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ELECTRICALLY-HEATED CERAMIC COMPOSITE TOOLING FOR OUT-OF-AUTOCLAVE MANUFACTURING OF LARGE COMPOSITE STRUCTURES

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ABSTRACT

This paper describes the development of electrically-heated ceramic composite tooling, aimed primarily at the manufacture of large composites structures, for aerospace or for wind energy. The tooling is designed to operate at temperatures up to 300°C, but has the potential to be used at temperatures up to 500°C and above. The ceramic material is an aluminosilicate material, reinforced by continuous fibres and thermoplastic polymer, and laid up with embedded electrical heaters. The ceramic and reinforcing layers are laid up by hand at room temperature, on a standard pattern and cured initially to 60°C, followed by a free-standing post-cure, in stages to approximately 400°C. Special-purpose gel-coats and surface sealing layers are employed to ensure a smooth, vacuum-tight surface. The tooling is lightweight, strong and durable, and has a low coefficient of thermal expansion. Electrical heating power per square metre of tool surface is typically between 5.0 and 15.0 KW/sq.m. Examples are given of the use of the tooling to manufacture 12.6 metre long glass-fibre/epoxy and glass-fibre/PBT wind turbine blades (250KW machine). Aerospace carbon-fibre epoxy prepreps are also processed on the tooling successfully. In all cases, the materials need to be processed between 180°C and slightly above 200°C. The integrally-heated ceramic composite tooling provides a more cost-effective tooling system for processing thermoplastic or thermoset composites at these temperatures than standard metal tooling.

1. INTRODUCTION

Out-of-autoclave (OOA) manufacturing of composite materials to autoclave standards has long been an important goal for the aerospace composites industry [1]. Recent activities have included concerted research and development programmes [2] and potential production of aircraft primary structure [3] using forms of non-autoclave or vacuum-bag-only processing of thermoset matrix composites. The main driver for these developments is the high capital cost and running costs of autoclaves, especially as structures become larger.

Most of the OOA prepreg and resin-infusion systems that have been developed for aerospace are confined to lower temperature cure systems (i.e. 150°C or below), with consequent longer cycle times than for higher temperature systems. This concentration on lower-temperature cure systems has been for two main reasons: 1) many of the developments have been aimed at composite prototyping, or at low aircraft production rates (less than 100 a/c), where rapid cycle

time is not a major concern; and 2) because efficient, integrally-heated and cost-effective composite tooling has not been available for processing temperatures above 150°C.

Many material suppliers offer “high temperature” polymer composite tooling solutions, including cyanate-epoxies (upper limit of 190°C), high-temperature epoxies (upper limit of 200°C), and bismaleimides (200-250°C). Newer entrants onto the market also include benzoxazines and hybrid tooling solutions such as Invar/bismaleimide tools and machinable ceramic/bismaleimide-faced tooling. However, the reality is that the number of thermal cycles available from many of these tooling solutions at their claimed upper-end temperatures tends to be disappointing, with many exhibiting microcracking and other forms of degradation after only dozens, or low hundreds of cycles. There is also interest in the aerospace industry in out-of-autoclave processing of the very “high-temperature” polymer composites that are being used for composite tooling, which is unlikely unless a new tooling platform is developed.

A further issue for out-of-autoclave processing of composites is the efficiency of heating of the composite tooling during processing. The most usual method of providing heat for the OOA process is via the use of ovens with radiant-heating and forced-air convection, though it has been recognized that large ovens can in themselves constitute a large capital cost. The wind-turbine blade industry uses the largest heated composite tools, up to 50 metres in length, but normally only uses tooling heated to around 120°C, which limits the types of resins that can be employed in the blades.

Novel heating methods for out-of-autoclave tooling such as microwave heating, the use of embedded electrical heaters, or the use of heated fluids have all been used with varying degrees of success [1], but are mainly limited by size and capital cost (in the case of microwave heating) or to processing temperatures at or below 150°C.

There is also interest in developing OOA or vacuum-processing techniques for thermoplastic composites, with materials such as carbon fibre PEEK [4] for the aerospace industry and materials such as PBT [5], PET and PA-6 [6] being investigated for large wind turbine blades. With processing temperatures ranging from 200°C to almost 400°C, clearly, a completely new type of heated tooling for vacuum processing of thermoplastic composites is necessary.

This paper presents a new concept in large composite tooling for out-of-autoclave processing of both thermoset and thermoplastic composites, an electrically-heated ceramic composite tooling solution that is low-cost compared to autoclaves, yet thermally efficient and capable of rapid, controllable heating and cooling.

2. REINFORCED CERAMIC COMPOSITE TOOLING

2.1 Earlier Generation of Electrically-Heated Ceramic Tooling

The concept of using embedded electrical heating tape to directly heat the B-side of a thin metal tool was developed by ÉireComposites in the period 2000-2005 for processing of glass-fibre reinforced polypropylene products. Initially, the heating system was applied to the rear surface of cast aluminium tooling using a high-temperature epoxy resin into which the electrical heating

tape was embedded. Difficulties with this system included insufficient thermal durability of the epoxy resin for repeated cycling to 200°C.

The replacement of the epoxy resin by a ceramic cement paste was an incremental development in this tooling technology. Ceramic cements used were alkali aluminosilicates [7] and calcium metasilicates [8]. These ceramic cements provided the thermal durability required for the tool heating system.

Figures 1 and 2 show the use of this electrically-heated metal tooling for production of sailing catamaran hulls in a glass fibre reinforced polypropylene, a production process with is currently continuing. The catamaran hull shown is approx. 4.5 metres long and weight 35 Kg. Cycle times of 2-3 hours can be achieved with the tooling, and many hundreds of cycles to a processing temperature of 200°C have been demonstrated.

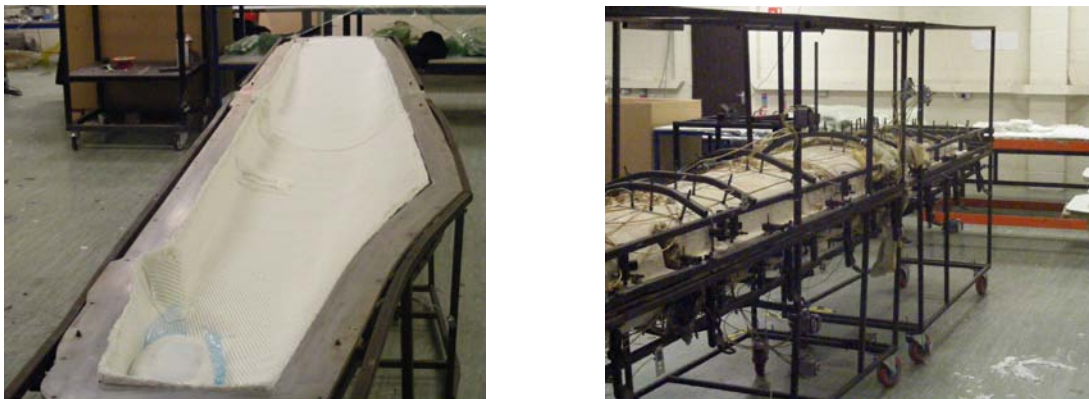


Figure 1. Electrically-heated ceramic applied to rear of metal tooling, showing (left) GF/PP layup in catamaran tool half; and (right) ceramic heaters on outside of tool during processing.



Figure 2. Sailing catamaran with GF/PP hulls, manufactured using the configuration in Figure 1.

The limitations of this approach as the surface area of the tool increases are twofold: a) the cost of metal tooling increases rapidly beyond a tool size with a single dimension over 5.0 metres; and b) the large difference in coefficient of thermal expansion (CTE) of metal tooling, when

compared to glass or carbon-fibre reinforced polymer products, becomes more problematic as dimensions increase.

The impetus for this research work is provided by the perceived need for improved materials and manufacturing processes for large composite structures, such as large wind turbine blades, whose lengths are typically between 40m and 60m. Initially, the work was directed at development of thermoplastic composite solutions [5] for these large structures, but it also led to the usage of novel thermoset materials which had various attractions in processing. What unified the project was the necessity for inexpensive tooling that could operate repeatedly and reliably at temperatures above 200°C. Therefore it was clear that a new tooling solution, not involving a metal tool, was needed.

2.2 Properties of Ceramic Cements

The approach adopted was to build electrically-heated tooling using the ceramic cements, reinforced with suitable reinforcements. Table 1 shows the basic mechanical and thermal properties of a typical ceramic cement, in this case a commercially-available aluminosilicate [7]. The material has many desirable properties for an electrically-heated tooling material, such as a high temperature resistance, a low CTE, low density and thermal mass, and low electrical conductivity. This class of material also has an important advantage in the production of large composite tools, in that it becomes rigid on an initial cure at 60°C, after which it may be removed from the pattern and further cured at higher temperatures. This means that inexpensive patterns may be used with this tooling solution.

The low tensile strength of the ceramic materials (<10.0MPa) is an obvious problem, and much of the research work was focused on the selection of appropriate reinforcements for the ceramic materials. Initial attempts at reinforcement with glass fibre [9] were successful to a point, but the resulting tooling was lacking in fracture toughness and had a poor thermal durability for this reason.

Table 1. Properties of a typical ceramic cement

Initial cure (°C)	Room Temperature to 60
Final cure (°C)	Typically above 150
Heat Resistance (°C)	c. 1000
Young's Modulus (GPa)	8.0 - 10.0
Ultimate Compression Strength (MPa)	20.0 - 30.0
Ultimate Tensile Strength (MPa)	< 10.0
Density (Kg/m ³)	1600 – 2000
Coeff. of Thermal Expansion (m/m/°C)	< 5.0 x 10 ⁻⁶
Thermal Conductivity (W/m.K)	0.3 - 0.5
Specific Heat Capacity (J/Kg.K)	0.3 - 0.45

2.3 Carbon-Fibre/Thermoplastic Reinforced Ceramic Tooling

The tooling described here utilizes a novel reinforcement solution for the ceramic cement – the cement is reinforced with a carbon-fibre reinforced thermoplastic [10]. This 3-part composite tooling provides a balance between the competing requirements of a high temperature composite mould:

- Ceramic cement: provides high temperature resistance and ability for tooling to be laid up without autoclaves and on 60°C patterns. Also provides electrical insulation for the electrical heating tape.
- Carbon fibre: provides stiffness and greatly increased tensile strength (up to 100MPa) to the ceramic
- Thermoplastic polymer: provides an “adhesive” between the carbon fibre and the ceramic, and also provides increased toughness and ductility for the tooling.

Figure 3 shows a schematic of the construction of the tooling wall, with alternating layers of ceramic paste and carbon-fibre reinforced thermoplastic polymer (in this case PEEK). Electrical heating tape is laid into the tool wall as a specific layer, as shown in the figure. An initial cure of the tooling is carried out at 60°C, at which point the tool is removed from the pattern. The tooling is then subjected to a further cure at 200°C, in order to fully cure the ceramic cement. A higher temperature process may then be necessary in order to fully melt the thermoplastic and to ensure a good bond between the thermoplastic, the carbon fibre and the ceramic. In the case of a carbon fibre/PEEK reinforcement, a one-time temperature cycle to about 400°C is necessary to finish the process.

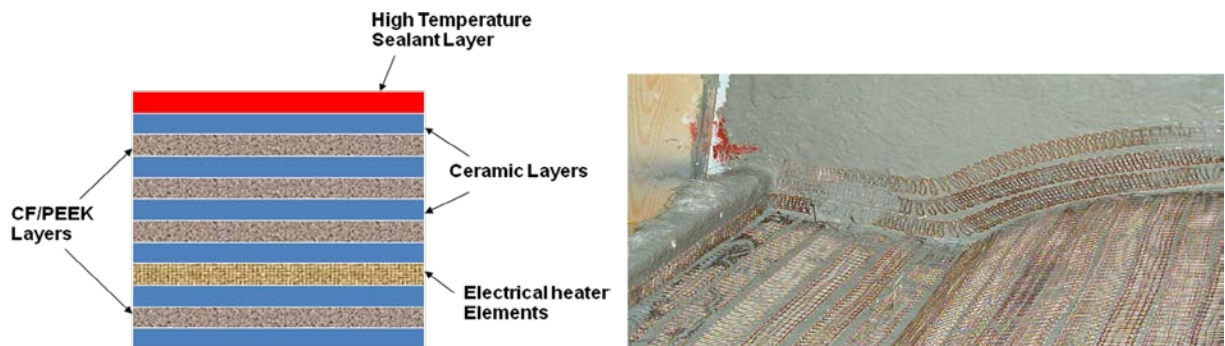


Figure 3. Schematic of construction of tooling material (left) and electrical heating tape being laid up into tool (right)

3. RESULTS

3.1 Thermal Performance of Electrically-Heated Ceramic Composite Tooling

Figure 4 shows a cross section of a 15mm wall thickness, with a carbon-fabric reinforced PEEK, but without the electrical heating tape. Figure 5 shows the results of CTE measurements of the same material, plotted against temperature, up to 400°C. The material was tested in three orthogonal directions, two in-plane directions and in the through-thickness direction. Table 2 gives the measured CTE values. The thermal strain values of the material increase in an

approximately linear fashion with increasing temperature. Note that the in-plane CTE values are less than $5.0 \times 10^{-6}/^{\circ}\text{C}$, generally accepted to be a “matching value” for processing of glass-fibre and carbon-fibre reinforced composite materials. The through-thickness CTE value is approx. 4 times higher than the in-plane CTE values, as there is no reinforcing carbon fibre in this direction.

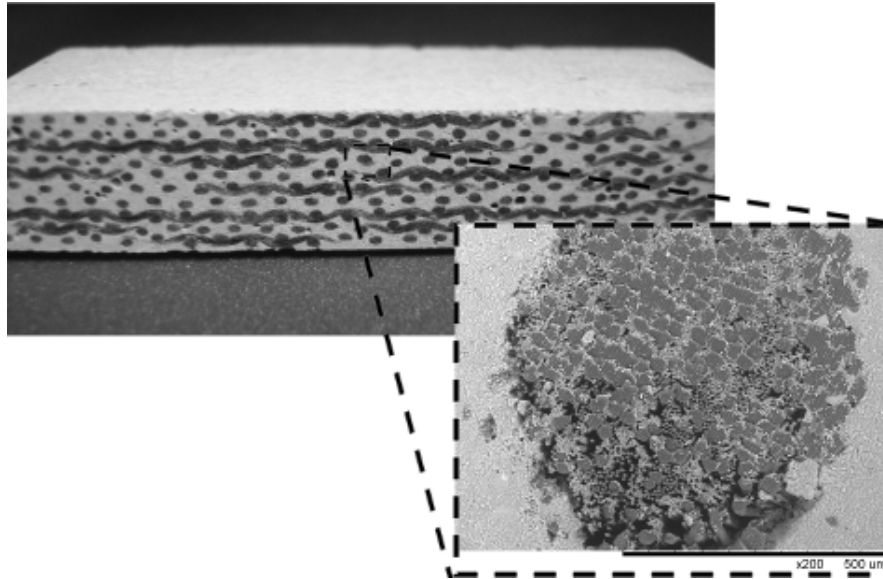


Figure 4. Cross-section of carbon fibre/PEEK/ceramic tooling material (without electric heating tape), from [11]

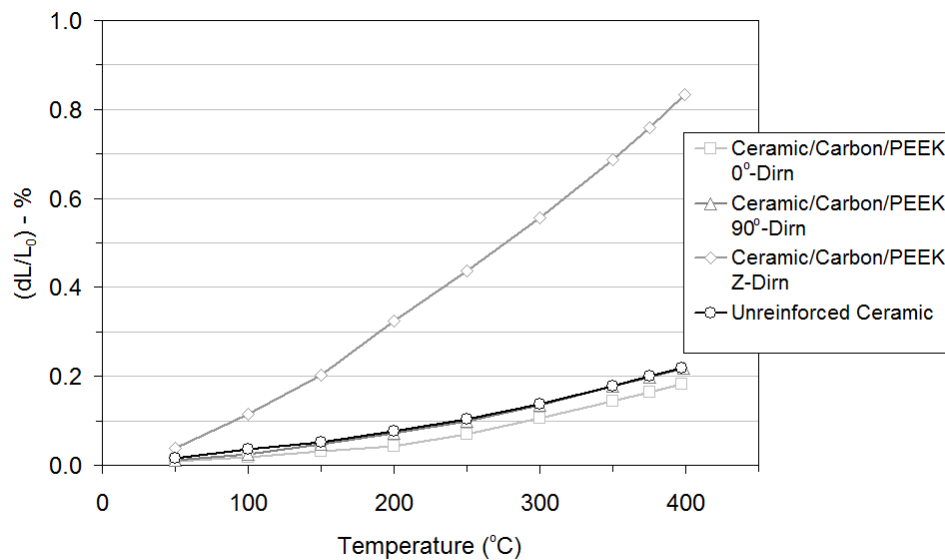


Figure 5. Coefficients of thermal expansion of carbon fibre/PEEK/ceramic tooling material in main directions, plotted against temperature, from [11]

Table 2. Coefficients of Thermal Expansion (CTE), from [11]

	Ceramic/Carbon/PEEK 0° Direction	Ceramic/Carbon/PEEK 90° Direction	Ceramic/Carbon/PEEK Z Direction	Unreinforced Ceramic Cement
Average CTE ($10^{-6}/^{\circ}\text{C}$)	3.24	4.32	18.0	4.89

Though the targeted service temperature for the tooling in this paper is just above 200°C, the mechanical properties of the tooling are only limited by the softening in the PEEK polymer that acts as an adhesive between the carbon fibre and the ceramic cement. PEEK is a highly-crystalline polymer, with a glass-transition temperature (T_g) of approx. 143°C, and a melt temperature (T_m) of approx. 343°C. Due to the highly-crystalline nature of the thermoplastic, it is likely that the tooling will perform well at temperatures in the region of 300°C.

The heat-up rate of the tooling depends on the power input per square metre of the tooling surface, or the wattage density. This can be controlled by varying the electrical power to the heating tape. Figure 6 shows that the tool surface can be brought to 200°C in under 10 minutes by using an electrical wattage density of 10KW/m², a rate which might be suitable for processing of thermoplastic composites, whereas a much lower wattage density of 2KW/m² results in a heating time of approximately 80 minutes, more suitable for processing thermoset composites.

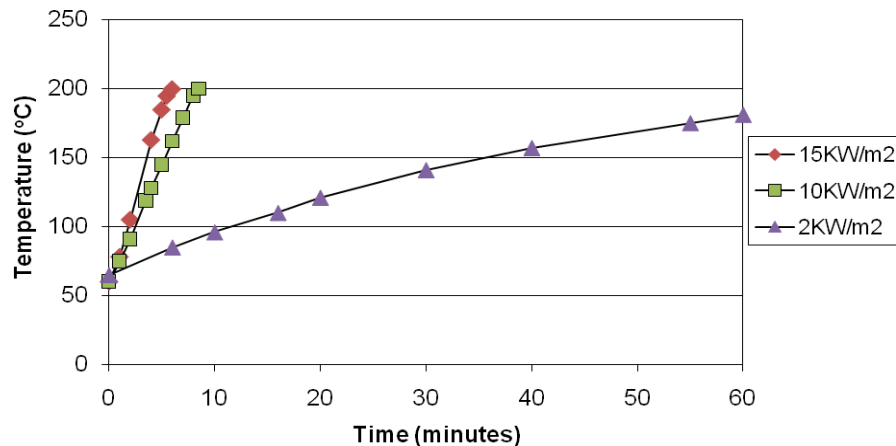


Figure 6. Heat-up rates of electrically-heated ceramic tooling depends on wattage density of heating tape.

3.2 Processing of Large Structures on Ceramic Composite Tooling – Wind Turbine Blades

In order to demonstrate the capabilities of the ceramic composite tooling, a 12.6 metre long electrically-heated wind turbine blade tool was constructed, as shown in Figures 7 and 8. The blade is a prototype blade for a 250KW wind turbine, the shape of which was made available to

the project by Mitsubishi Heavy Industries. Figure 7 shows the construction of the blade pattern from simple wood and filler materials. The tool is a clamshell-type tool, and is manufactured, one half at a time, by layering the ceramic cement paste and the carbon-fibre reinforced thermoplastic (in this case a CF/PEEK material). Special surface sealants are employed to achieve full vacuum retention against the moulding surface. Full details of the tool construction process are given in the relevant patent application [10]. The resulting blade tool is shown in Figure 8. It is remarkable that the tool shown is the only equipment needed to manufacture the wind turbine blade, i.e. no ovens or external sources of heat are needed to produce the composite blade, other than the tool shown.



Figure 7. Construction of 12.6m wind turbine blade pattern



Figure 8. Completed 12.6m wind turbine blade tool

3.2.1 Thermoset Composites – Glass Fibre/PBT

The mould shown in Figure 8 was used to construct a thermoplastic composite blade, using the in-situ polymerized CBT™ system from Cyclics Corporation [12,13]. This system of thermoplastic moulding involves the use of an activated monomer system at temperatures in the region of 200°C, which is used to infiltrate the glass fibre perform. The CBT™ material, once fully infiltrated into the fibre preform, then polymerizes and crystallizes at temperature to form a

glass-fibre reinforced PBT (polybutylene terephthalate) thermoplastic composite. Figure 9 shows a fully-moulded glass/PBT blade, as well as a moulded section of the blade. It is important to realize that this blade was manufactured in a “one-shot” process, i.e. in a single manufacturing operation, without secondary adhesive bonding or any other joining technique. The resulting blade is well consolidated and fully polymerized, with a fibre volume fraction of approx. 50%. To the authors’ knowledge, this is the largest, high fibre-volume thermoplastic composite structure ever manufactured in one piece, weighing approx. 600Kg. As the blade manufacturing process is not the main subject of this paper, the reader is directed to other sources for further information [5].



Figure 9. Glass-fibre reinforced PBT thermoplastic wind turbine blade, 12.6 metre length, manufactured at 200°C, (left) removing moulded blade from tool; and (right) a 4.0m moulded section of the blade, showing the spar-cap and shear-webs moulded in a “one-shot” process.

3.2.2 Thermoset Composites – Glass Fibre/Epoxy

The possibility of having reliable heated tooling operating at temperatures above 200°C also opens the possibility of using novel thermoset systems, particularly the type of heat-activated epoxy and polyester systems which we will call here “VOC-free thermosets” (VOC standing for Volatile Organic Compounds, environmental toxins which can be released from the chemical curing of some thermoset systems). The features of these VOC-free thermosets are as follows:

- Polyester and epoxy powders – base materials currently used by the painting and powder coating industries.
- Heat activated at 200°C or above. No heating exotherm seen in the reaction.
- No VOC emissions.
- Solid powder material at room temperature.
- No special storage requirements, indefinite shelf life.
- Polymerization not sensitive to moisture.
- No dwell time necessary at processing temperature.

Figure 10 shows a 12.6 metre glass-fibre/epoxy wind turbine blade, manufactured in a one-shot process on the electrically-heated ceramic composite tooling. Special in-mould UV-resistant coatings have also been developed for use with either epoxy or polyester resin systems. The epoxy resin system used to manufacture the blade shown in Figure 10 is a commercially-available Araldite GT7004 system from Huntsman Advanced materials [14].

The use of the ceramic composite tooling, combined with the VOC-free epoxy powders provides the following advantages for production of thermoset wind turbine blades:

- One-shot manufacturing process for blade
- Rapid heating of tooling and lack of exotherm in material leads to a reduction of overall blade production cycle time by as much as 65%
- The manufacture of preforms, by debulking under vacuum, at temperatures under 100°C
- Better quality blades without any glue line will give longer life with reduced maintenance cost.
- Ease of handling of raw material – glass fibres and solid resin powder
- No need for freezers and other specialised handling for prepreg
- Cost savings from reduced labour content and faster cycle time

References [15 & 16] give a more complete description of the manufacturing steps used in production of the glass-fibre epoxy blade.



Figure 10. 12.6m glass fibre/epoxy wind turbine blade manufactured on electrically-heated ceramic composite tooling, showing (left) an internal view of the full blade; and (right) a section of the blade showing an in-mould UV-resistant coating

3.3 Processing of Pre-Impregnated Aerospace Materials on Ceramic Composite Tooling

Another demonstration of the tooling was to process an aerospace 180°C-cure carbon-fibre epoxy prepreg material, using vacuum only. A special demonstration tool, comprising half of the hub-end of the wind turbine blade tool (shown in Figure 11) was used for the moulding. A thermal camera was used to demonstrate that the maximum temperature difference across the moulding surface of the tool was within the standard $\pm 5^{\circ}\text{C}$. The prepreg was processed in a cycle time of 2 hours and produced a fully-cured laminate. The advantages of the new tooling system for OOA composite production are discussed in the next section.

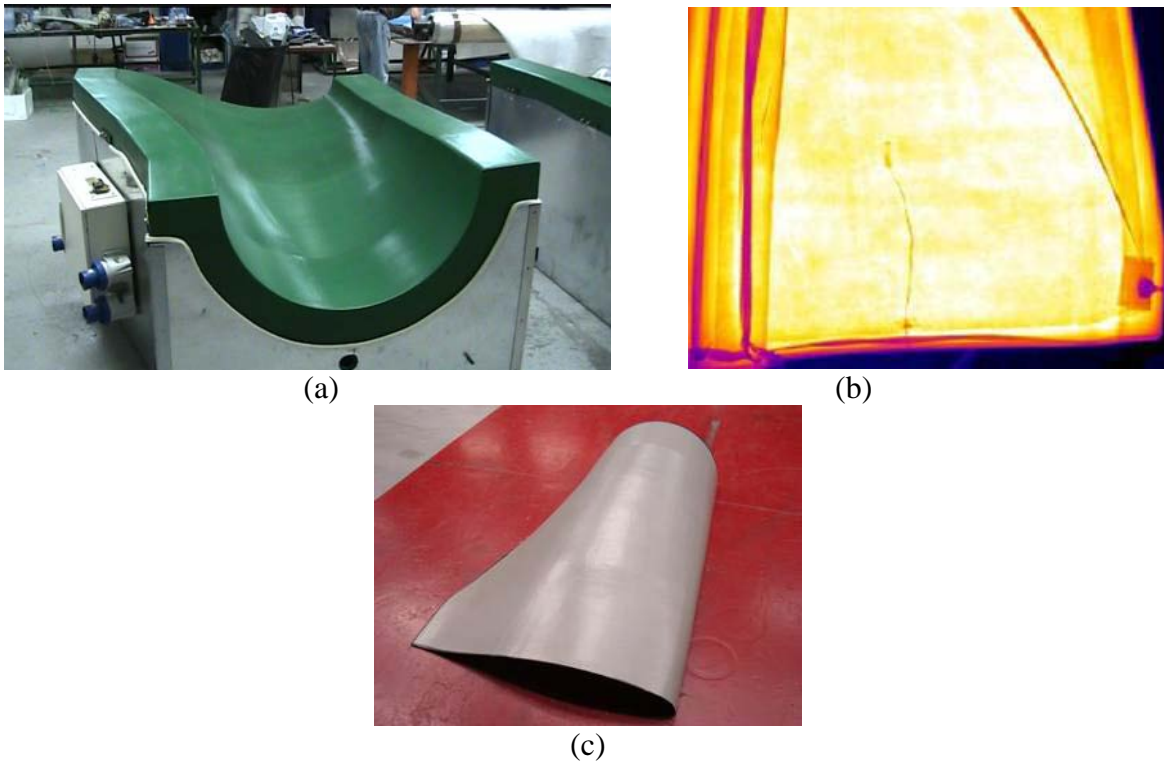


Figure 11. Demonstrator tool (a), measuring 2.0m in length; (b) thermal camera image of temperature in tool with electric heating; and (c) carbon-fibre/epoxy aerospace prepreg part manufactured on tool.

4. ECONOMICS OF TOOLING SOLUTION FOR AEROSPACE

The aerospace industry is moving away from expensive autoclaves and is developing manufacturing solutions for use outside the autoclave (OOA processing), where composite layups are processed under vacuum pressure only. Existing composite tooling solutions are largely unheated, so the existing OOA processes need an oven for heating, which can also be quite expensive.

The electrically-heated ceramic composite tooling solution is ideal for OOA processing of composites, as each tool is an entire production system, with no need for ovens or any other means of external heating. The tooling never needs to be moved in and out of ovens or autoclaves, which can prolong its life. For the purpose of an initial assessment of the economics of the new tooling, we will make a comparison with the industry standard in metal tooling, i.e. Invar, a low-CTE high-nickel tool steel.

4.1 Investment Cost Comparisons versus Invar Tooling

Table 3 shows the investment cost comparison between the electrically-heated tooling and the Invar tooling, used in an oven and also in an autoclave. The cost of the new tooling covers the total production system, whereas Invar requires an appropriate sized oven or autoclave. All figures used in Table 3 are cost estimates, based on current projections as to the cost of the

electrically-heated ceramic composite tooling, and based on quotations received from tooling suppliers, for the Invar tooling.

The table demonstrates that investment savings varying from 74% to 85% can be achieved by replacing an Invar tooling/autoclave process with the electrically-heated ceramic composite tooling as a stand-alone system. Savings over Invar tooling in an oven are projected to be between 45% and 62%, with greater savings for larger tooling sizes.

The size of the ceramic tooling is limited only by the logistics of getting it to the production site, and if necessary it can be manufactured on site. Invar tooling size is limited to the size of the machining centres available which currently are approx. 22 meters long by 6 meters wide.

Table 3. Capital investments compared to other manufacturing solutions

Tool Size (Sq.m)	Estimated Cost of Ceramic Composite Tool (€)	Estimated Cost of Invar Tool (€)	Oven Investment (€)	Saving over Invar + Oven (€)	Autoclave Investment (€)	Saving over Invar + Autoclave (€)
4.0	50,000	60,000	30,000	45%	100,000	74%
8.0	90,000	120,000	45,000	45%	400,000	83%
16.0	170,000	250,000	65,000	46%	900,000	85%
130.0	1,500,000	3,000,000	1,000,000	62%	7,000,000	85%

The number of thermal cycles that the new tooling is capable of must be also factored into the table, as Invar tooling is known to have a very long life. However, the technology is still at an early stage, and a comprehensive understanding of the thermal durability of the tooling is still not available. Initial indications, however, are that lifetimes of between 500 and 1000 cycles at 200°C should be easily achievable. Another factor would be the ability to repair the surface of the ceramic tooling in the event of surface damage, work on which is being carried out at present, with indications of success.

4.2 Running Cost Comparisons versus Invar Tooling

Table 4 lists the estimated savings in running costs of the new tooling compared to the running costs of Invar tooling, both in an oven and in an autoclave, for a 16.0 square metre tool size. The following assumptions were made in the calculations:

- Ceramic tooling will use approx. 10-12 KW/sq.m of surface x 2 hours of full power during process, e.g. for 16 sq.m tool, usage will be $12 \times 2 \times 16 = 384$ KW.hrs.
- A 16 sq.m Invar tool in an oven would use approx. 350KW x 3 hours = 1050 KW.hrs
- A 16 sq.m Invar tool in an autoclave would use approx. 500KW x 3 hours of full power = 1500 KW.hrs

The total amount of energy used per cure cycle is substantially less than that in an oven (63% less) or autoclave (85% less), yielding lower costs and environmental benefits with each cure cycle.

Table 4. Running costs of electrically-heated ceramic tooling compared to other solutions

Tool Size (Sq.m)	Electric Units required to run New Tooling (KW.hrs)	Electric Units required to run Invar Tooling in an Oven (KW.hrs)	Saving over Invar Tooling + Oven	Electric Units required to run Invar Tooling in an Autoclave (KW.hrs)	Saving over Invar + Autoclave
16	384	1,050	63%	1,500	85%

5. CONCLUSIONS

A novel tooling solution for out-of-autoclave processing of both thermoset and thermoplastic composites has been presented. The tooling is a ceramic cement material, reinforced with a carbon-fabric thermoplastic composite, and heated electrically with embedded electrical heating tape. The tooling is lightweight, strong and durable, with low coefficients of thermal expansion in the plane of the tool, and is capable of being heated to 200°C in less than 10 minutes. Special surface sealing and repair solutions have been developed to make the tool surface sufficiently vacuum tight.

Though the ceramic is heat stable to 1000°C, the expected upper temperature limit of the tooling is governed by the thermoplastic polymer used to bind the reinforcing fibres to the ceramic cement. In the case of a carbon fibre/PEEK reinforcement, the tooling has an expected upper temperature limit of approximately 300°C.

The new tooling technology has been used to successfully manufacture a 12.6 metre wind turbine blade in an in-situ polymerized glass/PBT material, and in a “VOC-free” glass-fibre epoxy material, both processed at temperatures around 200°C. Advantages of the tooling for large composite structures such as wind turbine blades include reduced process cycle times, and labour content, as well as “one-shot” manufacturing of the blades. Finally, an aerospace 180°C-cure carbon-fibre/epoxy prepreg was successfully manufactured on a section of the tooling.

Economic comparisons with aerospace-standard Invar metal tooling indicate that capital investment savings of up to 85% could be envisaged when compared with autoclave processing, and up to 65% when compared to oven processing. Running costs in terms of energy usage are also predicted to be in the order of 65-85% compared to ovens and autoclaves.

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