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Abstract

The performances of Cage System® and 3iTech® moulds designed by Roctool for the thermo-compression moulding of high temperature composites have been investigated and compared to a conventional hot press equipped with cartridge heaters. The Cage System® technology demonstrated its capacity to achieve rapid temperature cycles with heating and cooling rates higher than 200°C.min^{-1}, while allowing significant electricity energy saving. However, this heating technology induces critical thermal deformation of the moulding surfaces at high temperature. Advanced design is thus required for obtaining high thermal homogeneity and for satisfying dimensional accuracy of structural composites. As for the 3iTech® technology, the studied mould exhibited higher thermal performances than a conventional press with a heating rate up to 40°C.min^{-1} and a temperature homogeneity on the moulding surface lower than 10°C. Moreover, the carbon/PEEK laminate fabricated with this mould satisfied the dimensional tolerance for aerospace applications and therefore represent an interesting alternative to conventional heating systems.

Keywords

Thermoplastic composites, thermo-compression moulding, induction heating, hot press

Introduction

Hot press compression moulding has been used for many decades for the fabrication of thermoset and thermoplastic composites parts, in particular for Bulk Moulding Compound (BMC) or Sheet Moulding Compound (SMC) [1-2]. This composite manufacturing route is actually an attractive solution for high-volume production, as it allows obtaining good surface finish, gives flexibility in part design, reduces raw material wastage, and satisfies dimensional accuracy. Moreover, although the initial capital investment is relatively high, thermo-compression moulding presses have interesting cost/performance characteristics, as they require low maintenance.

Hot press compression moulding is also the most common way of manufacturing long fibre reinforced thermoplastic composites. Indeed, due to the high viscosity of thermoplastic resins, bulk consolidation of thermoplastic composites requires the application of both high temperature and high pressure and hot presses are efficient for enabling the resin to flow into and around fibre bundles [3,4]. And although many efforts have been devoted to the development of complex semi-finished products to enhance the availability of the resin to the fibre surface [5,6], autoclave and fibre tape placement processes are still limited to the consolidation of prepreg tapes: tapes are already well impregnated and consolidation then mainly consists in enhancing the intimate contact between the plies [3,7,8].

Whether a hot press is used as a stamping unit or for the direct consolidation of thermoplastic semi-finished products, heat of press platens is generally supplied by integrated heating systems working on the principle of resistive heating according to Joule's first law. Steam, oil or hot water systems are actually limited to applications where severe heating and cooling cycles are not experienced [9], and resistive cartridge elements regularly distributed in the platens are thus preferred for thermoplastic composites manufacturing.

The main advantage of electric cartridges among the various heating solutions is the possibility to control the temperature of the platens by a multi-zones regulation. It consists in dividing the platens into different areas containing one or several heating devices. The heaters of each zone are individually switched on or off by a temperature controller after comparing the pre-set target temperature with the actual temperature recorded by a temperature sensor in the zone. Resistive heating is thus an efficient technology when temperature uniformity is critical. However, this technology does not allow achieving a higher heating rate than 10°C per minute, which represents a strong restriction of the production rate of long fibre-reinforced thermoplastic composites for which large temperature amplitude is required during the manufacturing cycle.

This drawback of conventional hot presses is one of the main factors that explain the slow growth of thermoplastic composites applications in the aerospace or automotive industry. And consequently, the development of several innovative out-of-autoclave processes has been encouraged in the last decade with aim of increasing heating and cooling rates [9-11]. Among them, the two inductive moulding systems developed by Roctool, namely the Cage System® (CS) and 3iTech® (3iT) technologies, have already proved their efficiency with engineering matrices (PP, PA) [12-14]. However, even if these technologies are attractive solutions for the reduction of the total processing time, their efficiencies for high performances thermoplastic composites manufacturing have never been demonstrated.

The aim of this study was therefore to analyse the capabilities and limitations of two induction-heated moulds dedicated to the consolidation of high-temperature thermoplastic laminates. The CS and 3iT moulds have been designed respectively in 2009 and 2012 for high temperature processing, and this study then represent an inventory of these technologies that must be balanced as regards to Roctool's know-how at this time.

For matter of comparison, the performances of a conventional hot press are first analysed by means of the process data recorded during the consolidation of carbon/PEEK prepregs. The CS and 3iT moulds used in this study are then described, with a particular focus on heating and cooling performances, temperature uniformity and dimensional accuracy. The performances of both systems for the fast consolidation of carbon/PEEK composites are finally discussed.

Conventional hot press

Technology

The conventional hot press used as reference of comparison in this study is a fully automatic hydraulic lab press specially designed by Pinette Emidecau Industries (PEI) for high temperature composite manufacturing. The press is equipped with cartridge-heated platens of 700x700mm^2 that allow applying a process temperature up to 450°C, and has a maximum clamping force of 750kN.

All electric cartridges represent a total heating power of 65kW which allows heating the platens with a maximum heating rate of 10°C.min^{-1} according to the technical data sheet. A rough estimation of electricity consumption was calculated considering that 80% of the power of all cartridges is required during a heating ramp at maximum rate. Reaching a platen temperature of 400°C, i.e. typical processing temperature for Carbon/PEEK composites, was estimated to 40kWh of electric power.

As for cooling, it is achieved by pumping pressurized air and water through parallel cooling channels drilled in press platens, and the temperature control is assured by the simultaneous regulation of electric cartridges. The configuration of the press platens enables controlled cooling rate of -15°C.min^{-1} above 300°C and -10°C.min^{-1} between 300°C and 180°C.

For thermal regulation purpose, each platen is divided into 9 zones individually controlled by a digital temperature regulator. Platens temperature is monitored by thermocouples located in the centre of each zone. As mentioned in the technical data sheet of the press, the temperature homogeneity has been measured with temperature sensors regularly distributed at the surface of the platens, 50mm far from the borders of the heating platens. The measurements showed that temperature uncertainty was +/-5°C at 400°C and +/-2.5°C at 200°C after 15min of stabilisation.

Material and processing conditions

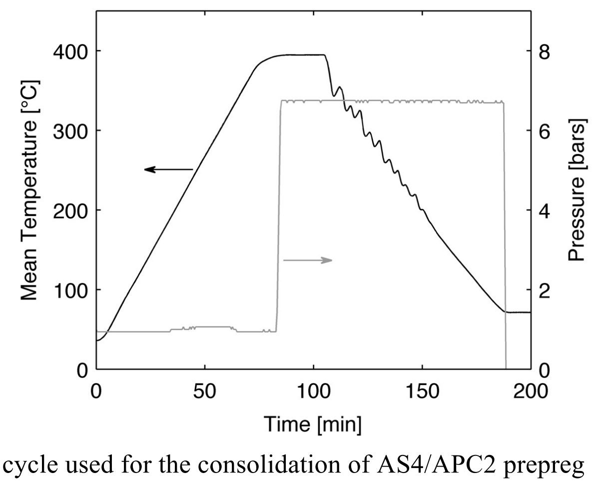

Figure 1 - Processing cycle used for the consolidation of AS4/APC2 prepreg in conventional hot press

In order to assess the actual hot press performances, the temperature recorded in each zone during the consolidation of a 400x400mm^2 carbon/PEEK laminate was analysed. The composite was made with 40 plies of Cytek AS4/APC-2 prepreg using a picture frame ([90/+45/0/-45]$_{5S}$ stacking sequence). A conventional processing cycle was used for the fabrication of the laminate, i.e. a heating rate of 5°C.min^{-1} under a pressure of 1bar, 35min isotherm at 395°C under a pressure of 7bars and a cooling stage at 4°C.min^{-1}. The actual processing cycle applied during consolidation is shown in Figure 1. The consolidation pressure is calculated from the applied force and the displayed temperature corresponds to the average temperature of all zones of top and bottom platens.

Thermal homogeneity

Figure 2 displays the temperature in each zone of the bottom press platen and the maximum temperature amplitude recorded during the entire processing cycle. The recorded data clearly demonstrate the capability of resistive cartridges for controlling temperature homogeneity when regulation only deals with heating: the ramp up is perfectly linear and the temperature gradient is less than 2°C until the end of isotherm. Inertia of resistive heating is however observable when changing from the heating step to the isotherm one, although it has no influence on temperature amplitude of the moulding surfaces.

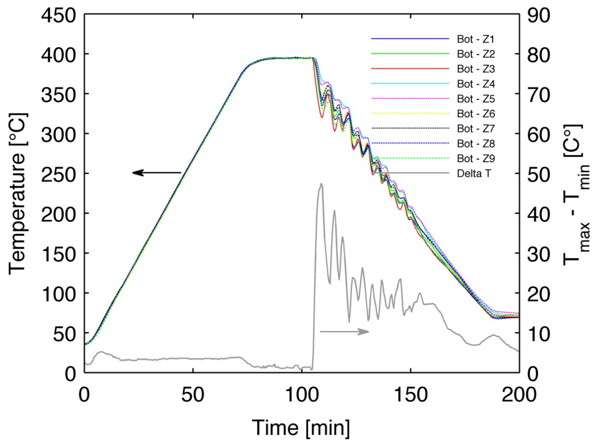

Figure 2 – Temperature recorded in each of the 9 zones of the bottom part of the moulding surface by the thermocouples sensors used for thermal regulation of press platens, and maximum temperature difference at the surface of the moulding surface of a hot press during consolidation of a C/PEEK laminate.

Contrary to heating, the cooling stage is highly irregular. The overall cooling stage actually complies with the set cooling rate, but the temperature decrease is characterized by regularly spaced temperature fluctuations that progressively disappear below 200°C. These fluctuations are the consequence of a too strong heat transfer at high temperature between the mould and the coolant fluid in cooling channels. When temperature is too low below the set temperature, the temperature controllers switch the heaters on in order to counterbalance the rapid decrease of temperature. These fluctuations appear periodically every 5 minutes during the cooling stage, which surely depend on the cooling rate setting, the design and the inertia of the cooling system as well as on the PID parameters of the temperature controllers.

The temperature oscillations during the cooling phase also induce a large temperature disparity in the press platens. The temperature amplitude is 50°C at the beginning of cooling (395°C) and slowly decreases to 10°C at demoulding temperature.

The fluctuations of temperature during cooling make difficult the control of solidification mechanisms in thermoplastic matrix composites, in particular when semi-crystalline polymers are involved. Prediction of process-induced residual stresses or degree of crystallinity is therefore complex and assessment of in-service performances of thermoplastic composites then requires composite properties to be experimentally identified after manufacturing. This is particularly true for polymers which crystallisation kinetic is highly sensitive to cooling conditions.

Dimensional stability

Likewise thermal homogeneity ensures a homogeneous molten state during consolidation, the dimensional stability of the mould is a critical parameter in hot press manufacturing as it governs the pressure homogeneity during impregnation and the dimensional accuracy of composite parts for later assembly operations.

Planarity and smoothness of hot platens usually amount to less than +/–0.1mm, and when settled in hot presses, the parallelism is generally ensured to be lower than +/-0.1mm. In the present case, because of the reasonable platen size, the press specifications are even better with a planarity and a parallelism lower than +/- 0.05mm. The geometrical accuracy of press platens at room temperature is however not the key factor for high quality composite manufacturing.

The dimensional accuracy of composite parts actually strongly depends on the mould deformation during matrix solidification, i.e. during matrix crystallization and/or at glass transition temperature. This deformation results on one hand from the thermal expansion of hot parts and on the other hand from their deformation under the stroke force. Measurement of mould dimensions during a thermal cycle is anyway challenging at high temperature and moreover, it would not give direct indications about the quality of composite parts. For this reasons, it was decided to use the thickness of the processed carbon/PEEK composite as an indicator of performance of cartridge heating technology on dimensional tolerances.

Measurements performed with a micrometre in many locations of the flat laminate show that the thickness of the 400x400mm^2 carbon/PEEK plate is 5.1mm +/-0.1mm, with randomly distributed thickness variations. This dimensional stability complies with standards of aerospace industry for structure applications and ensures obtaining high mechanical performances when optimal impregnation of fibre bundles is achieved. The Figure 3, that shows a representative micrograph of the as manufactured laminate, also demonstrates the high accuracy of hot platens: after consolidation, the initial pre-impregnated tapes remained perfectly flat and inter-ply planes are parallel.

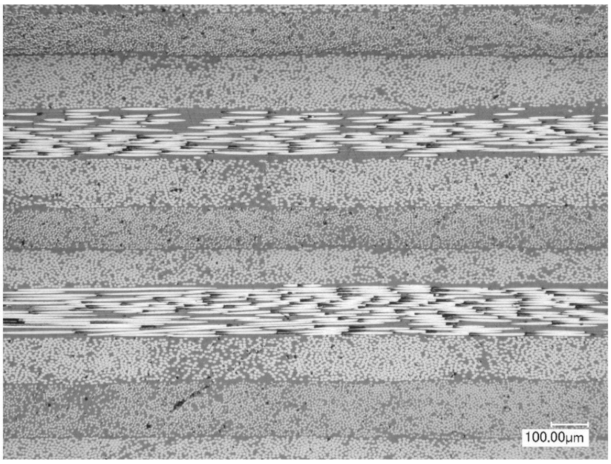

Figure 3 - Microstructure of C/PEEK composite manufactured from prepreg tapes with a conventional hot press

Induction heated moulds

The performances of Roctool's CS and 3iT technologies for the manufacturing of high-performance thermoplastic composites were assessed by analysing the in-service behaviour of two moulds dedicated to the fabrication of flat composite laminates. Both moulds are comparable as they both have a moulding surface of 400x400mm^2 and were used in the same environment (press, induction generator and cooling system).

Cage System® induction heated mould

Figure 4 – Cage System® induction heated mould

As shown in Figure 4, the CS mould used in this comparative study is composed of two 500x500x80mm^3 metallic blocks made of high permeability steel, and a 7-turn inductor coil positioned in two halves outside of the mould and shielded by the mould itself. When the mould is closed, both parts of the coil are electrically connected and form a solenoid. Then, when the induction generator supplies the high-frequency electrical power, the magnetic field induces alternative Eddy currents at the surface of the tool and generates the rapid heating of mould surface by Joule effect. In the present case, the inductive configuration was designed for moulding composite laminates of 400x400mm^2 at a temperature up to 450°C.

Because of the induced electric currents, risk of short-circuit between the two moulding surfaces exists. A ceramic layer had been coated on the mould surfaces, that makes it possible to process carbon-reinforced composites. However, this technology prevents the use of highly electrically conductive materials that would create a conductive contact between the two faces, like additional picture frames, inserts or stop blocks/shims made of metal.

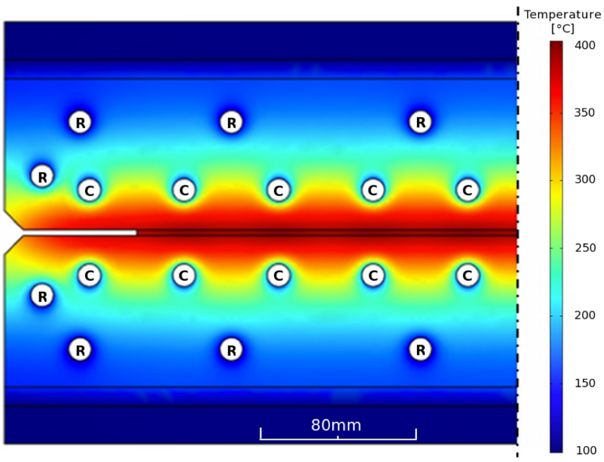

Figure 5 – Simulated temperature distribution through mould thickness after 170s of induction heating at maximum generator power (200kW) and 60s of temperature stabilization. C and R refer respectively to cooling channels and regulation channels.

As the moulding parts are free from any heating device, two rows of 10mm diameter cooling channels could be drilled through the steel blocks (Figure 5). The channels close to the moulding surface (C in Figure 5) correspond to the cooling channels. These 2x10 channels are used when fast cooling is desired and must be purged before heating. To the contrary, on the opposite side of the mould blocks, 2x8 channels, called regulation channels (R in Figure 5), are used during heating to create a thermal barrier and protect the press from the heat of the mould.

The simultaneous water flow in regulation channels and induction heating at moulding surface create a large thermal gradient through mould thickness (Figure 5). Therefore, although the efficiency of induction heating is 80-90%, heat exchange in regulation channels decreases the energy efficiency of this technology. Nevertheless, the regulation channels can be used for monitoring relatively slow cooling rates and yet allow achieving complex temperature cycles for dynamic control of processing conditions (for instance heating-cooling-heating cycles).

Mould with 3iTech® heating technology

Contrary to CS technology that directly heats the moulding surface, in 3iT systems, the induction heating is produced in inductive channels machined in the mould block, by means of a continuous inductor placed in this inductor network. The 3iT heating system then preferably heats the moulding surface by a conductive effect. With this technology, the risk of an electrical short-circuit between different parts of the tool is totally avoided.

The 3iT induction heated mould used in this study is shown in Figure 6. It features a moulding surface of 400x400mm^2 with an integrated picture frame. The inductor used is a copper braid of about 10mm diameter insulated by two insulating braids (inserted picture in Figure 6) that fit with the diameter of the inductive channels in order to optimize the inductive output. As shown in Figure 7, the inductive network (I in Figure 7) is formed of a single raw of 12 regularly spaced parallel inductive channels drilled at half height of each mould block. As for the cooling network, it is formed of two rows of 10mm diameter channels on either side of the inductive channels and machined perpendicular to the latter (C in Figure 7).

Thermal regulation of the mould bases is also required in 3iT technology to prevent damaging of the press. A row of 8 regulation channels machined in each mould base must be feed with a heat fluid during induction heating (R in Figure 7).

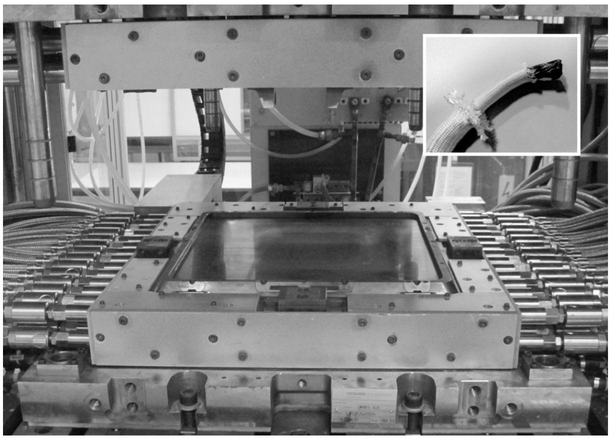

Figure 6 – 3iTech® induction heated die and copper braided wire inductor

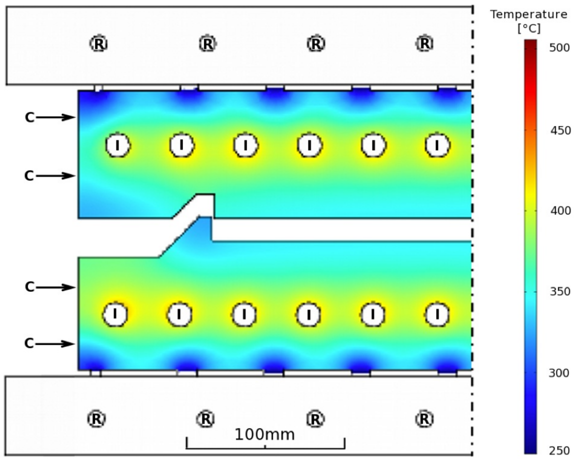

Figure 7 - Simulated temperature distribution through mould thickness after 360s of induction heating at maximum generator power (200kW) and 40s of temperature stabilization. C, R and I refer respectively to cooling, regulation and inductor channels.

The main difference with CS technology is that 3iT heats the entire moulding blocks (Figure 7), and heat loss is therefore a critical issue when designing 3iT moulds. Thermal bridges between the mould and other surrounding parts, in particular the mould bases, are thus reduced to a minimum and all non-moulding surfaces are covered with insulating material to limit convective heat loss. In return, the efficient insulation of the mould requires the use of the cooling system to decrease the temperature of the moulding surface, whatever the expected cooling rate. Consequently, as the cooling channels must be purged before heating to prevent steam pressure issues, it limits the possibilities of applying complex thermal cycles including heating or isotherm steps after cooling phases.

Pilot plant description

Contrary to conventional hot press, induction-heating technologies are build-in solutions in which the heating technology and the cooling system are included in the tool. The thermo-compression unit used in this study to assess the performances of CS and 3iT moulds was thus build around the moulds (Figure 8).

The moulds were installed in an instrumented vertical hydraulic compression press of a capacity of 1000kN. The press used is special in that the applied force is not controlled by the hydraulic pressure, but with a load sensor located in the nose of the press actuator like in tensile test machines. Moreover, press speed and position are monitored thanks to a LVDT sensor, which gives additional information to analyse the processing behaviour.

The heating system, regardless the inductor in the mould, consists of a 200kW medium-frequency induction generator and its capacity matching box. The power of the induction generator was selected according to the size of the moulding area (400x400mm^2) and the expected heating rate, although this latter also depends on the inductive technology used. Heating and temperature regulation are performed with a temperature controller that collect the mould temperature from a thermocouple sensor in the mould. In each mould, the sensor is located a few millimetres below the moulding surface in the middle of the bottom part of the mould.

A water-cooling unit was specifically designed for achieving fast cooling cycles whatever the processing temperature: the cooling unit can deliver regulated cold water at a flow rate of 150 l.min^{-1} at anytime of a cycle. This cooling capacity is obtained by using a 1m^3 buffer tank between the factory and the mould cooling systems and a heat exchanger of 200kW capacity. Moreover, for the purpose of cooling monitoring, distribution feeders with solenoid valves control the flow rate in the cooling channels and allow switching the water circulation from regulation channels to the cooling network.

Finally, all the equipment is controlled from an operating panel that coordinates the actions and centralizes the data from all plant, in particular mould temperatures, platen displacement and applied press load.

Figure 8 – Thermo-compression pilot plant with induction-heated mould

Capabilities and Limitations of induction technologies

Heating and cooling performances

The maximum heating and cooling performances of CS mould are depicted in Figure 9. They were obtained by continuously supplying the 200kW electrical power to the inductor in the heating phase and by using the maximum water flow during cooling. As shown in Figure 9, a processing temperature of 400°C can be reached within 3 minutes with a heating rate decreasing progressively from 270°C.min^{-1} to 85°C.min^{-1}. The 2min30s at maximum power that are required to heat the mould up to 400°C represent an electricity consumption of about 9kWh, which is far less than the consumption of a conventional hot press.

The maximum water flow rate allows applying cooling rates high enough to quench a thermoplastic matrix. For instance, a PEEK matrix processed at 400°C can be cooled below the glass transition in less than two minutes. Moreover, in CS technology, the thermal heat is concentrated in the skin of the mould and the thermal inertia of CS moulds is therefore particularly low. This low inertia is clearly observable by the absence of overshoot at the end of heating and by the prompt drop of mould temperature at the end of isotherm.

The performances of the pilot plant with the 3iT mould are shown in Figure 10. During the heating phase, as this technology requires the entire moulding blocks to be heated, the temperature rate is drastically decreased compared to CS. The 200kW generator output only allows a heating rate of 40°C.min^{-1}, which is nevertheless four times faster than with a conventional hot press. Also, the 9min30s of heating here represent an electricity consumption of about 32kWh, which is comparable to the consumption of a conventional hot press.

The Figure 10 also shows that cooling of 3iT mould can be highly efficient with a rate of 80°C.min^{-1} despite the high quantity of energy that the hot moulding blocks represent. This performance is significantly higher than what can be applied with a conventional press, although it is lower than with CS technology. However, contrary to the CS mould, the cooling rate was not obtained with the total capacity of the cooling unit but with a water flow rate of 20L.min^{-1}, i.e. less than 15% of the unit capacity. Faster cooling cycles can be achieved but it was limited in this study to preserve the cooling system: the cooling performance results from the highly energetic transformation of liquid water into superheated steam, and thermal fatigue and pressure issues may be critical for higher flow rates.

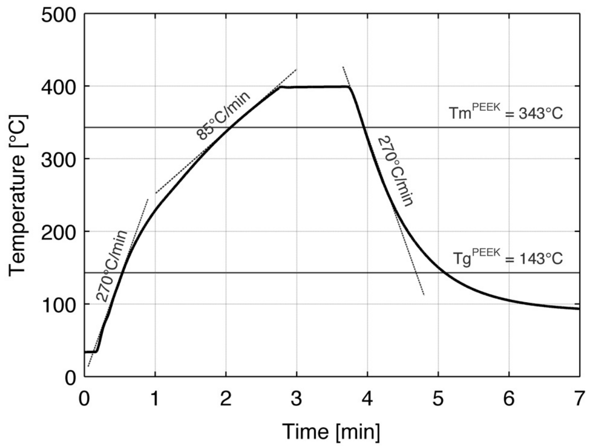

Figure 9 – Maximum heating and cooling rates allowed by the Cage System® technology

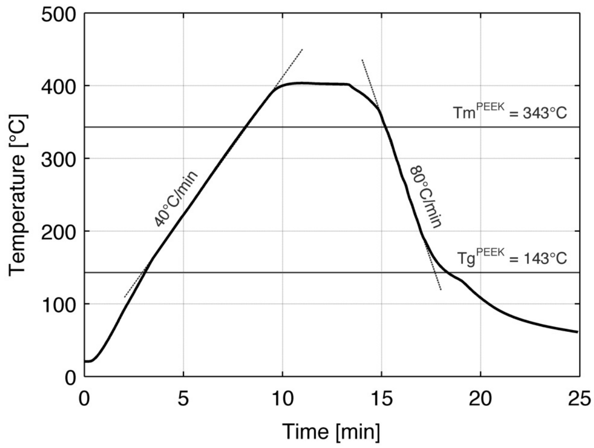

Figure 10 - Maximum heating and cooling rates allowed by the 3iTech® technology

Thermal homogeneity

As there is only one and unique heating system for the entire moulding surface, heating and cooling rate performances of inductive technologies must be analysed considering the thermal homogeneity of the moulding surface.

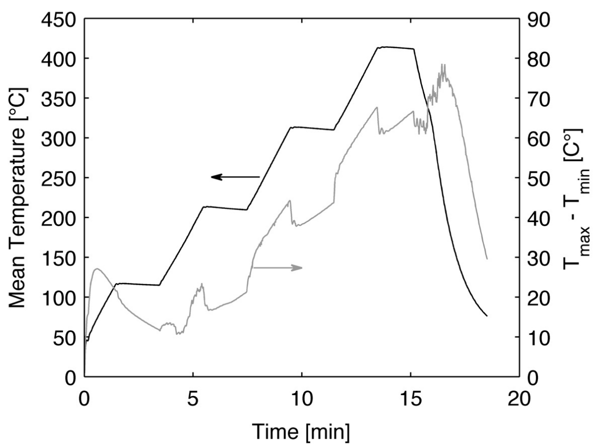

Figure 11 – Mean temperature and maximum temperature difference at the surface of the moulding surface of Cage System® mould. Temperature recorded at the surface of the bottom part of the mould by 27 thermocouples regularly distributed on the tool's surface.

In order to quantify the thermal homogeneity of the CS mould, 27 thermocouples were placed at the surface of the bottom part of the mould. They were positioned in three parallel lines of nine thermocouples perpendicular to the cooling channels direction so as to characterize a representative moulding area of

300x360mm^2 (width x depth). The temperature data were recorded using a Pico USB TC-08 Thermocouple Data Logger during a thermal cycle consisting first in a heating phase at 50°C.min^{-1} until 400°C interrupted by 2min isotherm every 100°C and then in a cooling phase at maximum rate.

The mean temperature and maximum temperature difference recorded during the test are displayed in Figure 11. The results show that the temperature heterogeneity is all the more large that the mould temperature is high: the temperature difference increases from 10 to 60°C when the mould temperature is heated from 100°C to 400°C. These temperature gradients however also depend on the heating conditions as switching from heating ramps to isotherms favours homogeneity.

The Figure 12 gives details of the temperature gradients in the moulding area during representative phases of the thermal cycle: at the end of heating when the generator supplies high electric power, and during the cooling phase. In both conditions, the temperature gradients exhibit a thermal imbalance between the centre of the moulding surface and the front and back edges of the mould. The cold area close to the edges is due to the systematic water circulation in either the cooling or regulation channels that are close to the surface in this zone (Figure 5). The temperature field at the end of heating (Figure 12a) also exhibits a thermal imbalance between the left and right parts of the mould caused by the solenoid dissymmetry. During cooling (Figure 12b), although the front and back gradient remains critical, the lateral dissymmetry is largely decreased.

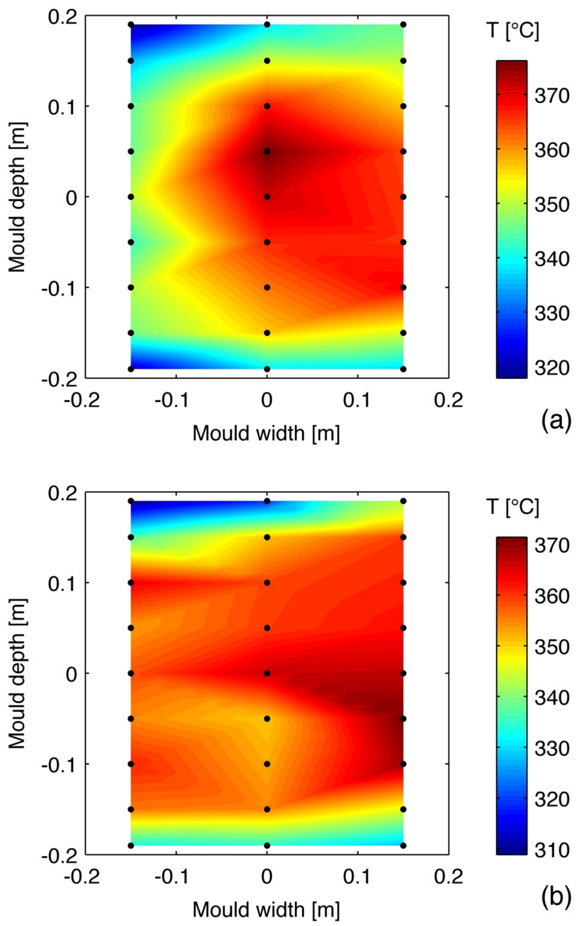

Figure 12 – Interpolated temperature fields at the surface of CS mould at the end of heating (a) and during cooling (b). Black dots illustrate the thermocouples location during the test.

A similar study was achieved on the 3iT mould with 21 thermocouples homogeneously distributed on the moulding surface 15mm far from the edges. The temperature recorded during a conventional processing cycle at 250°C is shown in Figure 13.

During the heating phase, the temperature gradient in the mould is less than 10°C and remains lower than 10°C during the temperature stabilization. This thermal homogeneity is obtained thanks to preferentially conductive heating from inductive channels to the moulding surface. This gradient increases during the cooling phase especially over the first minutes with a maximum of 25°C. This heterogeneity is due to the temperature difference between cold inlets and hot outlets of the cooling system, but no specific temperature pattern could be identified.

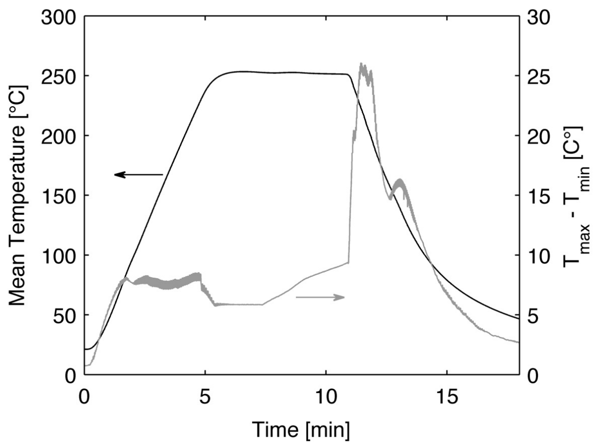

Figure 13 – Mean temperature and maximum temperature difference at the surface of the moulding surface of 3iTech® mould. Temperature recorded at the surface of the bottom part of the mould by 21 thermocouples regularly distributed on the tool's surface.

Dimensional Stability

As for the hot press, the dimensional performances of the CS and 3iT moulds for the fabrication of high-temperature thermoplastic composites were assessed by means of composite panels fabricated with the moulds. Carbon/PEEK laminates were thus manufactured with both technologies using similar processing conditions. The laminates were made with 6 plies of 2-faces powdered carbon fabric provided by Porcher Composites (Pi-Preg®). The material used was a 3k carbon 5H Satin fabric of 285g.m^{-2} areal weight covered with 200g.m^{-2} of PEEK powder, which corresponds to a fibre volume ratio of 50% in the prepreg.

Figure 14 shows the processing conditions used for the consolidation of a 300x300mm^2 laminate in the CS mould. The consolidation was performed under a pressure of 10 bars during 10min at 395°C, and the heating and cooling rates were respectively 50°C.min^{-1} and 20°C.min^{-1}. Moreover, neither stop block nor picture frame was used for the fabrication of the laminate.

The press platen position was recorded during the test, which allows following the consolidation kinetic afterwards. As shown in Figure 14, the platen position increases during the heating step because of the thermal expansion of both the mould and the material: in order to keep a constant force during heating, the press platen moved up until the PEEK matrix is molten and becomes viscous. Then, the application of the consolidation pressure startes the impregnation process: the prepreg stack thickness decreases and stabilises when consolidation is globally achieved. After cooling, the final position of press platen is lower than the position at the beginning of the trial. The position difference corresponds to the total reduction of the stack thickness.

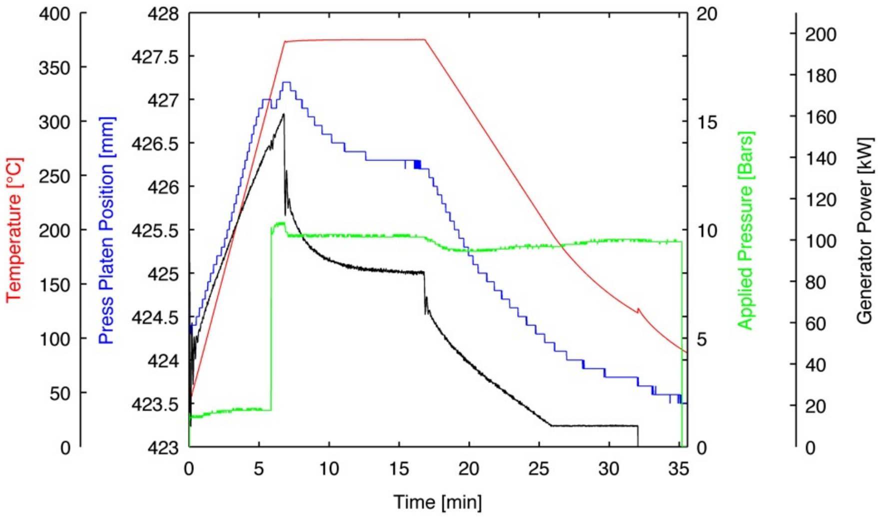

Figure 14 - Processing cycle used for the consolidation of powdered carbon/PEEK prepregs with the Cage System® technology

After manufacturing, the laminate thickness was measured with a micrometre and the microstructure of the composite was investigated in many locations (Figure 15). The thickness measurements show that the mean laminate thickness is 1.8mm, which is in good agreement with the nominal thickness of the prepreg ply that is 0.3mm. However, the laminate exhibits a critical gradient with a minimum thickness in the middle of the laminate and a maximum thickness in the plate corners. The final variability is +/- 0.3mm, which is far too much according to the aeronautical specifications for structural composite parts.

The investigation of the resulting composite microstructure also leads to the distinction of three different concentric areas. In the middle of the laminate (3), macro-porosities (0.5mm) can be observed between the carbon yarns while the fibre bundles are well impregnated. Between 50mm and 100mm from the laminate centre (2), the composite is fully impregnated and only a few micro-porosities remain visible around the carbon filaments. And finally, outside this central area of 200mm diameter (1), the microstructure is characterized by poor impregnation: the core of fibre bundles lacks of impregnation while all the space between the yarns is filled with PEEK matrix.

The apparition of these porosities and thickness gradients is the consequence of differential thermal deformation of the mould during the consolidation. Indeed, the large thermal gradient through the mould thickness causes a convex curvature of both moulding blocks, and therefore induces an increasing gap distance from the middle to the edges of the mould.

As a consequence, the pressure distribution during manufacturing is heterogeneous on the stack and the periphery lacks of pressure for achieving complete impregnation. The resulting microstructure close to the edges (3) is thus similar to what has already been observed in film stacking configurations when a low pressure is applied [15]. In the centre of the laminate, the apparition of large porosities may result from a different mechanism. At the end of isotherm, thanks to the high pressure applied in this area, consolidation is likely totally achieved and matrix even squeezed towards the periphery. The macro-porosities are thus probably created during the cooling step, as a result of the mould contraction: the loss of mould curvature during cooling may lead to the composite deconsolidation before the matrix solidification, which has been observed as a source of macro-porosities in rich matrix zones [16-17].

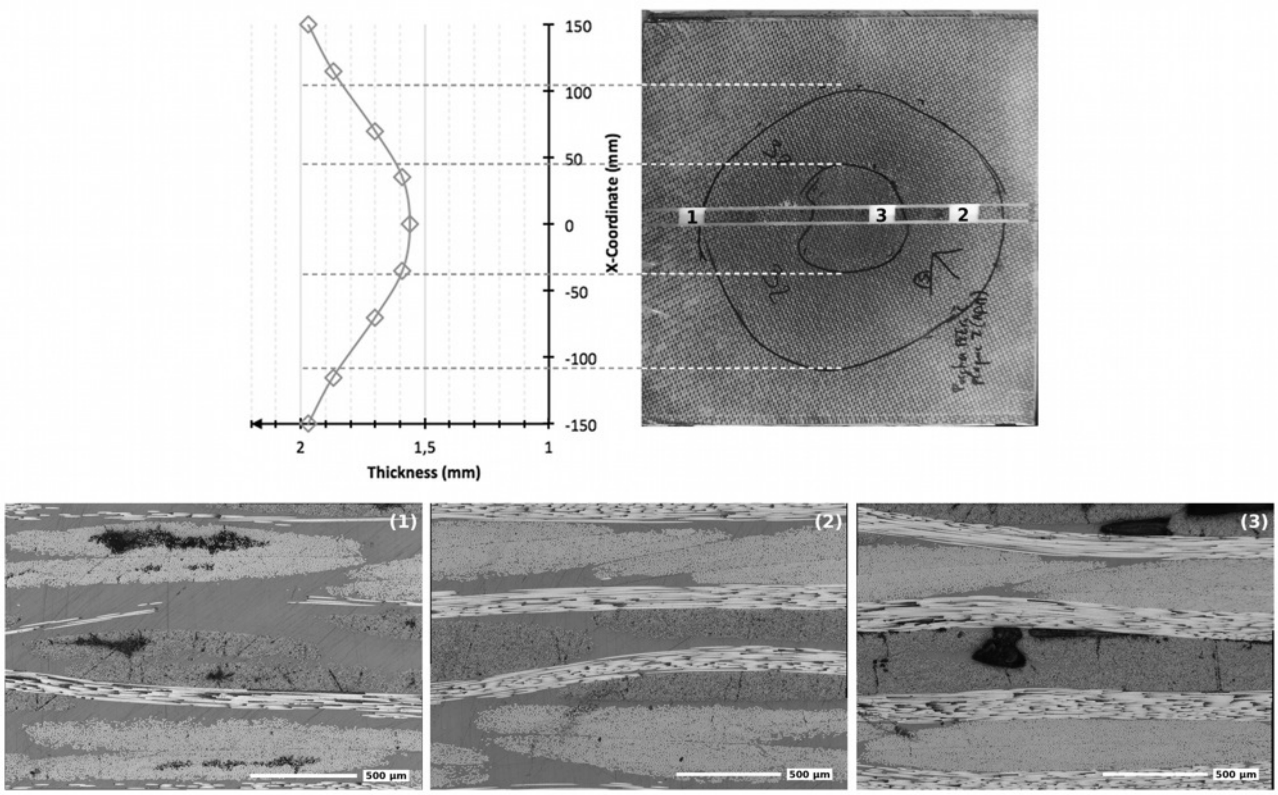

Figure 15 – Thickness distribution and morphology of a C/PEEK laminate made from powdered prepregs after consolidation with Cage System® technology.

As shown in Figure 16, similar processing conditions were applied in the 3iT mould for the consolidation of a 6 plies stack of 300x300mm^2 carbon/PEEK prepreg: 10min at 390°C under 12bars. Both the heating rate above the melting temperature and cooling rate until PEEK glass transition at 143°C were approximately 40°C.min^{-1}. After processing, the laminate was analysed in term of microstructure and thickness homogeneity, like the one fabricated with the CS technology.

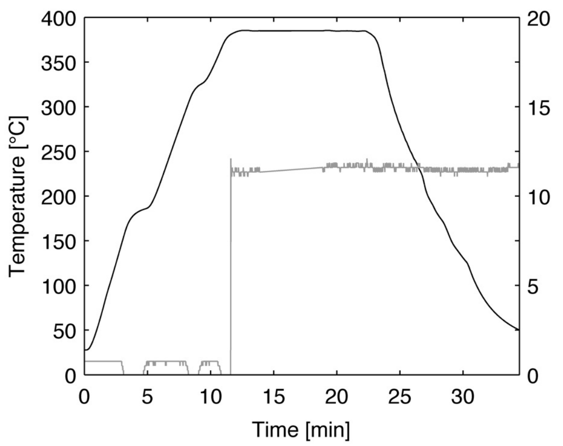

Figure 16 - Processing cycle used for the consolidation of powdered prepreg in the 3iTech® mould

Like for the CS laminate, the composite microstructure was investigated in different locations in the panel. And contrary to the laminate made in the CS mould, the microstructure of the composite panel fabricated in the 3iT mould is identical whatever the sample (Figure 17): the fibre bundles are fully impregnated and only few micro-porosities can be observed around carbon filaments.

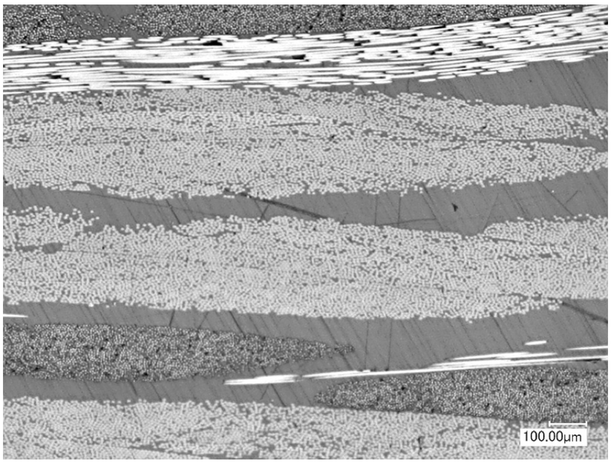

Figure 17 – Microstructure of C/PEEK composite fabricated from powdered prepreg and manufactured with 3iTech® technology

Thickness measurements with a micrometre lead for the 3iT laminate to a constant thickness of 1.8mm, which agrees with the nominal ply thickness. The micrometre technique is however deficient for identifying an effect of the inductive technology and ultrasound time of flight method was thus used to characterise the thickness distribution over the entire surface of the 300x300mm^2 panel (Figure 18). This sensitive measurement technique confirms the mean laminate thickness, but it also highlights a specific pattern of thickness distribution in the laminate.

The laminate part consolidated in the rear side of the mould indeed exhibits a lower thickness than the rest of the laminate. The thickness variability is however only +/-0.1mm and confirms the consistency of impregnation in the laminate as well as it satisfies aeronautical specifications.

Like in the CS mould, the slight variation of laminate thickness is likely caused by a different thermal expansion in the rear part of the 3iT mould. The dissymmetry of the inductor network in this area is then probably the cause of a locally different thermal deformation in the mould at high temperature. Part of the inductor network indeed follows the back side of the mould until the outlet box protecting the electric connectors.

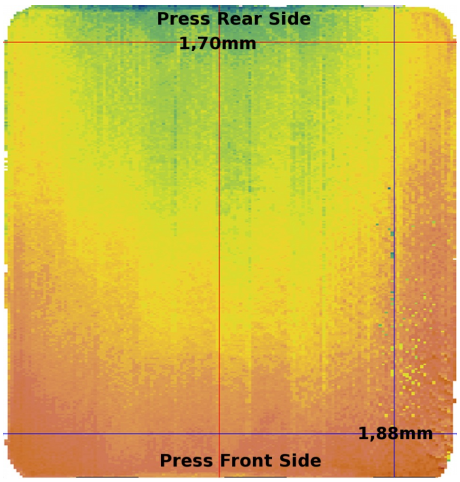

Figure 18 – Thickness distribution of a 300x300mm^2 C/PEEK laminate manufactured with 3iTech® technology from powdered prepreg

Discussion

Conventional hot press technology is a reference process for the fabrication of high temperature thermoplastic composite parts as it complies with quality standards of the aerospace industry in terms of dimensional accuracy and thermal homogeneity. The main drawback of this process is however the thermal inertia of the resistive heating platens. Indeed, although cartridge heaters allow achieving homogeneous heating thanks to individual zoning regulation, platens heating rates are limited to 10°C.min^{-1}. Moreover, the simultaneous use of the air-water cooling system with these heating devices induces imperfect control of cooling rates that may be critical for the prediction of final composite properties.

The comparison with inductive technologies for high temperature composite manufacturing shows that induction heating is an attractive solution for the reduction of the processing time. Both CS and 3iT technologies allow applying high heating rates, and as the heating phase can represent a large part of the total processing time, these processes offer new possibilities for the optimization of thermoplastic composite manufacturing as well as thermoset composite curing. Moreover, inductive technologies allow significant reduction of electricity consumption, in particular the CS system. The use of induction heating is therefore an interesting way for reducing the manufacturing cost of a composite part.

The use of heating rates higher than 200°C.min^{-1} nevertheless requires particular attention to be paid to the through-the-thickness thermal homogeneity of the processed material. While conventional processes allow considering the material as thermally homogeneous during manufacturing, this is no longer the case in a thick composite stack of low thermal conductivity.

Although inductive technologies demonstrated their efficiency for achieving fast heating, they exhibit some critical drawbacks inherent to the use of induction heating. Induction process generates localized heating and in the case of CS technology, non-uniform thermal expansion that may cause unacceptable defects in the processed composites is induced. Moreover, one unique heating system is used for the thermal regulation of the CS and 3iT moulds and the thermal behaviour then strongly depends on the initial design of the inductive network whether it is a solenoid or an inductive copper braid.

Because 3iT technology consists in heating the entire moulding blocks, this induction heating system provides an interesting compromise of heating rate and dimensional accuracy. Its performances make it the most versatile mould for composite manufacturing among the three studied technologies, and hence represent an interesting solution for reducing the processing time without decreasing the quality of composite parts.

The thermal inertia of 3iT system and the insulation of all non-moulding surfaces is the main limitation of this moulding technology. The possibility to achieve complex temperature cycles combining heating and cooling steps is limited, and complicates the control of low cooling rates. The simultaneous use of the heating and cooling systems should be avoided in 3iT technology as it would lead to temperature oscillations like in hot press, and would degrade the benefit of induction heating. In order to improve cooling control, one option consists in adjusting the cooling system to the desired processing condition. This can be achieved by modifying the cooling network of the 3iT mould: the fast coupling used for the connexion of the cooling system allow reducing the number of cooling channels or reorganising heat fluid circulation easily, which is usually impossible with the rigid cooling network of conventional hot platens.

Contrary to 3iT and hot press, only the extreme surface of the mould is heated with the CS technology and a fast cooling can therefore be promptly interrupted by an isotherm stage. The CS capability of applying complex cooling paths then offers new options for the optimization of processing cycles. For instance, during the fabrication of thermoplastic composites, the degree of crystallinity of a thermoplastic matrix may be improved by means of an isothermal crystallisation stage while reducing the overall cooling time using a high cooling rate.

Of course, these performances must be balanced as the studied CS and 3iT moulds were respectively designed in 2009 and 2012. Since then, Roctool's know-how has evolved and the better understanding of induction heating as well as composite behaviour (thermal expansion, shrinkage) may have led to more advanced mould design with better homogeneity. In particular, nowadays CS technology can be likely optimized for a specific application, i.e. a specific matrix and a specific part geometry, which would make it a cost effective solution for mass production where the cycle time is crucial. As for the 3iT technology, solutions exist for running multi zone heating. This option is likely to counterbalance moulds dissymmetry for obtaining a homogenous moulding surface temperature.

At last, although the optimisation of the induction network is crucial and may affect the cost of an inductive tool, the final cost of inductive moulds is substantially identical to the cost of a conventional tooling with cartridge heaters, the cost of the inductor being very lower than the cost of cartridge heaters. Therefore, the selection of induction heating technology must be made after analysing the cost-effectiveness of the technology, taking into account the cost of the inductive technology itself, its maintenance, the return on investment in the generator, and the benefit of the expected processing time.

Conclusions

The thermal characterization of the induction technologies designed by Roctool show that induction heating is a promising solution for saving time during the consolidation of high temperature composites, as they allow applying high heating and cooling rates up to 280°C.min^{-1}, while requiring less electrical energy for heating.

Among the two studied technologies, the studied Cage System® mould however exhibits critical drawbacks for high-performance thermoplastic composites manufacturing, which main one is due to differential thermal expansion of the moulding surfaces that cause defects in the processed composite parts. Nevertheless, as Roctool's know-how has evolved since the Cage System® mould was designed; part of its limitations may have been solved. This technology thus represents a particularly interesting solution for mass production.

On the other hand, although heating performances of the 3iTech® technology are lower, this heating system allows obtaining high thermal homogeneity and dimensional accuracy while improving the heating capability compared to a conventional hot press with cartridge heaters. Therefore this is an interesting versatile technology for composite manufacturing.

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