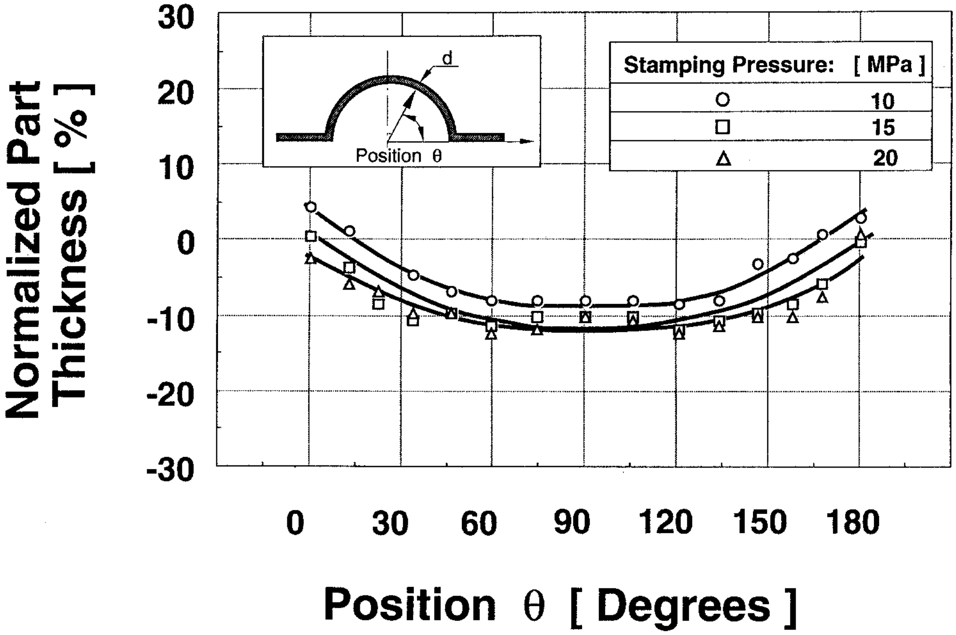


Fig. 16. Thickness change of stamped spherical segment at different stamping pressures

increase of stamping pressure. But the amount of thickness reduction due to the increase of pressure is not so big when being compared to UD fiber reinforced laminates [15], since the behaviour of the woven fabric is almost entirely that of a pin-jointed net. It can effectively prevent great resin and fiber flow during forming, even under high pressure.

5. Conclusions

1. An experimental three-dimensional matched die (hemisphere) was successfully designed and employed in a hydraulic press for stamp forming of GF/PEI FIT Fabric composite.
2. A temperature range useful enough for sufficient stamp forming of this composite was found to be at least 95°C above the glass transition temperature of the amorphous polymer matrix PEI.
3. The necessary condition for successful transfer of a flat laminate into a hemispherical cavity is that the tensile force exerted by the stamper exceeds or equals the sum of bending, frictional and compression forces, i.e.
   $F_t \geq F_b + F_r + F_c$.
4. Typical cycle times (including pre-heating time of the pre-consolidated laminate) are about 3 min. Useful stamping conditions are determined as:

Heating temperature:	330°
Closing velocity:	230 mm s^{-1}
Compression velocity:	4.2 mm s^{-1}
Stamping pressure:	10–20 MPa

5. An instability phenomenon in the composite part, known as "shear-buckling", was investigated and can be prevented by applying a suitable hold-down pressure on the flat laminate.
6. Thickness distributions in hemispherical parts are symmetric about the central line through the apex and vary from -15 to 10%, which depends on the stamping pressure applied.

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