THE OPTIMISATION OF THE DIAPHRAGM FORMING PROCESS FOR CONTINUOUS FIBRE REINFORCED THERMOPLASTIC COMPOSITES

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ABSTRACT

In order to optimise the diaphragm forming process, forming and heating studies have been carried out for continuous fibre reinforced polyetherimide laminates and polyimide diaphragms. Different tooling concepts have been evaluated with respect to the reduction of the manufacturing time. Based on these experimental results a new machine has been designed and built for the automated manufacturing of advanced thermoplastic composite parts.

Keywords : thermoplastic composites, diaphragm forming, process automation.

1. INTRODUCTION

In previous publications, it has already been demonstrated that the diaphragm forming process[1] is a suitable manufacturing technique for complex continuous fibre reinforced thermoplastic components /1/. Diaphragm forming in hot autoclaves is necessary to study the forming of thermoplastic composites and the associated flow mechanisms as well as the biaxial deformation of the diaphragms. However in the composite technology, especially in the field of continuous fibre reinforced materials, there is a lack of standard test methods and material characteristics to investigate their forming behaviour for different manufacturing processes. These standard test methods should supply the material data needed for the interpretation and the simulation of the forming process. A critical aspect of diaphragm forming compared to other processes, like press forming for example, is the length of the cycle time, which is determined by the heating phase, the forming and the consolidation of the laminate and the cooling phase (Fig. 1).
In a first stage, the forming of the diaphragm set-up, which is influenced by the mechanical behaviour of each component and their interactions, including :

- the viscoelastic deformation of the thermoplastic diaphragms,
- the interaction diaphragms / thermoplastic prepreg plies,
- the deformation mechanisms of the laminate, like resin percolation, interply-slip, intraply-slip /2/,
- the contact between tool and diaphragm

will be characterised experimentally. Because diaphragm forming in hot autoclaves is economically not conceivable for series applications, the second stage concentrates on the reduction of the manufacturing time and costs with the development of a new machine concept, taking into account the following requirements :

[1] US patent nr. 4'657'717-1987

- the optimisation of the manufacturing technique should lead to the reduction of the cycle times without any concessions concerning the laminate properties,
- the process automation should allow the forming of parts with reproducible characteristics together with a reduction of the manufacturing costs.

These requirements represent the most important conditions to be fulfilled, beside the reduction of the material costs, to permit a broader use of advanced thermoplastic composites in the aircraft and machine industry and possible applications of engineering thermoplastics for structural components in the automotive industry.

2. THE DIAPHRAGM FORMING TECHNIQUE

The diaphragm forming process originally comes from the superplastic forming of aluminium sheets. In the case of fibre reinforced thermoplastics, the lay-up is fixed under vacuum between two thin plastically deformable, usually polymeric films, the so called diaphragms, which are clamped around the edges (Fig. 2). The forming of the laminate onto a heated tool occurs above the melt temperature of the thermoplastic matrix by applying a pressure gradient normal to the diaphragms. A dwell time at constant temperature allows the laminate to be fully consolidated. The formed part can be removed from the tool after having been cooled under pressure below the temperature at which the structural stability of the laminate is achieved.
During the forming process the laminate is maintained under tension due to the adhesion of the molten matrix to the biaxial stretched diaphragms. This allows the laminate wrinkling and splitting effects to be reduced and permits a controlled fibre placement /3/. The hydrostatic pressure application is further responsible for the smooth forming of the laminate and its homogenous consolidation even for complex curvature parts.
Generally the geometrical complexity of the components to be formed is limited by the stretching and creeping behaviour of the diaphragms, which is strongly temperature dependant (Fig. 3). For high temperature thermoplastic matrix systems such as polyetheretherketone or polyetherimide the use of polyimide diaphragms has been established, while engineering thermoplastics have been successfully formed in the lower temperature range with polyamide based diaphragms /4/.

3. FORMING STUDIES

3.1 Experimental set-up

In the metal technique it is usual to investigate the biaxial deformation behaviour of a metal sheet with the ERICHSEN deep drawing test or the bulge forming test in accordance with PANKNIN or GOLOGRANC /5/. For the deformation testing of plastic films the so called blow- or bubble forming test is used /6 and 7/, which is similar to the bulge forming test of metal sheets. An adapted test for the diaphragm technique is the stretch forming test, which could be defined as a mixture of the PANKNIN bulge forming test and the bubble forming test. Figure 4 shows the stretch forming set-up positioned in a laboratory autoclave, which can be heated up to 450°C. This set-up consists of

- the diaphragms, the laminate and the tool (1, 2),
- the position transducer (3), which measures the displacement of the diaphragm centre point during the forming phase,
- an adjustment frame (4), where the position transducer is fixed,
- the amplifier and the X/Y/t-plot system (5, 6),
- and thermocouples (8), which are connected with the temperature control system (9).

The tool and the vacuum ring are connected with tubes to the vacuum system (10, 11). The heating process is realised by hot air in the computer controlled autoclave (12). The different

pressure and vacuum curves versus time are also computer controlled for the experimental series.

3.2 Investigated materials

Thermoplastic polyimide of the type Upilex™ 125R[2] has been used as diaphragm material. Figure 3 shows its elongation at rupture determined by the uniaxial tensile test versus the temperature /8/.
One can say that there is a maximum of the uniaxial elongation in the area of 330°C up to 350°C. The diaphragm forming experiments have been performed with unidirectional glass and carbon fibre reinforced PEI-prepregs[3]. Polyetherimide is an advanced amorphous thermoplastic, which offers excellent mechanical and thermal properties. But the viscous behaviour of the polyetherimide melt often leads to processing problems. The dynamic viscosity varies from ~10^4 Pas to ~10^3 Pas within a temperature range from 330°C to 370°C and a shear rate from 0.1 s^{-1} to 300 s^{-1} (Fig.5).
Taking into account the melt viscosity of the polyetherimide matrix and the deformation behaviour of the polyimide diaphragms a processing temperature of 330°C has been selected.

3.3 The free form experiment

The free form experiment is analogous to the PANKNIN bulge forming test. The heated diaphragm set-up is deformed by a pressure difference without tool contact (Fig .6). The tool has a diameter of 150 mm. The pressure difference is realised by vacuum. In a first step the deformation behaviour of the single diaphragm has been examined with pressure differences of 1.10^4 Pa and 2.10^4 Pa. For the interpretation of local deformation zones, the diaphragms were marked with concentric circles and crosshairs. The thickness distribution before and after forming has been measured. In the next step the diaphragm set-up was used with a polyetherimide film (thickness of 400 µm) between the two polyimide diaphragms. The "real" diaphragm free forming experiments were done with unidirectional glass and carbon fibre reinforced polyetherimide. Hereby the number of the prepreg plies and the stacking sequence was varied. The standard stacking sequence was $(0/90)_S$. After the preparation of the diaphragm set-up and the fixation on the free form tool, the position transducer is adjusted on the centre of the "diaphragm crosshairs" and the heating process is started (Fig. 8). The pressure difference for the forming can be applied in two ways : the sudden evacuation of the tool or gradually in a defined time, for example 100 s.

3.4 The cone form experiment

The cone form experiment is a set-up to study the contact mechanisms between tool and diaphragm. The geometry of the cone is described in figure 7. It has to be mentioned, that the basic cone diameter is 150 mm, the opening angle is 45° and the depth is 70 mm. The systematology of the experiment is the same as the free form experiment. The selected stacking sequences are: $(0/90)_S$, $(0/90/45/-45)_S$, $(0/45/90/-45)_S$ and $(0)_8$. The diaphragm set-up is fixed on the cone tool, the position transducer is adjusted on the centre of the "diaphragm crosshairs" and the heating process is started (Fig.8). The pressure difference can be applied by the evacuation of the cone tool (pressure from 4.10^4 Pa to 8.10^4 Pa) or by increasing the autoclave pressure (10.10^4 Pa to 40.10^4 Pa). These fast forming experiments were performed with a pressurisation time of 100 s.

The results of selected free form and cone form experiments are presented in the figures 9 to 14. Each experiment was done with six samples (UD-glass and carbon reinforced PEI). The figures show the centre displacement of the diaphragm versus time. The curve corresponds to

[2] Upilex™ is a PI-film from Ube Industries, Japan
[3] Cetex™ RD 2403 and CD 5534 are carbon and glass fibre prepregs based on PEI matrix from Ten Cate, The Netherlands

the mean value of the samples. In the diagrams with more than one curve the standard deviations are not shown.

3.5 Results of the free form experiment

Figure 9 shows the centre displacement versus time of PI-film with a thickness of ~130 µm formed suddenly with a pressure of 2.10^4 Pa. It has to be remarked that the largest amount of the deformation has been done within the first seconds. After ~2 s a certain creep forming takes place, which runs unstable after 50 s. The same effects can be seen in figure 10, which shows the curve of the forming of two polyimide films "lubricated" by a PEI melt film placed in-between. This kind of sandwich was formed with a pressure of 4.10^4 Pa. In the first 25 s the curve is very similar to the curve in figure 9.

The creep phase is not so distinctive, which could be explained by a certain flow resistance of the polyetherimide melt. In the second step the influence of the pressure gradient on the deformation behaviour on a "real" diaphragm set-up was studied.
The stacking sequence of the plies was $(0/90)_s$. The experiments have been done with continuous glass and carbon fibre reinforced polyetherimide with a pressure of 4.10^4 Pa. Figure 11 shows the difference obtained by applying the pressure in 100 s or suddenly.
One can say that the two curves are similar between the limits of the standard deviations. The influence of the fibre type, -carbon or glass-, concerning the forming behaviour of the diaphragm set-up can be neglected. Figure 12 shows the centre displacement of $(0/90)_s$ samples (glass fibre reinforced PEI) for different forming pressures (2.10^4 Pa, 4.10^4 Pa, 6.10^4 Pa) versus time.

3.6 Results of the cone form experiment

The curves of figure 13 show very clearly the muffling of the diaphragm set-up (glass fibre reinforced PEI, laminate $(0/90)_s$) through the tool contact. To form a cone with a height of 70 mm the minimum pressure is 20.10^4 Pa. The adhesion between the PI-diaphragms and the molten PEI-prepregs leads to the anisotropic deformation of the marked diaphragms. The concentric circles and the crosshairs are deformed to elliptic geometries. Figure 14 shows curves in function of the stacking sequences of eight UD-carbon fibre reinforced PEI-prepregs. Each experimental serial was formed with 30.10^4 Pa. It is an astonishing fact that the $(0)_8$ laminate deforms so fast, compared to the multidirectional laminates which deform in a similar way. The difference is the severe buckling of the prepregs for the $(0/45/90/-45)_s$ stacking sequence. The figures 15, 16 and 17 show the deformed "diaphragm circles" for different stacking sequences.

4. HEATING STUDIES

The diaphragm forming process can be divided into three steps, which are the heating of the tool and the laminate, the forming and consolidation of the laminate and finally the cooling of the tool and the formed part (Fig. 1). Optimised forming cycles of 30 min have already been achieved for APC-2™ parts[4] within an autoclave designed for high heating rates /9/. Nevertheless this reported cycle time neither includes the 30 min pre-heating stage of the autoclave up to the 380°C processing temperature, nor the approximately 10 min needed to install the tool and the laminate in the autoclave or to demould the formed part, which leads to an overall cycle time of more than 60 min.
Considering that the deformation rates, which are controlled by the creeping of the diaphragms, are slow (see paragraph 3 and /3/) and that the consolidation time, which depends on the resin percolation mechanism, is short /10/, the reduction of the manufacturing time

[4] APC-2™ is a UD-carbon fibre prepreg based on PEEK matrix from ICI Fiberite, CA

should therefore concentrate on the heating phase and the handling tasks. On the one hand, the automation of the forming process allows the relevant parameters like pressure or temperature to be continually controlled, which is a necessity to guarantee a constant quality over series production. On the other hand, the automation is also responsible for the mechanical taking over of manual handling tasks, resulting in lower manufacturing costs. Additionally the efficiency of the heating system as well as the design of the forming tool should be optimised with regard to shorter heat-up times.

4.1 Heating of thermoplastic laminates

Forced convection, conduction and infrared are the most common heating methods applied to thermoplastic sheets, each of them having its own advantages and disadvantages. Forced convection heating in air or inert gas circulation oven usually needs the longest heat-up time depending on the laminate thickness, without any risks of overheating the matrix system. Conduction heating between heated press platens leads to shorter heat-up times, whereas the molten matrix sticks to the contact surfaces, making handling difficult. Infrared, as a non-contact heating technique, allows similar heat-up times as the conduction heating, however temperature gradients can appear for thick laminates.
Taking into account the flexibility provided by the IR-heating concerning the lay-up geometry and thickness as well as the efficiency and control possibilities, it has been decided to carry out a set of heat-up experiments in order to quantify the achievable heating rates.

4.1.1 Experimental set-up

These experiments have been performed using a standard thermoforming machine, which was equipped with two IR-fields of quartz-heaters (dimensions 120 mm X 60 mm, heating power 200 W). Series of 6-, 12- and 18-plies laminates (based on woven fabric PEI-glass and PEI-carbon fibre prepregs[5]), either as organic sheets or unconsolidated, have been heated up. The dimensions of the laminates (250 mm X 160 mm) have been selected according to the IR-fields to obtain an homogenous temperature distribution over the laminate surface. During the heating process the laminate, which was fixed under vacuum between two Upilex™ 125R diaphragms, was placed at a distance of 150 mm from each IR-field. The heating power was set up to 80 %, respectively 100 %, until the desired surface temperature was reached and then reduced to keep it constant. The temperature control and measurements have been carried out using an infrared pyrometer and type-K thermocouples.

4.1.2 Results and discussions

The study of the influence of the laminate consolidation on the temperature gradients through the thickness (Fig. 18) has shown that larger temperature differences occur for unconsolidated laminates, which can be easily explained by the poor surface contact between the plies. However, this effect is can be neglected for thin laminates up to 2 mm. Higher heat-up rates of the laminate surface achieved with 100 % heating power further increased this effect. Shorter heat-up times do not allow the heat conduction, as a time dependant process, to reduce the temperature gradients.
The influence of the fibre reinforcement on the heating time of consolidated laminates is shown in the next series of experiments (Fig. 19 and 20). The lower thermal mass of the carbon fibres (AS-4 carbon fibre : 1.33 MJ/m³°C, E-glass fibre : 2.12 MJ/m³°C), defined as the product of the specific heat capacity and the density, and the higher thermal conductivity (AS-4 carbon fibre : 16 W/m°C along the fibre, E-glass fibre : 1.3 W/m°C) are mainly responsible for the high heating rates, up to 150°C/min, measured on carbon fibre reinforced laminates. Further

[5] Cetex™ CD 282 and FS 303 are carbon and glass fibre prepregs based on PEI matrix from Ten Cate, The Netherlands

the carbon fibres can be considered as a black body, which absorbs 100 % of the emitted IR-radiations.
The results of these experimental heat-up tests have demonstrated, that IR-heating is a very effective technique to heat up the laminate and the diaphragms prior to forming. For carefully controlled heating power, high heating rates combined with an homogenous temperature distribution over the laminate surface have been measured. For thicker laminates up to 4 mm, the surface temperature has to be kept constant for a dwell time in order to reduce the temperature gradients through the laminate thickness without overheating the laminate surface.

4.2 Tooling concept

The evaluation of two distinct tooling concepts has been carried out to study the influence of different tooling materials on the heat-up time and temperature homogeneity of the tool surface to avoid any cooling of the thermoplastic matrix during the forming process, and thus reducing the formability of the laminate, the tool temperature has to match the laminate temperature. Therefore the possibility to reduce further the manufacturing time strongly depends on the thermal behaviour of the forming tools. For the same reasons, as mentioned under the paragraph 4.1, infrared heating has been selected to heat up the tools as well.
The first concept involves thick tools having only their top surface heated. These tools have to withstand the whole forming pressure and consequently have to be supported on their backside. Graphite[6] and castable ceramics[7] have been selected as potential tooling materials because of their high temperature resistance, needed for manufacturing advanced thermoplastic composite parts. Graphite, which behaves as a black body, absorbs a high percentage of the emitted IR-radiations. In the case of castable ceramics, which show a poor heat conduction (2.4 W/m°C), the heat energy should concentrate on the tool surface.
The second tooling concept is based on thin, lightweight tools with reduced thermal mass, which are heated on both sides. Further, the pressurisation has to be uniform to avoid any deformations, therefore a perfect vacuum integrity is needed. High temperature NiCr-alloys (nickel, chromium) and SiC-fibre[8](silicon carbide) reinforced ceramics /11/ have been selected with regard to their high mechanical properties at elevated temperatures.

4.2.1 Experimental set-up

These heat-up experiments have been realised within a prototype of the diaphragm forming machine (Fig. 21). This prototype has been designed with two IR-fields of quartz-heaters (dimensions 120 mm X 120 mm, heating power 800 W) integrated in the two halves of the pressure vessel, between which the diaphragms and the laminate are clamped. The forming tool is fixed in the lower half of the pressure vessel and is pre-heated using a third moveable IR-field having the same characteristics as the previous ones. The heating rates and temperature differences have been measured with type-K thermocouples on the surface of the different circular top-hat tools (diameter 285 mm) manufactured out of the potential tooling materials. The heating power was set up at 100 % and continuously controlled using a thermocouple fixed in the centre of the tool surface.

4.2.2 Results and discussions

Heating rates up to 25°C/min have been measured on the ceramic tool, however with a temperature difference of more than 100°C, which is not acceptable (Fig. 22). The application of a 0.5 mm thin copper coating reduced the temperature difference up to 40°C, but the mismatch between the coefficients of thermal expansion of the castable ceramic and copper led to the delamination of the copper coating. The high heat conduction coefficient of graphite (75

[6] Graphite G-1300 from Alectro GmbH, Germany
[7] Lafarge F-820 is a castable ceramic from Lafarge Refractaires Monolithiques, France
[8] Nicalon™ NP1616 is a silcon carbide fibre from Nippon Carbon, Japan

W/m°C) is responsible for the homogenous temperature distribution (maximum temperature difference of 20°C), as well as for the slow heating rates of 12.5°C/min because not only the surface but the whole tool has been heated up.
More promising results have been obtained for the thin metallic tool (thickness 3 mm) with heating rates up to 80°C/min and a temperature difference of 30°C on its surface. The shortest heating time has been measured on the SiC-fibre reinforced ceramic tool (thickness 4 mm), which has been heated up from 50°C to 400°C in less than 3.5 min (heat-up rates of more than 100°C/min) with a maximum temperature difference of 25°C, probably due to its lower thermal mass. However experimental studies of this last tool have shown that its vacuum integrity was insufficient. Further work is therefore needed to seal its surface before considering this type of fibre reinforced ceramic as tooling material for the diaphragm forming process.
A comparison of the IR-heating and the forced convection cooling of carbon fibre reinforced thermoplastic laminates and thin metallic tools has shown that their heat-up and cooling times are in the same order of magnitude, below 5 min, for a forming temperature of 380°C and a demoulding temperature of 200°C, which finally should lead to a drastic reduction of the cycle times considering the diaphragm forming process in autoclaves as a reference.

5. THE DEVELOPMENT OF THE DIAPHRAGM FORMING MACHINE

The design of the automated diaphragm forming machine is based on the experience acquired by work with the first prototype machine. The dimensions of the forming area have been scaled up to exploit the PI-diaphragms in their full commercially available width of 1000 mm. With regard to the previous heat-up experiments, the infrared heating method has been selected. Further the manual handling tasks have been undertaken by different drive units.

5.1 Machine Design

The main part of the forming machine (Fig. 23 and 24) is the two-piece cylindrical pressure vessel (diameter 1000 mm, height 1100 mm). Each vessel part can be locked separately with a bayonet catch on the so called forming table, which is clamped in-between. The pressure vessel can be opened and closed using electrical drive units, which are bolted on the steel frame. The two axis handling system is used to place the diaphragms with the laminate on the forming table and to remove the formed part. The heating system consists in four IR-fields, each of them being composed of 60 quartz-heaters (dimensions 120 mm X 60 mm, heating power 375 W) independently controlled, with an overall heating power of 90 kW. Two IR-fields are integrated in the pressure vessel to heat up the laminate and the forming tool, which is fixed in the lower vessel part. The others are installed in the movable pre-heating unit.

5.2 Programming environment

The process parameters like the temperature and pressure values versus time and the heating power of the IR-heaters are defined on a workstation, which works as a master computer and then downloaded to the cell computer, where the different sets of process parameters are managed. Afterwards the selected set is transferred to the control system and the process can be started. The feedback values of the temperature and pressure are visualised on the cell computer together with the set-point values. The control system is responsible for the heating and pressurisation stages as well as for the handling tasks. Its characteristic feature to control independently each of the 240 IR-heaters allows an homogenous temperature distribution over the laminate and the forming tool.

5.3 Manufacturing process

At the beginning of the process, the two-piece pressure vessel is open. The laminate and the diaphragms are placed on the forming table using the handling system. The upper part of the

pressure vessel is then closed and the pre-heating unit is moved between the forming table and the lower part of the pressure vessel. At this moment the pre-heating phase can start, heating up the laminate and the forming tool on both sides with the four IR-fields. After having reached a certain set-point temperature, the pre-heating unit is removed and the lower vessel part closed. The pressurisation and thus the forming of the thermoplastic laminate occurs while the integrated IR-heaters are still active. After the consolidation stage, the formed part is cooled under pressure by forced convection, the pressure vessel opened and the part removed from the forming table using the handling system.

5.4 Experimental results

During the first heat-up experiments, heating rates of more than 110°C/min have been measured between 50°C and 330°C on the surface of a 2 mm thin metallic tool, with a maximum temperature difference of ± 5 % at 330°C. During analogous experiments on PEI carbon fibre laminates, heating rates of 80°C/min have been recorded on their surfaces, with a maximum temperature difference of ± 2 %. The improved homogeneity of the surface temperature was achieved through the heating power control of selected IR-heaters. The influence of this control method has not been tested up to now for the metallic tool, however it is assumed, that it will lead to a reduction of the temperature difference in the same order of magnitude as for the laminate itself.

6. CONCLUSIONS

A so called diaphragm stretch forming test, developed from the bulge forming test for metal sheets, has been presented. This stretch forming test was carried out in two different ways. The free form test is a method to interpret the cohesion and adhesion effects between the thermoplastic prepregs and the diaphragms. The cone form experiment is a method to study tribological mechanisms during the contact diaphragm / tool surface. The results of these basic investigations are:

- The diaphragms influence the over all forming behaviour of the diaphragm set-up more than the laminate thickness and the stacking sequence.
- The adhesion polyimide diaphragm / polyetherimide has been proved by the anisotropic deformation of the diaphragms for different stacking sequences.
- The effect of the fibre wrinkling and prepreg buckling is influenced by the stacking sequence and the tool geometry.

The diaphragm stretch forming test can be used for the determination of material parameters, which are needed for the simulation of the diaphragm forming process.
The analysis of a standard autoclave process has shown that the handling tasks, as well as the heating phase of the laminate and the forming tool, are the most time consuming steps. Consequently infrared, as a fast heating method, has been considered and the heating behaviour of thermoplastic laminates and forming tools has been experimentally characterised for different fibre reinforcements and tooling materials.
Based on the previous results a new machine has been designed for the cost effective manufacturing of advanced thermoplastic composite parts. This has been achieved through the reduction of the cycle times and the automation of the process. The computer control of the forming parameters and the automation of the process allows components with reproducible properties to be manufactured. With regard to the measured heating rates, a reduction of the heating phase from 30 min down to 5 min parts is achievable. The further reduction of the handling time from 10 min to 2 min added to a 10 min forming and consolidation phase lead to an overall manufacturing time in the range of 20 min for complex curvature advanced thermoplastic composite parts.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

/1/ P. J. Mallon, C. M. O'Bradaigh, R. B. Pipes, Composites, 20, (1), 48, 1989

/2/ A.J. Smiley, Diaphragm Forming of Carbon Fibre reinforced Thermoplastic Composite Materials, dissertation at the University of Delaware, 1988

/3/ R. K. Okine, Journal of Thermoplastic Composite Materials, 2, 50, 1989

/4/ S. Delaloye, G. Ziegmann, ECCM-5, 519, 1992

/5/ K. Lange, Umformtechnik, 2nd edition, Springer Verlag, Berlin, 116-118, 1984

/6/ L.R. Schmidt, Biaxial Stretching of Heat-Softened Plastic Sheets, dissertation at the University of Colorado, 1972

/7/ M.R. Monaghan, FPCM Symposium, University of Limerick, 1991

/8/ M.R. Monaghan and S. Delaloye, personal communication, 1991

/9/ M. R. Monaghan, P. J. Mallon, Composites Manufacturing, 1, (1), 8, 1990

/10/ F. N. Cogswell, D. C. Leach, Sampe Journal, 3, 11, 1988

/11/ J. Davidovits, M. Davidovics, Sampe International Symposium, 31, 1, 1991

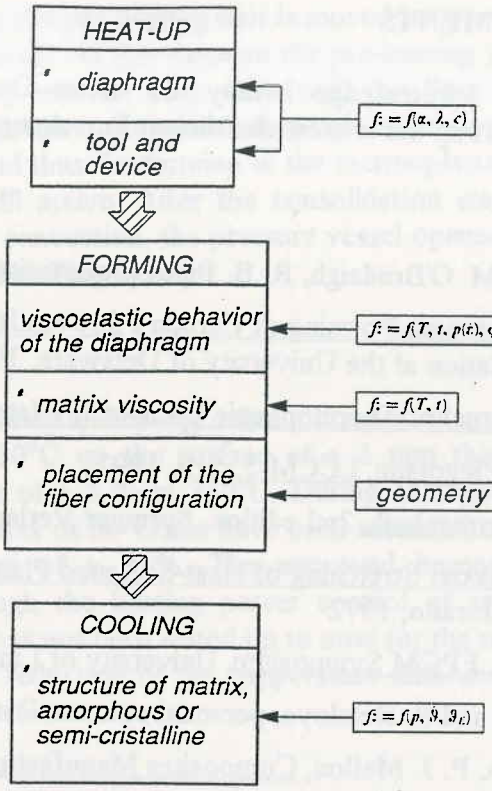


Fig. 1 : Scheme of the diaphragm forming process

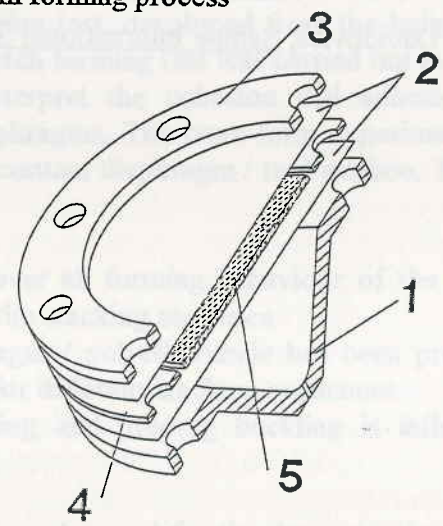


Fig. 2 : Diaphragm set-up with a cone tool

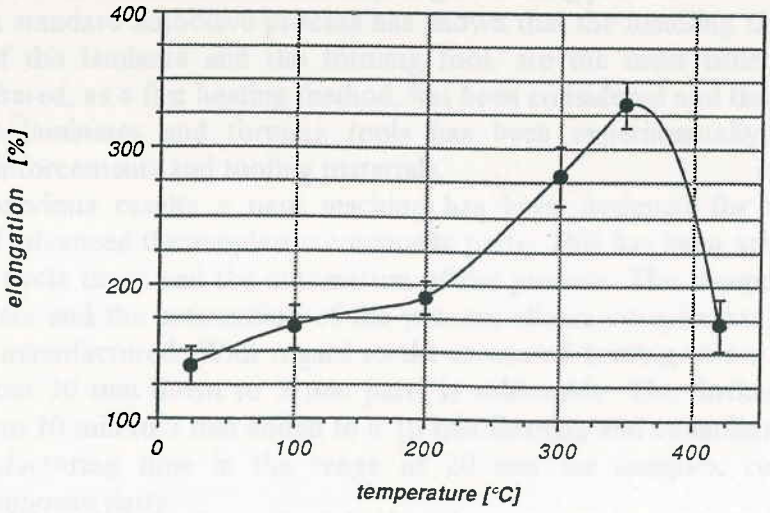


Fig. 3 : Uniaxial strain behaviour of polyimide /8/

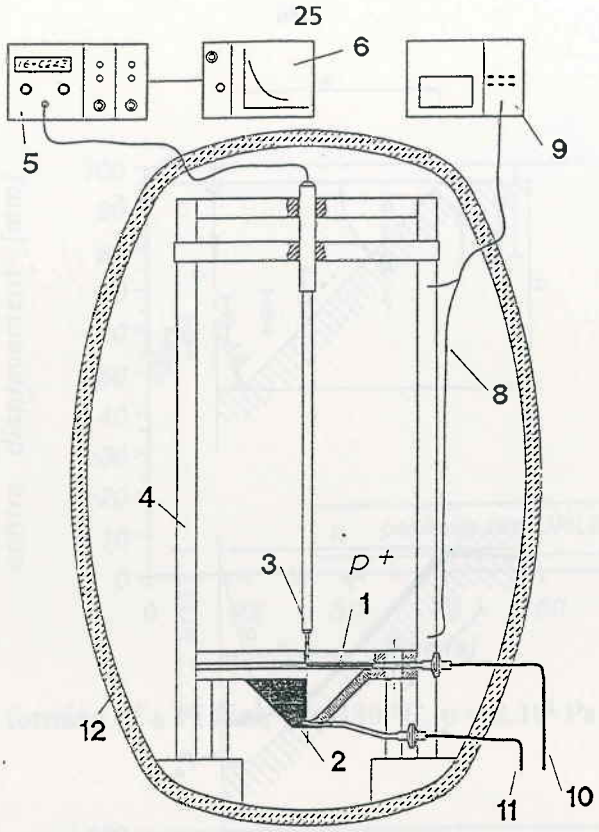


Fig. 4 : Stretch forming device

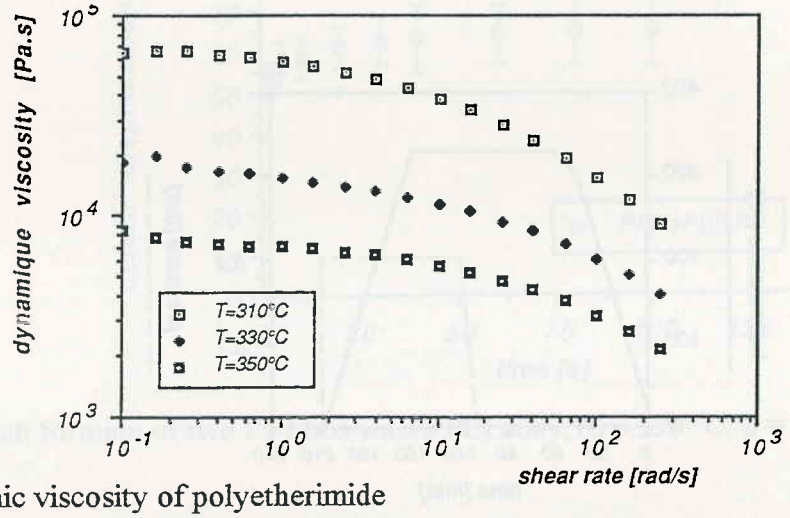


Fig. 5 : Dynamic viscosity of polyetherimide

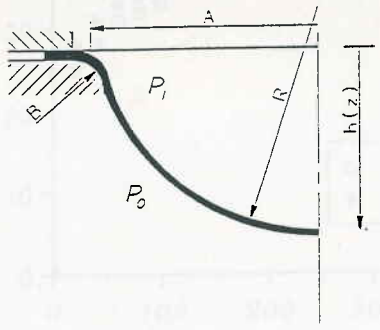


Fig. 6 : Free form geometry

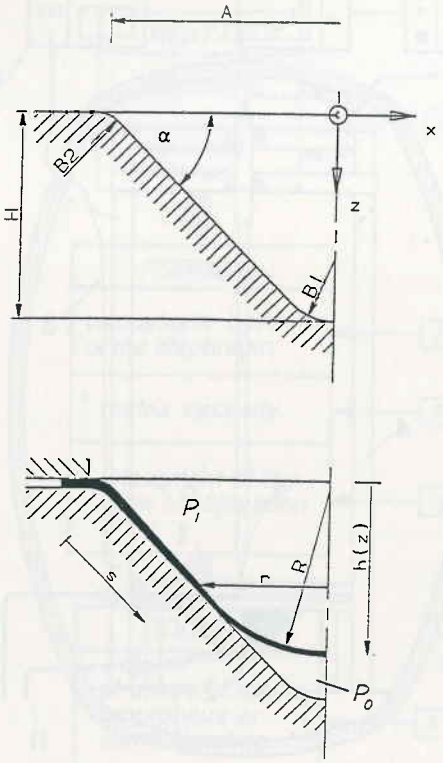


Fig. 7 : Cone form geometry

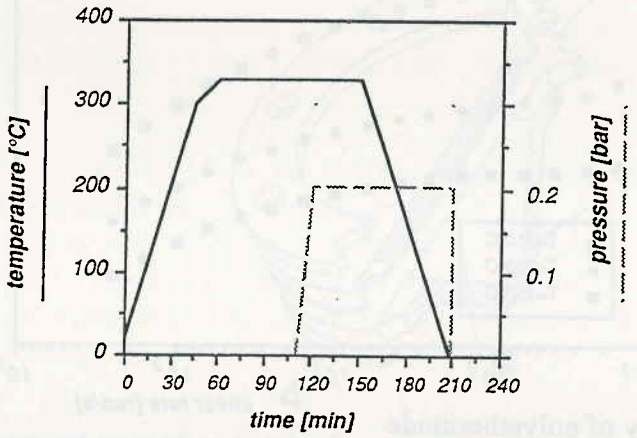


Fig. 8 : Example for a heating and pressure cycle

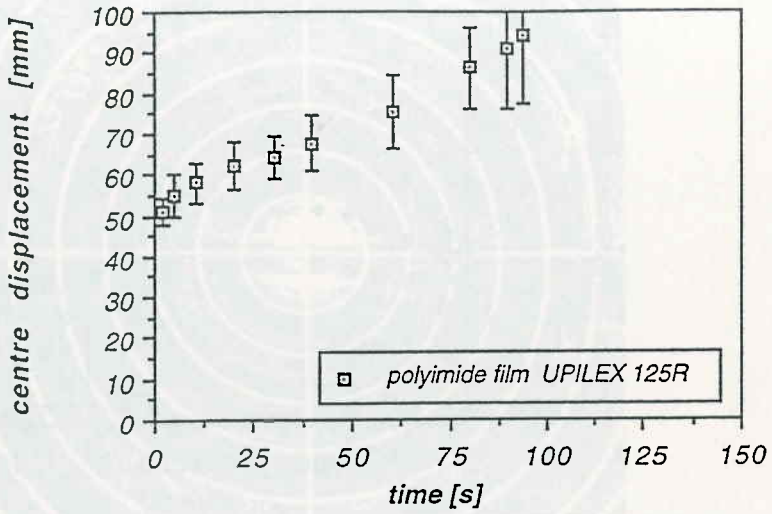


Fig. 9 : Biaxial stretch forming of a PI film, T = 330 °C, p = 2.10^4 Pa

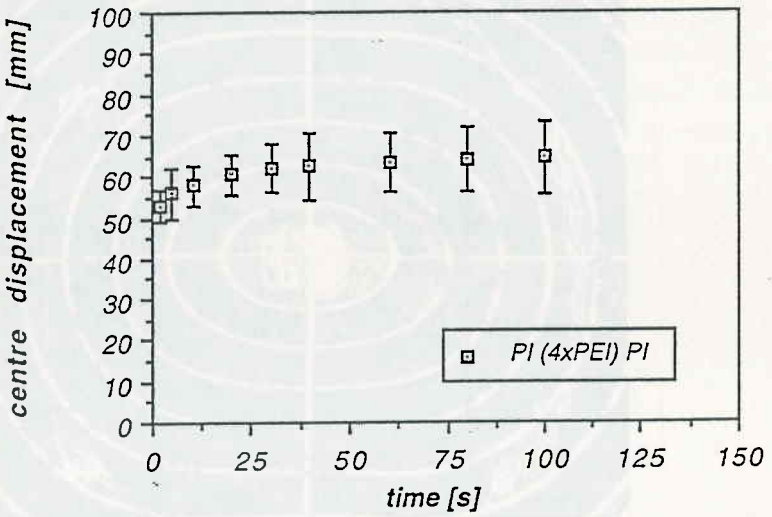


Fig. 10 : Stretch forming of two PI-films with a PEI inlay, T = 330 °C, p = 4.10^4 Pa

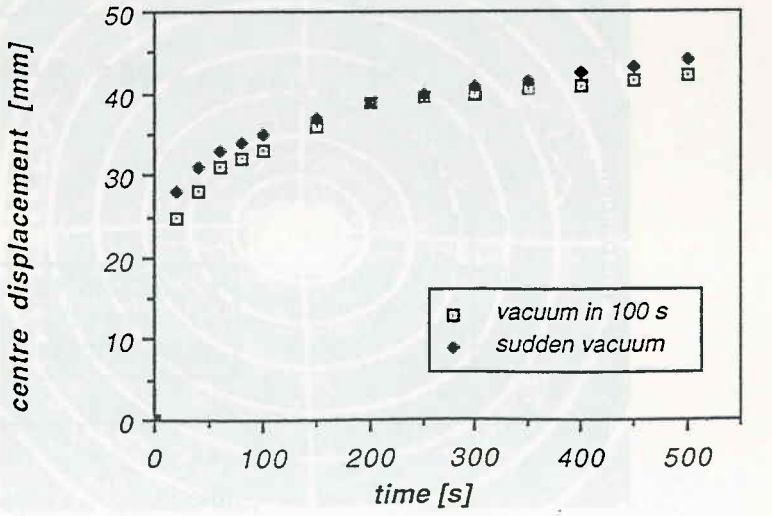


Fig. 11 : Diaphragm free forming, UD-glass fiber reinforced PEI, T = 330 °C, p = 4.10^4 Pa

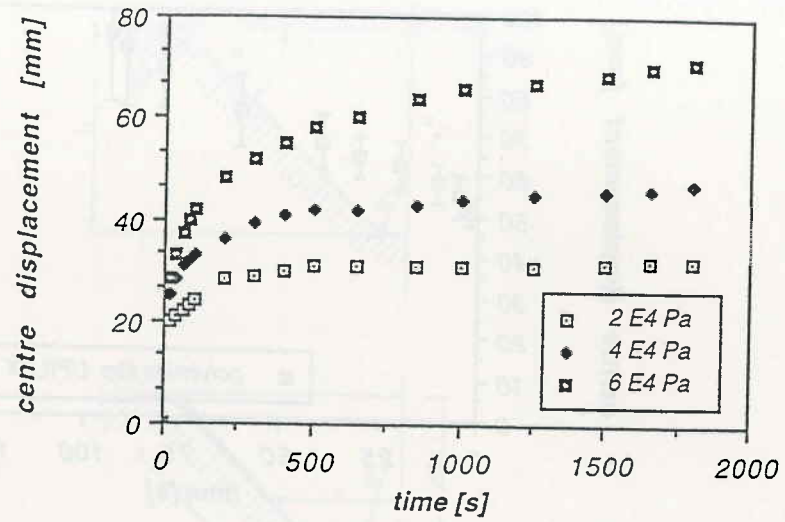


Fig. 12 : Free form experiment, UD-glass fiber reinforced PEI $(0/90)_s$

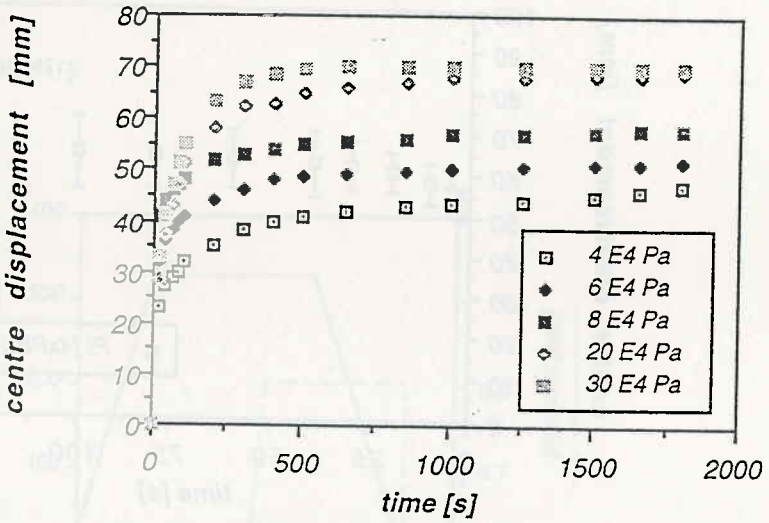


Fig. 13 : Cone forming experiment, UD-glass fiber reinforced PEI

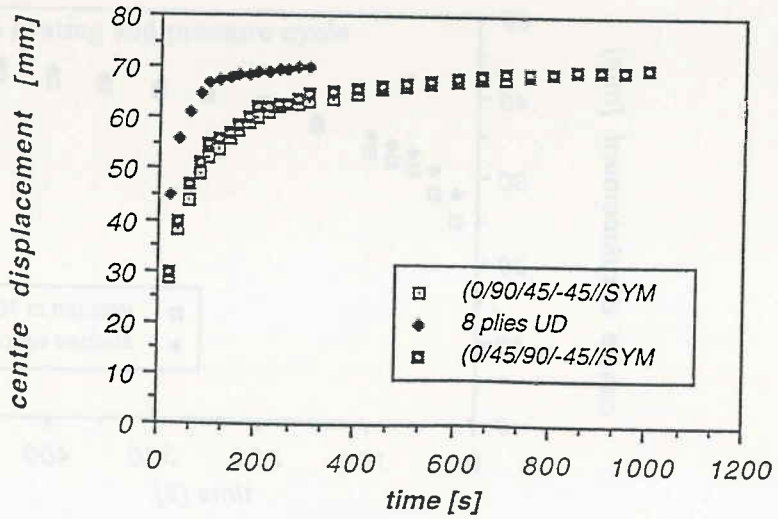


Fig. 14 : Cone form test with UD-carbon fiber reinforced PEI, T = 330 °C, p = 30.10^4 Pa

Fig. 15 : UD-carbon fiber reinforced PEI $(0/90/45/-45)_s$

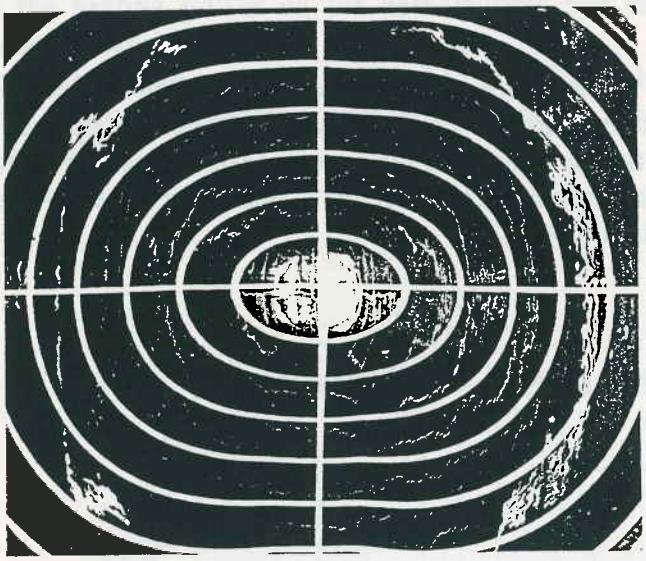


Fig. 16 : UD-carbon fiber reinforced PEI $(0)_8$

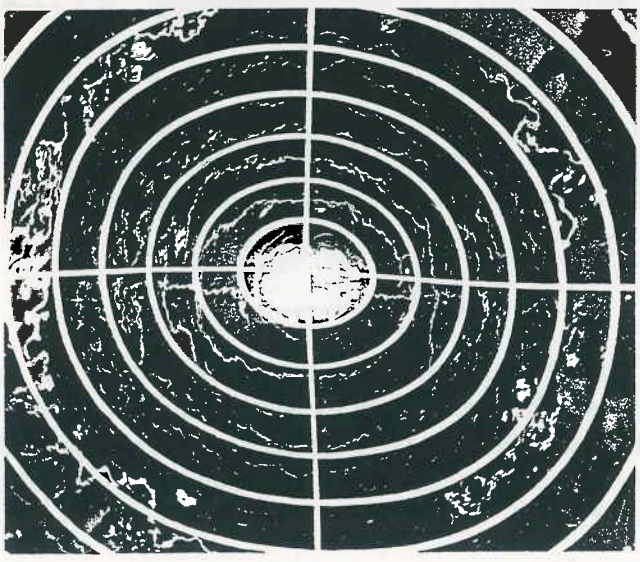


Fig. 17 : UD-carbon fiber reinforced PEI $(0/45/90/-45)_s$

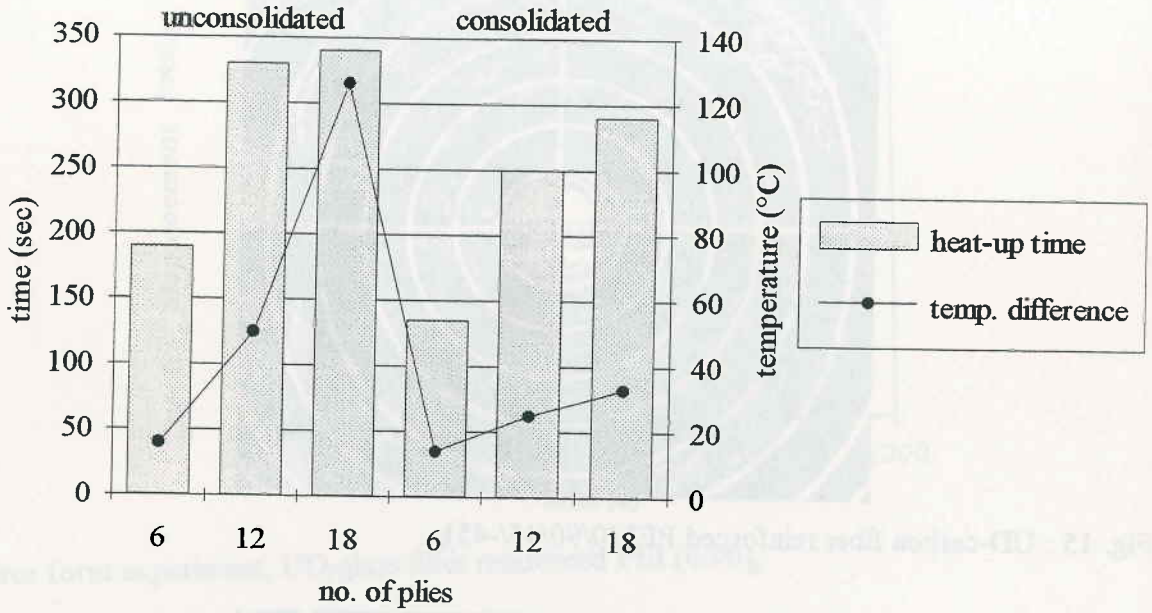


Fig. 18 : Influence of the laminate consolidation on the heat-up time and temperature gradient of glass fabric reinforced PEI-samples at 80 % heating power.
The heat-up time is defined as the time needed to heat the laminate surface from 50°C to 300°C. The temperature difference is measured between the middle of the laminate and its surface at 300°C.

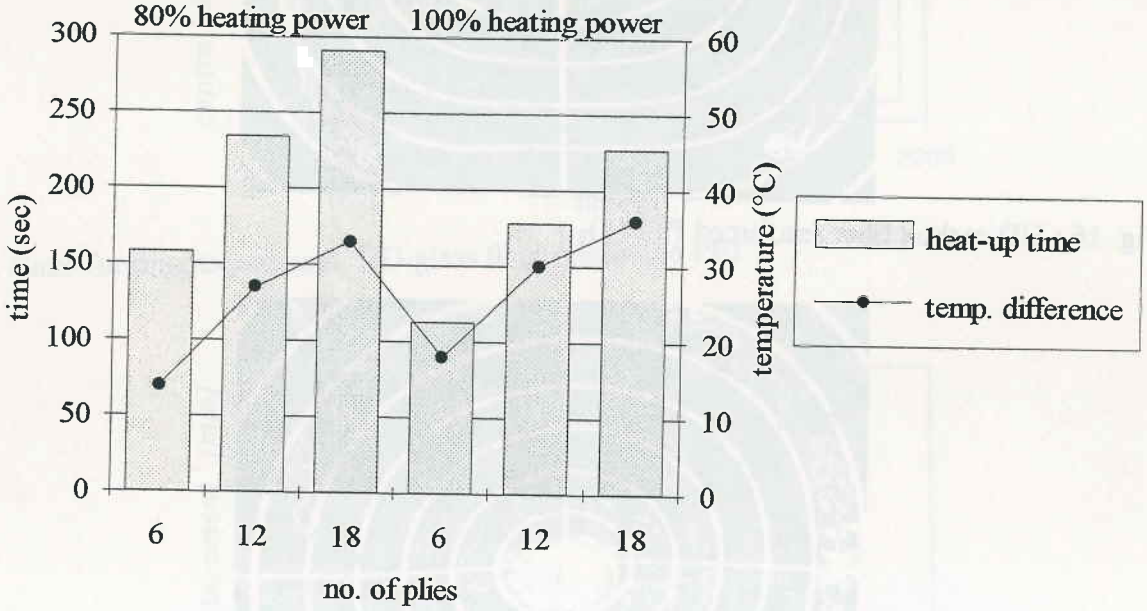


Fig. 19: Influence of the heating power on the heat-up time and temperature gradient of consolidated glass fabric reinforced PEI-samples.
The heat-up time is defined as the time needed to heat the laminate surface from 50°C to 330°C. The temperature difference is measured between the middle of the laminate and its surface at 330°C.

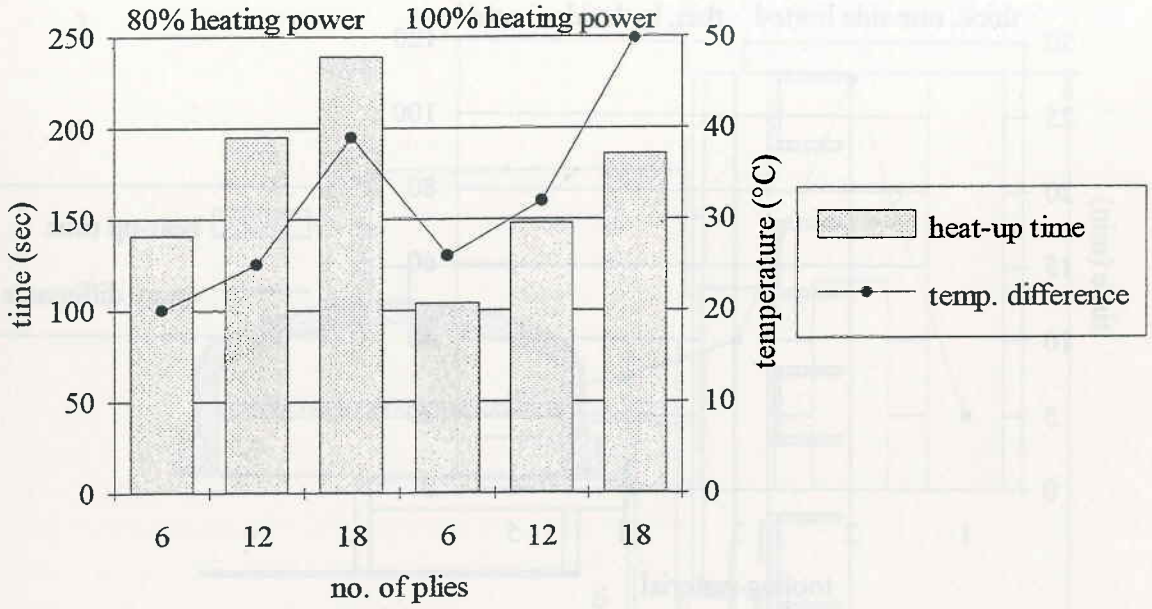
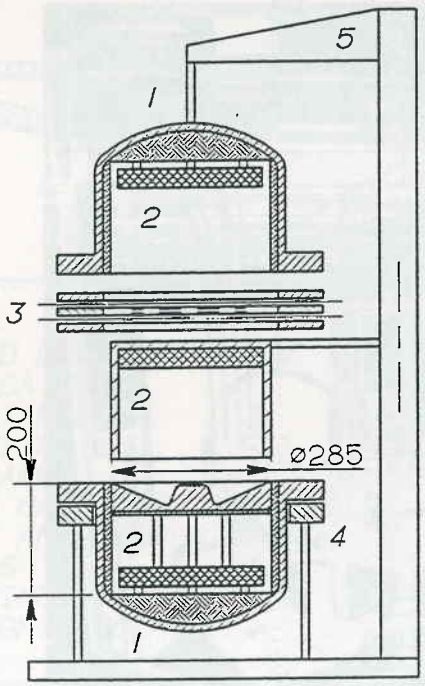


Fig. 20: Influence of the heating power on the heat-up time and temperature gradient of consolidated carbon fabric reinforced PEI-samples.
The heat-up time is defined as the time needed to heat the laminate surface from 50°C to 330°C. The temperature difference is measured between the middle of the laminate and its surface at 330°C.



1---UPPER AND LOWER PARTS OF THE PRESSURE VESSEL
2---IR-HEATERS
3---LAMINATE AND DIAPHRAGMS
4---CLAMPING SYSTEM
5---LIFTING SYSTEM

Fig. 21 : The prototype diaphragm forming machine.

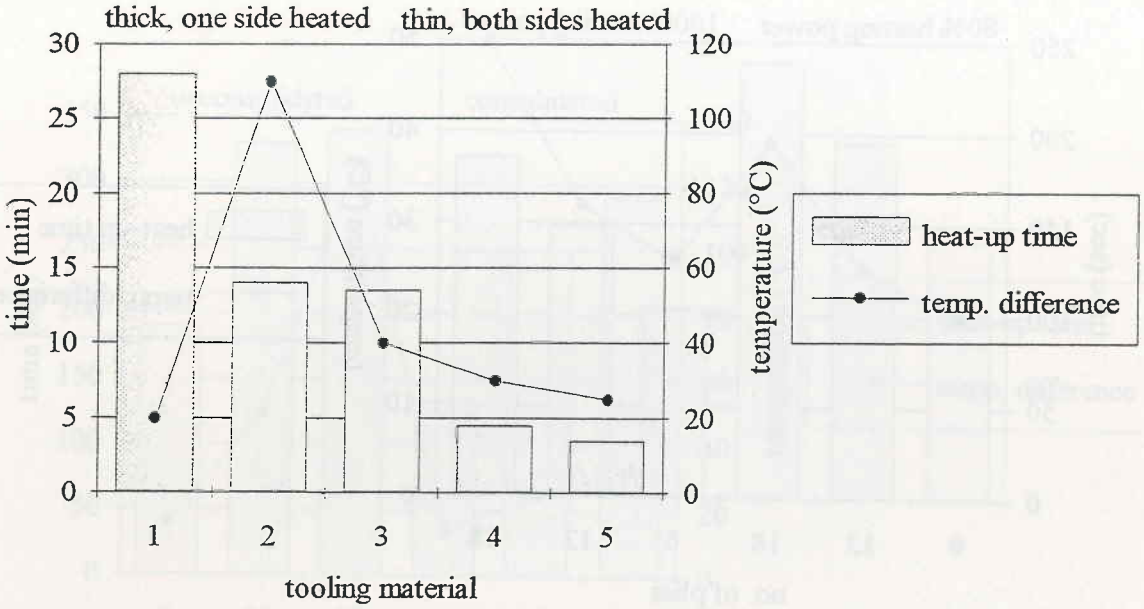


Fig. 22 : Heat-up time and temperature homogeneity measured on IR-heated top-hat tools, manufactured out of different tooling materials.
The heat-up time is defined as the time needed to heat the tool surface from 50°C to 400°C. The temperature difference is measured between the centre of the circular tool (diameter 285 mm) and a point on a diameter of 180 mm at 400°C. The tooling materials 1, 2 and 3 are graphite, castable ceramic and castable ceramic with copper coating. The tooling materials 4 and 5 are the NiCr-alloy and the SiC-fibre reinforced ceramic.

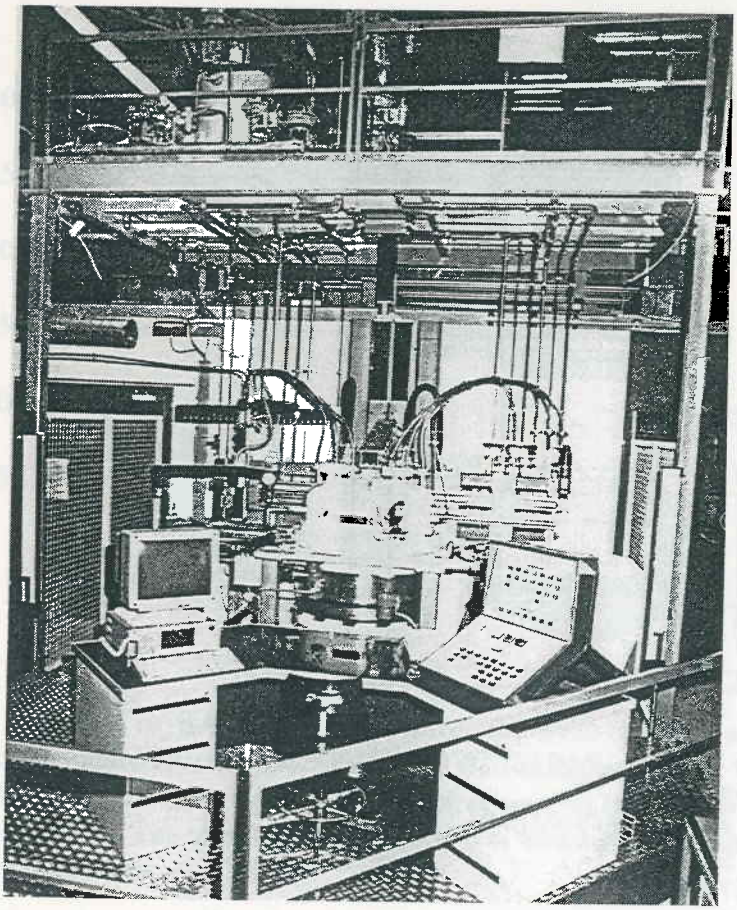
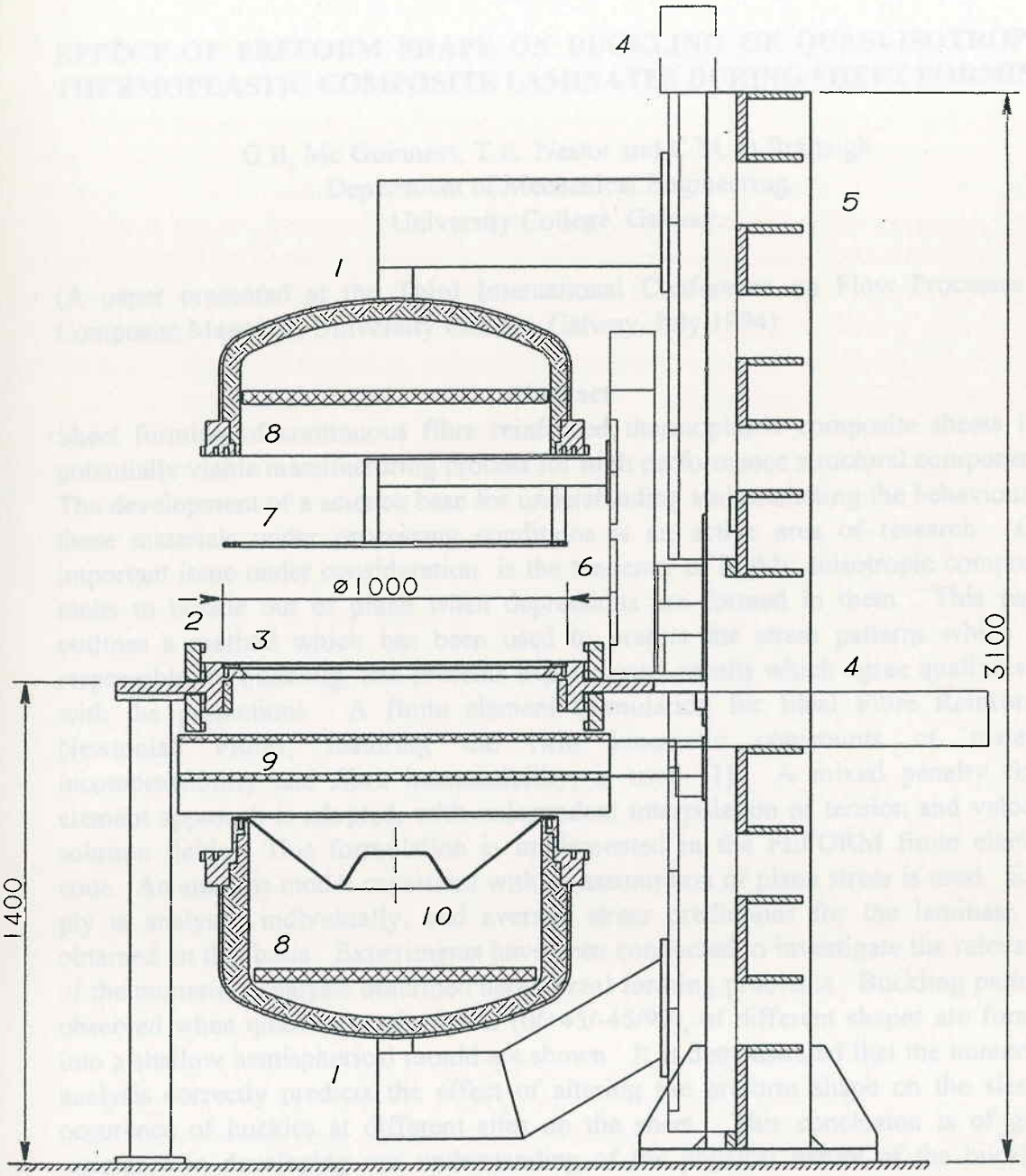


Fig. 23 : The automated diaphragm forming machine.



1---UPPER AND LOWER PARTS OF THE PRESSURE VESSEL
2---BAJONET CATCH
3---FORMING TABLE
4---DRIVE UNITS
5---STEEL FRAME
6---TWO-AXIS HANDLING SYSTEM
7---LAMINATE AND DIAPHRAGMS
8---IR-FIELDS
9---PRE-HEATING UNIT
10---LIGHTWEIGHT TOOL

Fig. 24 : Design of the automated diaphragm forming machine.