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Low-cost resin infusion mould tooling for carbon fibre composites manufacture

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Abstract: This article describes the research to date carried out under the BAE Systems/Engineering and Physical Sciences Research Council (EPSRC)-funded programme 'Flapless Aerial Vehicle Integrated Interdisciplinary Research' (FLAVIIR), aimed at developing innovative technologies for the low-cost manufacture of next-generation Unmanned Aerial Vehicles. The aim of the researchers in FLAVIIR was to develop low-cost innovative tooling technologies to enable the affordable manufacture of complex composite aerospace structures. The advances in tooling technology were achieved through the application of rapid prototyping, tooling and manufacture technologies to provide rapidly configured and reconfigurable tool concepts, for low-cost resin infusion moulding. This article introduces three tooling innovations: reconfigurable tooling concept, variable cavity tooling, and porous cavity tooling.

Keywords: carbon fibre composites, tooling, unmanned aerial vehicle

1 BACKGROUND

Resin transfer moulding (RTM) is widely used for the manufacture of high-quality carbon fibre composite (CFC) components in a range of sectors including aerospace and defence [**1**], automotive parts [**2**], and other cost-sensitive applications. RTM has many advantages, including relatively short cycle time [**3**], low volatile emissions [**4**], and provides high-quality components [**5**]. The manufacture of high-quality large components using RTM is complicated by the restricted flow of resin through the carbon fibre, which can lead to components with high void contents [**6**] and low strength [**7**]. The use of higher resin injection pressures and multiple inlet ports has been investigated to achieve higher infusion rates [**4**], although higher flowrates can result in movement of the 'fabric wash' and deformation of the fabric structure. A number of process modifications have attempted to mitigate this problem, including Seemann composite resin infusion moulding (SCRIMP) [**8**] and vacuum-assisted RTM (VARTM) [**9**], both of which employ a resin porous layer to encourage resin flow longitudinally over the component area. SCRIMP and VARTM are single-sided moulding processes that limit the surface quality and accuracy of the component.

The development of low-cost unmanned aerial vehicles (UAVs) is being driven by commercial (UK competitiveness) and social (to reduce or eliminate pilot attrition rates) pressures. The Flapless Aerial Vehicle Integrated Interdisciplinary Research (FLAVIIR) project, which is a joint initiative between BAE Systems and EPSRC, aims at providing technologies to deliver such vehicles by 2020. To reduce maintenance requirements, the UAVs need to have a high utilization of the CFC, and the research presented here has focused on developing tooling technologies that will provide high-quality CFC components using the low-cost resin infusion moulding (RIM) process.

Three tooling technologies have been investigated in this project, porous cavity tooling (PCT), variable cavity tooling (VCT), and reconfigurable tooling concept (RTC). This article will provide an overview of these technologies.

2 POROUS CAVITY TOOLING

2.1 Introduction to PCT

PCT offers enhanced resin infusion and improved fibre consolidation through a combination of resin and air porous tooling materials being used in critical areas of the tool such as at the resin injection and exit ports,

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and in locations where there is a significant risk of either air or gas entrapment, for example, at the bottom of rib features, and allow air or any gases liberated during resin processing to vent out of the cavity, preventing entrapped gas pockets that could degrade the surface quality of the component. Unlike the SCRIMP and VARTM processes, where the porous media is a flexible cloth, in PCT they are stiff and resistive, and thus provide a uniform force on the CFC during curing. The unique benefits of PCT are:

(a) the ability to provide resin injection over large areas of the component while also maintaining component accuracy;
(b) the flexibility to provide gas venting at any location in the mould;
(c) the ability to have complete flexibility in injection location, since the correct alignment of the fibres is maintained.

2.2 PCT research methodology

A test tool was developed (Fig. 1) to allow a range of porous materials to be evaluated for CFC component manufacture, with the following capabilities assessed:

(a) resin/air permeability and its effect on component quality;
(b) ability to provide fibre consolidation;
(c) ability to maintain fibre alignment;
(d) effect on moulded component surface roughness.

CFC samples (120×120×10 mm) were manufactured from Triaxial Non-Crimp Fabric (MCX 1181270 – Sigmatex UK Ltd, Runcorn, UK) and Araldite LY3505 epoxy resin, using XB 3404 hardener (Huntsman Advanced Materials (Europe) BVBA, Belgium) using a range of resin porous media.

1. Sintered metallic filters (2–35 mm pore size).
2. Porous injection mould tooling plate (7 mm pore size).
3. Rapid Manufactured inserts (Electron Beam Melted using the Arcam S12T system – Arcam AB, Mölndal, Sweden).

Fibre orientation and consolidation of the CFC test samples were determined through cross-sectional analysis, and surface roughness was measured using a Wyko NT-2000 Optical Profiler (Veeco Instruments Inc, New York, USA).

2.3 PCT results and discussion

An innovation over conventional composite moulding processes was provided by the use of sintered metal inserts with a pore size of between 6 and 35 mm. These offered sufficient resin flow to prevent excessive porosity forming in the component as a result of premature resin gellation and resin starving of the carbon fabric (Fig. 2), and also, significantly, maintained fibre orientation through application of a uniform compressive force (Fig. 2). This has significant implications for composite forming as it will allow large area resin infusion of a component while retaining fibre alignment, and thus component strength and quality should not be reduced. Below 6 mm, the restriction on resin infusion was found to be too large with gellation of the resin initiating prior to complete infusion (thus the 2 μm porous inserts were not suitable for this application). At pore dimensions of 35 mm, the surface roughness

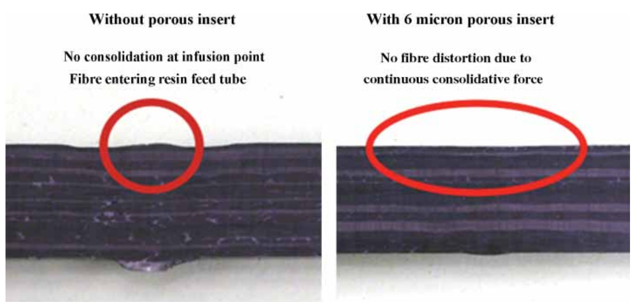

Fig. 2 VCT, schematic, during component manufacture and during component removal

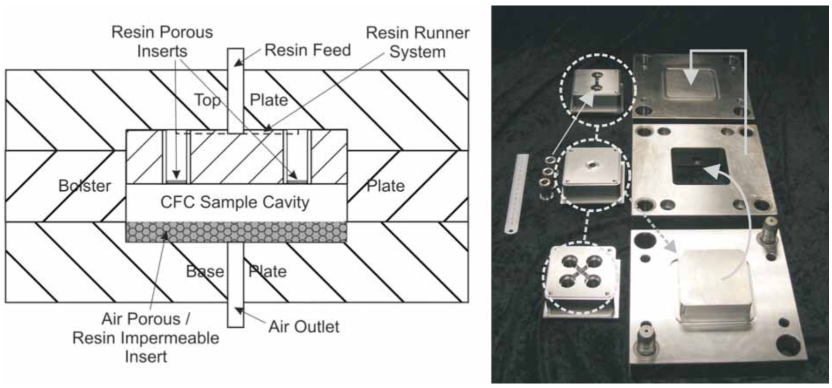

Fig. 1 PCT, schematic, components and research set-up

Table 1 Surface roughness over the insert contact area of CFC manufactured using different porosity inserts

Insert porosity size (μm)	Ra (mm)	Rq (mm)	Rt (mm)
0	13.0 ± 0.4	17.0 ± 0.6	165 ± 20
2	14.5 ± 0.6	16.4 ± 0.6	141 ± 26
6	14.8 ± 0.8	18.3 ± 0.9	142 ± 5
20	12.8 ± 0.5	15.7 ± 0.6	141 ± 12
35	27.4 ± 0.2	21.1 ± 0.2	189 ± 10

of the component was found to increase (Table 1) due to the greater contact area between the resin and the fabric for higher pore cross-sectional area. Parameters were also obtained for the Rapid Manufacturing Electron Beam Melting process to provide porous sintered titanium inserts with sufficient compressive strength to withstand the RIM moulding pressures (0.1–0.2 MPa). The parameters were based on the standard parameters used to melt Ti 6 4 alloy, but scan spacing and beam scan velocity were increased to induce porosity in the formed parts. This provides further innovation as this allows the rapid manufacture of porous inserts containing the three-dimensional geometry of the component surface, thus extending the application of porous inserts to non-planar geometries.

3 VARIABLE CAVITY TOOLING

3.1 Introduction to VCT

The use of ‘active’ cavities has been investigated as a means of applying a mechanical pressure to the resin so as to induce a local high-pressure gradient at positions remote from the injection port. Examples include movable mould halves to provide a compressive squeezing force onto the resin [**3**], thus increasing infusion rates, and articulated adjacent moveable core blocks, with resin compression and infusion delivered through sequential raising and lowering of the blocks [**4**]. The articulated mould technologies demonstrated enhanced resin infusion rates but the results were not extended to increasing fibre fractions and no mechanical evaluation of the components was performed. The VCT tool development allows the volume of an RTM cavity to be increased or decreased (or variable modulated) during or after the resin infusion process. VCT offers the potential to be able to increase the loading of CFC in a component to achieve higher carbon volume fractions and thus higher component strength, and maintains complete resin saturation in low-cost dry CFC fabrics. The cavity volume may be significantly larger than that required for component forming while maintaining vacuum integrity. Infusion of a high fabric loading may thus be achieved prior to further mould closure (at a controlled rate) to the final mould gap. The primary aim of the research was to identify the effect of the principal process parameters (initial tool gap, d_i, number of carbon fabric layers, n, and mould cavity closure rate, v_c); to optimize the process for maximum part quality; and to determine the process capability index (C_{pk}). This index gives a measure of how capable a process is of meeting a target output value that is between two specification limits, an upper and a lower specification limit (USL and LSL). A higher C_{pk} value tells us that a higher number of outputs are within the specification limits, and that the average value is less offset from the centre value between the two specification limits.

3.2 VCT research methodology

A variable cavity test tool was developed to enable the process capability to be determined. The tool was designed to accommodate a bulkhead and a rudder component that forms part of the demonstration activities in FLAVIIR. Cavity movement was obtained using a 50 kN jack with programmable logic control, allowing accurate control of axis movement distance and velocity. This offered a capability to mould with a process resin injection pressure of up to 0.3 MPa (Fig. 3), although a pressure of 0.1 MPa was employed for all mouldings.

The effect of process parameters was investigated using a design of experiment (DoE) methodology (three parameters, three levels, central composite design with one centre point, 15 runs, and six repetitions). The parameters employed in the optimization experiments are presented in Table 2. For each of the CFC samples obtained from the above evaluation, mechanical properties (tensile modulus, E_t, strength, U_t, flexural modulus, E_b, and strength, σ_f)

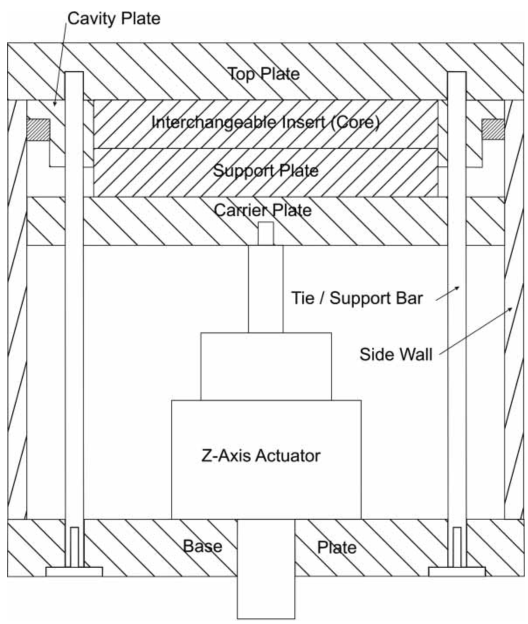

Fig. 3 Schematic of variable cavity tool

Table 2 Variables employed in VCT research trials

Parameter	Description	Units
N	Number of layers of CFC fabric	–
d_i	Mould gap at the beginning of resin infusion	mm
v_c	Mould closure rate	mm/min

were evaluated using appropriate mechanical techniques. Tensile and flexural strengths and moduli were evaluated using the sample and test specifications described in EN ISO 527 part 4: 1997 and EN ISO 14125: 1998, respectively. Six samples were prepared for each of the runs and were taken from an area away from the edges and the gate. The location of the samples was consistent between runs (samples CNC machined from the test plates). The process was optimized using statistical techniques (analysis of variance (ANOVA) to obtain the regression equations and Y-hat linear regression optimization), and a confirmation run was performed. The process capability, C_{pk}, was determined for the non-optimized and optimized process.

3.3 VCT results and discussion

The variable cavity process has been shown to provide components having tensile and flexural properties that compare very favourably with those obtained for RTM-processed components. The results obtained for the average mechanical properties, the significant process parameters, and the representative properties from the literature are presented in Table 3 ($A = d_i$, $B = n$, and $C = v_c$). The two-way interaction (i.e. interaction between d_i and n parameters) is denoted as AB. This means that the change in the output measurable (e.g. E_t) is highly determined by the change in d_i, and n parameters together (i.e. the effect due to the change in d_i is linked to the effect due to a change in n). An analogy to this is cooling a hot room. If the door is opened on its own (1 parameter) then the room cools a little (2 °C). If the window is opened on its own (1 parameter) then the room cools a little (3 °C). If both are opened, then the room cools a lot (10 °C) due to the generation of a draught; thus the two single parameters interact to have a larger change in the output (room temperature). The three-way interaction (i.e. interaction between all three process parameters resulting in a change in the output measurable (e.g. E_t) is denoted by ABC. In this case, the change in a measurable output is determined by the change in d_i, n, and v_c parameters together (i.e. the effect due to the change in d_i is linked to the effect due to a change in n, which is linked to the effect due to a change in v_c). The per cent values given in Table 3 are the per cent contribution of the input parameter or parameter interaction that controls the output (e.g. E_t). These values are obtained from an ANOVA analysis of the experimental results. Thus, a higher per cent value means that a change in the input parameter (or interaction between parameters) will result in a large change in the output parameter, and vice versa. 'VCT Range' in Table 3 is the minimum to maximum values that were measured over all the test specimens.

The interaction between the three primary processing parameters is highly significant (as indicated by the two- and three-way parameters being most significant 'highest per cent contribution' for all observables). The overwhelming contribution to the level of the observable responses for a single parameter was found to be due to the initial mould gap (d_i). The contribution of the two other parameters was low in all cases, indicating that the improvement in resin flow and infusion quality was primarily determined by d_i and was largely independent of the volume fraction of carbon in the final component (within the range used for the parameters). This is inferred from the observation that changes in n (the number of laminations) did not result in any statistically significant change in the observables. Although volume fraction was not measured for the samples, it can be inferred that samples with equal volume but with different masses of carbon fibre will have different volume fractions of carbon in them. The optimal value for d_i for all observables was 8 mm (i.e. the initial mould gap should be set open to maximum extent (within the parameter range employed)). Thus a 3 mm gap exists between the initial and final mould gap.

The process capability index (C_{pk}) was determined statistically from the experimental data using DoE ProXL software (Air Academy Associates Inc, USA) and was found to be quite poor, with values for the LSL for the measured mechanical properties being below the range acceptable for RTM processing (with the exception of s_f) to maintain a C_{pk} acceptable for an

Table 3 Results of the ANOVA analysis of the VCT process variables, indicating range of measured mechanical properties and significant process parameters

			Most significant factors					
Property	VCT range	Literature	1st		2nd		3rd	
E_t	41–70 GPa	65–70 GPa [**10**]	AB	27.71%	d_i	26.57%	ABC	19.16%
U_t	696–1035 MPa	830 MPa [**11**]	ABC	53.38%	d_i	32.08%	AB	22.62%
E_b	37–47 GPa	44 GPa [**12**]	AB	45.43%	d_i	23.36%	ABC	12.67%
σ_f	1040–1200 MPa	536 MPa [**12**]	ABC	70.27%	d_i	33.41%	AB	24.15%

existing ($C_{pk} = 1.25$) or new ($C_{pk} = 1.45$) process. The process optimization (performed for flexural properties) was found to improve the process capability, bringing the LSLs into the range acceptable for RTM-processed components (Table 4). This is achieved by raising the average mechanical properties of the test specimens and reducing the width of spread of property values (reducing the standard deviation of results – σ). The number of defects per million (DPM) is the number of parts that one would expect to have properties outside of the USL and the LSL. DPMs are calculated statistically based on the normal distribution, with an average and standard deviation as calculated from the input data.

This has demonstrated that high-quality resin infusion at low pressure (0.1 MPa) can be achieved by introducing a larger cavity during the infusion stage of the VARTM process. The optimization has indicated that an optimal value for d_i (the initial mould gap) of 8 mm (maximum setting in this research) has resulted in a significant increase in the average value measured for all four mechanical properties, and also, a significant decrease in standard deviation of the measured mechanical properties. Thus, the process is more capable (lower numbers of defects) using a large initial mould gap. This allows lower-cost materials to be used for the tooling (e.g. aluminium and potentially tooling grade cast resins, etc.).

4 RECONFIGURABLE TOOLING CONCEPT

4.1 Introduction to RTC

Pin-matrix tools (discrete dies) employ a set of pins that are positioned either by active systems or by passive configuration. Such devices are currently employed in fixturing applications [**13**] to locate and hold components (e.g. machining applications). The application of pin-matrix tooling to composite forming has been investigated, although work has been limited to improving process performance in vacuum composite forming [**13**], and for the incremental Double Diaphragm forming of composites [**14**]. Northrop Grumman Corporation, USA enhanced the pin functionality by using them as heated jets for the hot forming of thermoplastic components [**15**]. There has been limited application of pin-matrix tooling to the manufacture of large aerospace structures except for forming aircraft body panels through stretch forming or composite forming [**16**]. For the latter, an elastomeric interpolator material was used to prevent dimpling of the composite between pins. This research successfully demonstrated the technology capability for a 4×4 pin array but there has been no subsequent reported scale-up of this technology. This lack of scale-up is likely to be because of difficulties in achieving the tolerances demanded by the sector, which is primarily due to the use of flexible interpolator materials. The use of novel conformable interpolators was investigated, including superplastic formed aluminium (superplastic formable (SPF)) and shape memory polymer (SMP), and means of forming these materials into the desired tool surface geometry using a low-cost process.

4.2 RTC research methodology

In the prior art, a reconfigurable discrete die employs a flexible sheet (or interpolator) to cover the gap between pins to provide a moulding surface. An RTC innovates over this by providing a rapidly configurable, stiff interpolator surface (which forms the CFC moulding surface) using a low-cost system. Research focused on conformable and reconformable interpolator materials.

1. SPF aluminium (5083 grade, 1 mm thick).
2. SMP – Veriflex (CRG Industries), Veritex (CRG Industries), both 2 and 4 mm thicknesses were evaluated for each material.

Both SPF and SMP are relatively low cost and are easily deformed. The forming process is akin to the traditional superplastic forming of aluminium and vacuum forming of polymeric sheet. A pin array forms the component definition. Heating of the interpolator was performed using an array of independently controlled quartz infrared heating elements (able to deliver a sheet temperature up to 500 °C, with thermocouple sensing of the sheet temperature). Sheet forming was achieved through the application of helium gas at 0–0.3 MPa and/or application of vacuum pressure below the sheet. The variable parameters

Table 4 LSLs and DPM for a C_{pk} of 1.25 and 1.45 for the measured mechanical properties

	E_t (GPa)		U_t (MPa)		E_b (GPa)		σ_f (MPa)	
	Existing	New	Existing	New	Existing	New	Existing	New
LSL (non-optimal)	32.06	29.97	617.00	567.64	33.92	33.14	902.04	880.01
LSL (optimal)	38.25	35.95	749.01	709.10	41.61	41.04	1104.30	1092.62
σ (non-optimal)	3.48	3.48	82.87	82.87	1.29	1.29	36.72	36.72
σ (optimal)	2.87	2.87	66.48	66.48	0.95	0.95	19.46	19.46
C_{pk}	1.25	1.45	1.25	1.45	1.25	1.45	1.25	1.45
DPM	93.00	7.20	93.87	7.28	93.73	7.29	93.84	7.29

Table 5 Variables employed in RTC research trials

Parameter	Description	Units
T	Sheet temperature	°C
P	Applied gas pressure	MPa
P_v	Applied vacuum pressure	MPa
T	Pressure application time	min
X	Depth of draw on profile	mm

employed in the research are given in Table 5. A tool was developed to allow process parameter evaluation. The steel pins were insulated from the sheet material using machined glass-ceramic (Macor – Corning GmbH, Wiesbaden, Germany) pin headers.

Two different depths of draw (X) were investigated: 10 and 20 mm. These were provided by radii of 286.25 and 150.63 mm, respectively. The formed shape was convex in the direction of applied pressure. The process variables were evaluated, with the formed sheets measured for dimensional accuracy and surface finish. The dimensional accuracy was measured using an articulated CMM (Platimum FaroArm, FARO UK, UK) and surface finish was measured using a Talysurf (Taylor-Hobson Ltd, UK). Using a DoE approach for the SPF aluminium sheet trials, full-factorial, with three factors (T, P, and t), each at three levels (100, 150, and 200 °C; 0.1, 0.2, and 0.3 MPa; 1, 8, and 15 min), a regression equation for the process was determined using ANOVA, and multiple response optimization was employed to determine optimal process parameters for the geometrical accuracy of the SPF aluminium sheets. Since the SMP material may be less able to support the CFC moulding loads than SPF aluminium, two thicknesses were investigated (2 and 4 mm).

4.3 RTC results and discussion

4.3.1 Superplastic aluminium interpolator forming

For the $X = 10$ mm depth of draw, the optimal forming capability was less sensitive to process conditions, and a range of temperature-pressure combinations were identified that provided good forming capability. Forming capability was found to be within ±0.1 mm for ±20 mm from the geometry centre, and ±0.2 mm for ±50 mm from the geometry centre. Further to the edge of the geometry (>±30 mm) the SPF was not formed sufficiently and deviations from the required geometry in excess of ±0.4 mm were observed. For $X = 20$ mm, the ability to form the geometry defined by the pin array was more sensitive to processing parameters. Using ANOVA analysis on the results of the DoE experimental data, optimal processing (best forming accuracy) parameters were obtained (400 °C/0.2 MPa). Time was not found to be a statistically significant parameter (1 min was sufficient to form the sheets). The surface finish was not found to be affected within the range of the parameters used.

The forming process was found to be limited by the development of indentations in the interpolator at the pin locations due to the higher local pressures at these points. To mitigate this effect, which was not conducive to forming a capable moulding surface, a range of support materials between the pins and the SPF sheet were investigated. A solution was identified as an inorganic fibre board (Thermotex 500, Thermotex Industries Inc, South Carolina, USA). As a supporting layer (2 mm), the cloth eliminated the indentations and also had no statistically significant effect on surface forming accuracy (Fig. 4).

4.3.2 SMP interpolator forming

A successful solution was also found for the processing of SMP. This material has the advantage of processing at very low temperatures (75 °C – Tg of 68 °C), and 0.01 MPa and below. Although forming trials were performed for the 4-mm-thick SMP, the 2-mm-thick material was found to be sufficiently stable for the application, and thus forming accuracy trials were only performed on the 2–mm-thick sheet. Figure 5

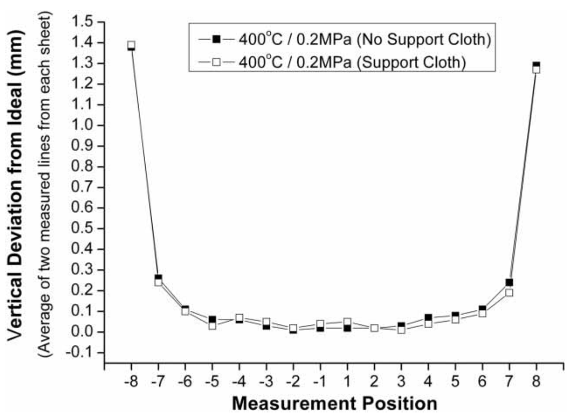

Fig. 4 RTC forming of SPF ($X = 20$ mm) with and without Thermotex 500 support

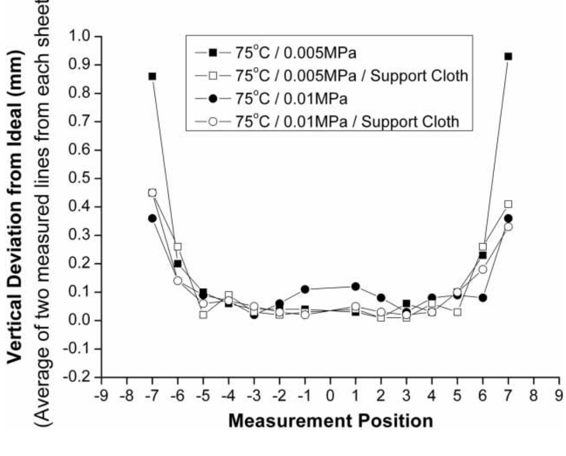

Fig. 5 RTC forming of SMP ($X = 20$ mm) with and without Thermotex 500 support

demonstrates that the forming accuracy of the SMP is very similar to that of the SPF. SMP offers the opportunity to form tool skins using traditional vacuum forming equipment but the stiffness of SMP is likely to be significantly lower than that of SPF aluminium.

5 CONCLUSION

The research into the development of three tooling developments that can aid the low-cost manufacture of CFCs has been presented. The use of porous cavity materials such as sintered metal inserts has been shown to allow the infusion of resin into an RTM cavity at low pressure (0.1 MPa) and to prevent the disruption of the laminations at the resin feed points, allowing more optimal positioning of feed points without deleterious effects on the fibres. An application of a novel VCT has been demonstrated for the manufacture of epoxy matrix carbon fibre composites by RTM at low pressures. The benefit of a cavity height larger than the final part height during resin infusion has been demonstrated in providing improved mechanical properties to the CFC. Process optimization has also been shown to be beneficial in reducing the standard deviation of the mechanical properties of parts manufactured using the tooling and in raising the average values of the mechanical properties, making the process more capable, delivering mechanical properties on par with traditional RTM processing with acceptable process capability indices of 1.25, which is acceptable for an existing process. Finally, an RTC has been developed and shown to be a promising method for the low-cost rapid forming of aluminium tool skins for subsequent moulding of CFCs. This is a particularly important technology for supporting low-volume manufacture of CFC components and structures, where part geometry changes are often seen, and where tooling costs would be prohibitive.

ACKNOWLEDGEMENTS

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APPENDIX

Notation

C_{pk}	process capability index
d_i	initial mould gap
E_b	modulus of elasticity in bending

E_t	tensile modulus
n	number of CFC fabric layers
P	pressure of applied gas in RTC processing
P_v	pressure of applied vacuum in RTC processing
s	standard deviation
s_f	flexural strength
t	time of applied pressure under RTC processing
T	temperature of interpolator sheet under RTC processing
U_t	ultimate tensile strength
v_c	mould cavity closure rate
X	depth of draw on a pin array profile under RTC processing