A STUDY ON THE EFFECT OF JOULE-HEATING DURING THE LIQUID COMPOSITE MOLDING (LCM) PROCESS AND ON THE CURING OF CFRP COMPOSITE LAMINATES

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ABSTRACT: Liquid composite moulding and autoclave processes for manufacturing CFRP composites laminates are highly temperature sensitive. So far, this problem was tackled using complex mould setups for resin heating and large ovens for laminate curing. All these procedures are inefficient from an energy point of view and increase total cost. The novel procedure presented in this paper utilizes the material's physical properties and one simple physical phenomenon, carbon-fiber electrical conductivity and Joule-heating respectively. The novel approach of the current work omits the need of external mould heating as it uses the preform itself as the heating element. Three different methods (vacuum bagging, autoclave, SCRIMP) were studied in order to estimate the temperature distribution on rectangular plates made from different type carbon fiber (CF) preforms. For the vacuum bagging and autoclave manufacturing methods, the results of interest concerned the resin curing degree. For the SCRIMP method, not only the curing degree but also the possibility to accelerate resin flow and reduction in the total saturation time were investigated. The mechanical properties of the manufactured laminates are compared to ones manufactured using conventional methods.

KEYWORDS: Joule Heating, LCM Resistive Heating, CFRP electrical conductivity

INTRODUCTION

Carbon fibers are used in many industrial products mainly as a reinforcing material in low weight applications. Several works [1,2,3] have been conducted concerning the use of carbon fibers as heating elements in order to cure prepregs and cure resin in carbon fiber tows. Bending tests [2] on prepreg specimens using the direct heating method have shown a slight reduction of bending strength. DSC tests have shown that the degree of resin curing into CF tows is the same as the conventional methods. On the other hand, [3] has shown that the use of carbon fibers is very energy efficient. As for the use of ovens in order to cure various composite structures it is stated that 70 to 75% of the required energy is used for the heating of the surrounding air and the inside of the oven. Manufacturing open heated moulds for the SCRIMP or single-sided VARTM methods result in increased cost as they require a complex water/oil heating system. CFRP moulds have been recently presented as mould solutions and can be easily heated using their CF reinforcement.

THEORY

In the fiber direction, the resistivity of the composite depends on the resistivity of the fibres (0.9 Ωm - 1.8 Ωm) [5] and on the fibre content. In the transverse direction the current follow a statistical zigzag path across the fibre-fibre contacts [8]. In general, carbon fiber fabrics are strongly anisotropic concerning the electrical conductivity. The electrical conductivity is described as a second order tensor and there is a direct dependence on the fabric architecture, the applied pressure on the surface of the fibers and, therefore, on the fiber volume content. The lesser the fiber content, the lesser the electric conductivity of the material is. Temperature is another parameter that affects the CF resistivity.
An electric field in the presence of a current does mechanical work on the current carrying particles moving in the conductor. The work done per unit time and volume is evidently equal to the scalar product $\vec{J}\cdot\vec{E}$. This work is dissipated into heat in the conductor [6]. Hence the heat equation in the preform is:

$$\rho C_p(T)\frac{\partial T}{\partial t} = \nabla\cdot k\nabla T + \vec{J}\cdot\vec{E} \qquad (1)$$

And the heat equation in 1D problem is:

$$\rho C_p(T)\frac{\partial T}{\partial t} = \nabla\cdot k\nabla T + \frac{J^2}{\sigma} \qquad (2)$$

Where E is the electric field and J is the current density

RESISTIVE HEATING SETUP

In the current method, all types of moulds, metallic or non metallic can be used. As far as metallic moulds are concerned, an electric insulation between the surface of the mold and the CF performs is required and can be achieved by applying a thin wax film or a thin glass fiber fabric.

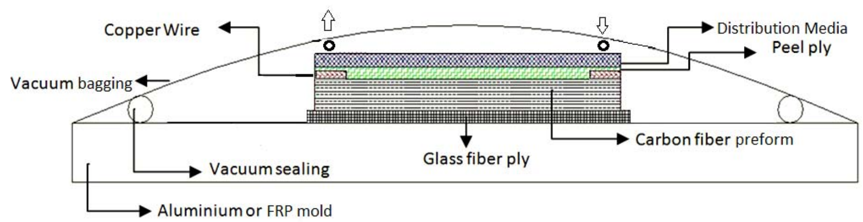

Fig. 1 Setup using the SCRIMP method and Resistive Heating

This method can be applied mainly to geometries with large length-to-width ratios. When the proposed method is applied to single or sandwich parts manufactured using one of the previously mentioned manufacturing methodologies and with FRP or aluminium mould significant advantages appear, one of them is the ability to process high viscosity resin systems (cyanesters, polyimide, high temperature epoxy resins, thermoplastics), which due to the elevated cost of conventional heated moulds were not widely used. The temperature rise on the preforms using this methodology is limited by the mould material and the manufacturing accessories. So far, temperatures up to 700K have been achieved under controlled environment (vacuum environment). This results in the ability to handle the whole temperature range of every resin system in order to optimise resin flow acceleration and curing. The setup is very simple and consists of: a) a DC power supply, b) copper electrodes, c) thermocouples, d) mold made from aluminium with a glass fiber insulating surface or an FRP mold, e) all the required moulding accessories according to the manufacturing procedure.

EXPERIMENTAL RESULTS

The temperature distribution on different CF preforms with rectangular geometry was studied. In the following figures concerning the temperature distribution using three different resin systems and CF preforms are presented.

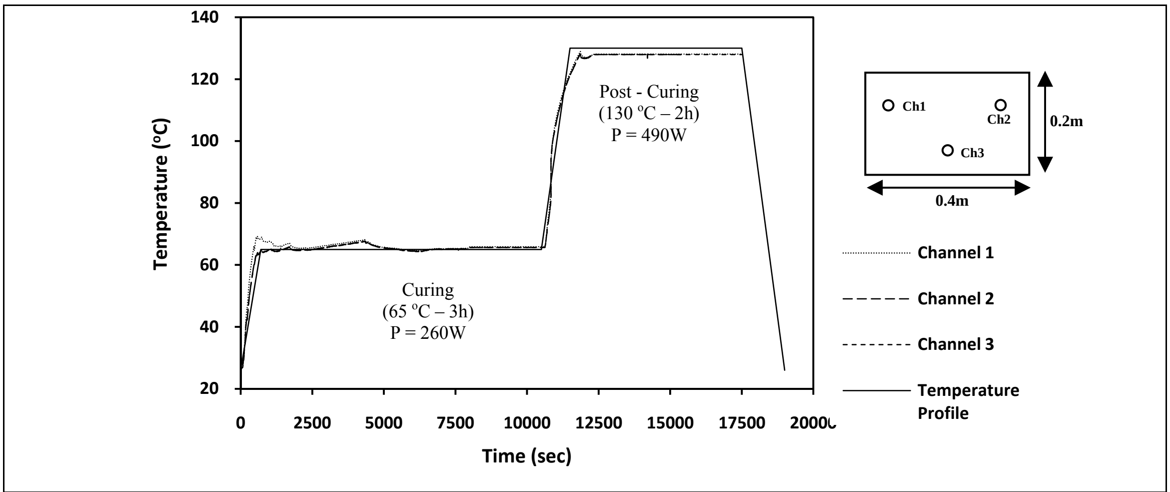

Fig. 2 Temperature distribution on CF Fabric/Epocast52 using vacuum bagging method

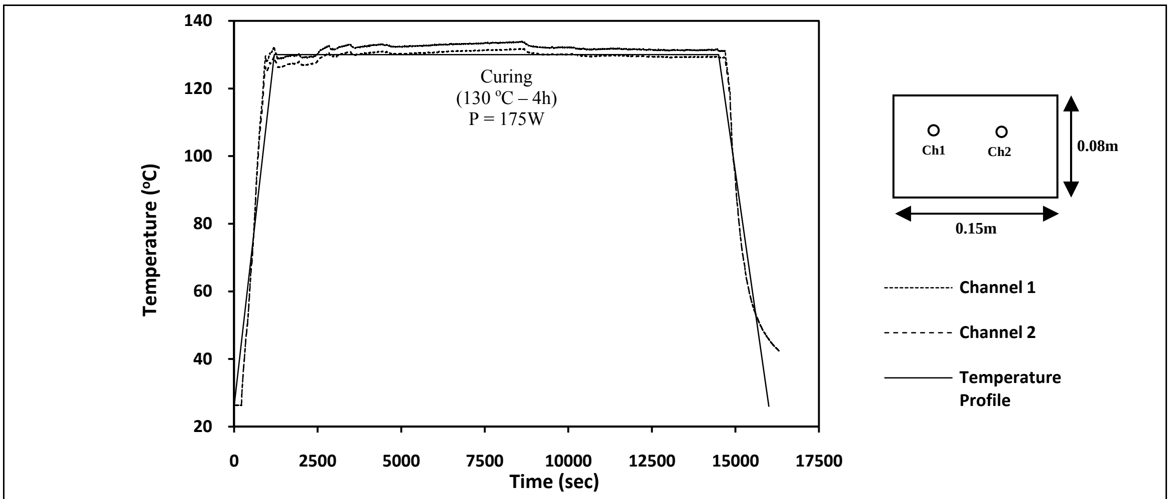

Fig. 3 Temperature distribution in UD Sigrafil/E022 prepreg

In Figures 2 and 3 the temperature at different positions during the curing process and post-curing process is presented and compared to the temperature profile of the resin curing according to the resin manufacturer.

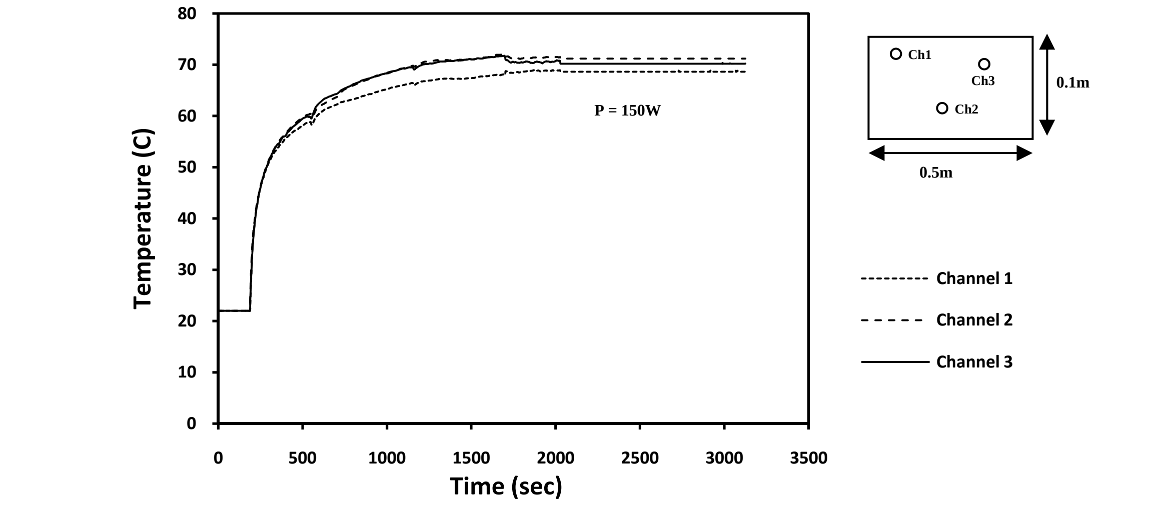

Fig. 4 Temperature distribution in UD T700S before the resin flow, using SCRIMP method

In Figure 4 the temperature distribution before the initiation of the resin flow is presented for different depth and locations. During the resin flow with the SCRIMP method, the inlet temperature of the resin was the same as of the pre-form. L20 resin with a viscosity of 400 mPa s, at room temperature was used. The temperature distribution was constant until the end of the impregnation procedure. The time required in order to complete the procedure was 240 sec while the saturation time at room temperature was 1500sec.

Table 1 Degree of curing

	Oven (%)	**Resistive Heating (%)**
CF fabric / EPOCAST 52AB	93.1	92.4
UD Sigrafil / E022 prepreg	92.2	92.7
UD T700S - SCRIMP	92.4	93.2

After the curing and post curing procedures, the curing-degree was checked with DSC tests. In the following table, the curing degree is presented for three different cases using the oven and the direct heating method.
The mechanical properties under tension loading of the manufactured laminates are compared to ones conventionally manufactured using conventional methods.
Finally, a sandwich panel (0.3m x 1.2m) was manufactured using the SCRIMP method so as to prove the applicability of the method.

Table 2 Comparison of mechanical properties

	Oven		**Resistive Heating**	
	E(GPa) Mean Value ±S.D.	**Max. Tensile Strength (MPa) Mean Value ±S.D.**	**E(GPa) Mean Value ±S.D.**	**Maximum Tensile Strength (MPa) Mean Value±S.D.**
UD Sigrafil/E022 prepreg	122.5 ± 8.2	1601.4 ± 56.12	125.1 ± 7.37	1580.0 ± 38.73
UD T700S - SCRIMP	108.8 ± 7.57	1809.96 ± 40.65	107.1 ± 6.13	1826.17 ± 25.71

CONCLUSIONS

The temperature distribution was studied on different CF preforms architectures using different manufacturing methods. The specimens were flat plates of various dimensions. It was proved that in simplified geometries the deviation at different locations on the plate was lower than 3 ^{o}C in every case. The method can be used for flow acceleration, curing and post-curing of the resin system. It can be applied to the following manufacturing methodologies: single-sided VARTM, SCRIMP, RFI, Vacuum Bagging, prepreg preforms with or without core material and in the RTM and VARTM methods as well. In addition, resin system with high viscosity can be processed. The curing-degree is the same as for the conventional methods. The mechanical properties do not show differences.

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