EXPERIMENTAL EVALUATION OF HEAT TRANSFER MEASUREMENTS DURING LCM PROCESSES BY INTRUSIVE AND NON-INTRUSIVE HEAT FLUX SENSORS.

U. Pineda[1]*, N. Montés[1], F. Sánchez [1], L. Domenech[1]
[1] University of Cardenal Herrera, 46115 Alfara del Patriarca, Valencia (Spain)
* Corresponding author (upineda@uch.ceu.es)

Keywords *Degree of cure, heat flux sensors by radiation and conduction, heat transfer in LCM*

Abstract

This paper evaluates the ability of infrared thermography for measurements of heat transfer during the curing stage in LCM (Liquid Composite Molding) manufacturing processes. For that stage it demonstrates the potential of non-intrusive measurement methods in respect of intrusive (conductive) techniques.

1 Introduction

LCM processes can be mainly divided in four stages, forming, filling, curing and post-curing. The first one is the fiber cutting and the filling strategy allocation in the mold. The second one is the mold filling where the main goal is the fulfilled mold without dry spots. The third and the last stages are the curing and post curing. Actually the heat transfer phenomenon in applications is analyzed in two phases. The first one, the exothermal behavior resin is analyzed off-process under laboratory conditions using the well-known DSC (Differential Scanning Calorimeter), [1;2]. The characterized resin in the DSC is named in [3] as “neat resin”. After of these, operators use the resin in the manufacturing process where the operators expects that the neat resin has the similar behavior, under controlled conditions, than DSC. The reality is sometimes, the behavior is different than the DSC because the presence of fiber sizing or resin handling, [3]. For this reason there are works that treats to analyze the heat transfer phenomena in real manufacturing process [3]. A deeper understanding of the heat transfer phenomena during the curing stage in the industrial manufacturing is necessary to ensure the best mechanical properties in the parts.

According to the literature, there are two methods to measure the heat transfer phenomena which are intrusive and non-intrusive methods.

Intrusive methods have some drawbacks: usually, this type of sensors must be embedded in the mold or at least put them in physical contact over the surface of flexible mold. This manner of use conductive sensors may affect the heat transfer for different zones in the mold where there is sensors placed. Additional to this, the intrusive sensor has an additional cost because it must be embedded in the mold. For instance, the temperature sensors, thermocouples, RTD (Resistance Temperature Detectors), are intrusive sensors, [1]. Also the sensors used in the DSC are intrusive.

Within non-intrusive methods, researches focus their attention on infrared technologies (wavelengths from 8 to 15 µm). In [4] use this technology to evaluate the final quality of the parts. Moreover, in [5] use an IR curing sensor inside the continuous manufacturing process but it is not based on thermal image. In [6] utilizes a real-time thermal imaging analyzer for detecting anomalies during composite material layup.

In general, sensors used in the literature, intrusive or non-intrusive, are defined as zero-dimensional, which are punctual sensors, [7]. These sensors are usually placed in fixed positions and it does not give flexibility to the process of monitoring the dynamic of heat transfer for large areas. Therefore, the optimal sensor should be an array of zero-dimensional sensors that gives the flexibility in the monitoring process. This sensor can be a thermal camera that gives the flexibility to analyze the heat transfer phenomena in actual manufacturing processes.

This paper is described as follows. Section 2 analyzes the different heat transfer modes for the degree of cure estimation. Section 3 describes the heat-PAG mold by which is developed to do the comparative study of heat transfer measurements between both sensors by radiation and conduction. It explains the developed hardware and software tools. Section 4 presents the comparative results. Conclusions and future works are shown in section 5.

2 Analysis of the different heat transfer modes for the degree of cure estimation.

For a object given, there are heat exchange energy between it and the near objects to itself. If the object is isolated, the heat exchange is with the air that surrounds it. There are three modes of heat transfer measurement: by conduction, convection and radiation techniques.

Conduction technique needs that the sensor is in contact with the object to measure. This sensor measures the amount of thermal energy that passes through it. This measurement is governed by the following equation:

$$q_c = k(T_c - T_s) \qquad (1)$$

Where T_s, is the temperature onto the object surface, T_c is the temperature in the surface that is not in contact with the object (upper surface sensor) and k is thermal conductivity of the sensor material. Then q_c is the amount of thermal energy that passes through the sensor area.

For convection measurement technique, the main difference between conduction techniques is the medium that is crossed by the heat exchange. In this case, the medium behaves as a fluid where the air accomplishes this behavior. Focusing our attention in the air medium, the equation that governs the measurement is similar than conduction exchange (1), that is;

$$q_{cv} = h(T_s - T_A) \qquad (2)$$

Where T_A, is the ambient temperature; h, is a convection coefficient of the air. Then q_{cv} is the amount of energy that passes through a specified area in the air medium.

Radiation measurement technique is based on the energy emitted or radiation heat loss by the object in a predefined band of wavelengths. The energy emitted can come from two sources mainly, the energy emitted by the object itself and the energy reflected in the object surface from the near objects. For minimizing the energy reflected, there are two possible ways. The first one is coating the object by a thin conductive material that presents the higher emissivity or the second one is obtaining a calibration curve by best linear fit as proposed [8]. In whatever case radiation measurements are governed by the following equation:

$$q_{IR} = \varepsilon\sigma\left(T_s^4 - T_A^4\right) \qquad (3)$$

Where ε is the emissivity coefficient (for an ideal absorber, it is a black body, this coefficient is 1 and less than 1 for an actual object surface which is not an ideal absorber [9]); σ is the Stefan-Boltzmann´s constant, which is equal to 5.6704x 10^{-8} w/m2. Then q_{IR} is the amount of infrared thermal energy that emits a specified area onto a surface.

In the case of heat transfer measurements in LCM processes, the neat resin, the fibers, the additives and the mold are the object. The exothermic resin reaction produces the thermal exchanges with the environment. This thermal exchange has been studied in the literature extensively by means of conductive sensors. By conductive sensors is measured the degree of cure as it abovementioned. Therefore, our main goal during curing stage is to determine the degree of cure α, defined as;

$$\alpha(t) = \frac{1}{H_T}\int_0^t \left(\frac{dH_t}{dt}\right)dt \qquad (4)$$

This degree of cure is defined as the ratio between the amount of heat flux generated, H_t, at time t, and the total heat of reaction H_T, [10]. In order to know the degree of cure in an actual part, previously it is necessary to known the amount of energy that the resin should release to the environment. This fact is developed in the DSC. In that device, conductive sensors are used as also in the manufacturing parts for the degree of cure estimation [1].

Conduction measurement techniques are ever intrusive techniques meanwhile the convection and radiation measurement techniques are non-intrusive, that is, do not touch the object given. In particular, IR thermal cameras can be used as a sensor for radiation measurement techniques but also for convective techniques by the *h* parameter estimation, see [7].

According to abovementioned, the goal of our research is to use non-intrusive sensor, in particular IR cameras for the degree of cure estimation as is well evaluated in the literature by conductive sensors. As the first step, and the goal of the present paper, is to evaluate the capability of the thermal camera to estimate the same parameters than the parameters estimated by conductive sensors.

3 Experimental Setup: Heat PAG Mold

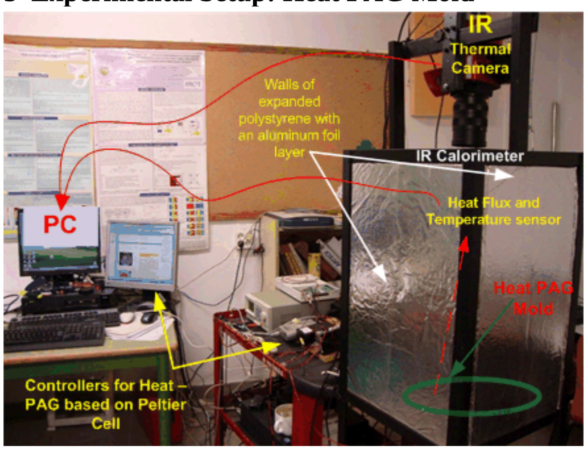

Fig. 1 Experimental setup.

For the goal of the present paper it is necessary to compare measurements of sensor by conduction with thermal camera in an exothermic process. *Heat PAG Mold* is developed due to this exothermic process using actual resin is complex and the repetitively of it is always not guaranteed in the required precision for the goal of this study. Then, Heat Flux Programmable Artificial Generator (Heat PAG Mold) simulates the heat transfer behavior of a part in manufacturing or a neat resin in the DSC, see Fig. 1. Then, Heat PAG Mold allows generating exothermic heat fluxes controlled by previous thermal log or history of temperatures in a manufactured sample during curing stage. For this propose, Heat PAG Mold is composed of a thermoelectric cell (Peltier cell).

For this work, the sensors that are shown in Fig. 2 are placed in the installation, mainly. In particular, *TVS 500EXZ* from *NEC* and a *Heat flux sensor* from *Captec Entreprise* are used in this experiment.

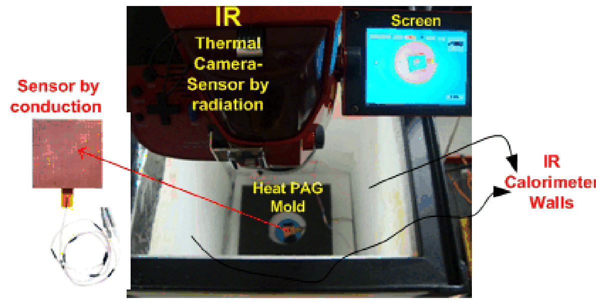

Fig. 2. Top view of the installation.

In Fig. 3 we can see thermal two-dimensionality of the IR camera. For our experiment only one pixel of the matrix (320x240 pixels) is selected, see Fig. 4. The temperature measured in this pixel is named T_{IR}.

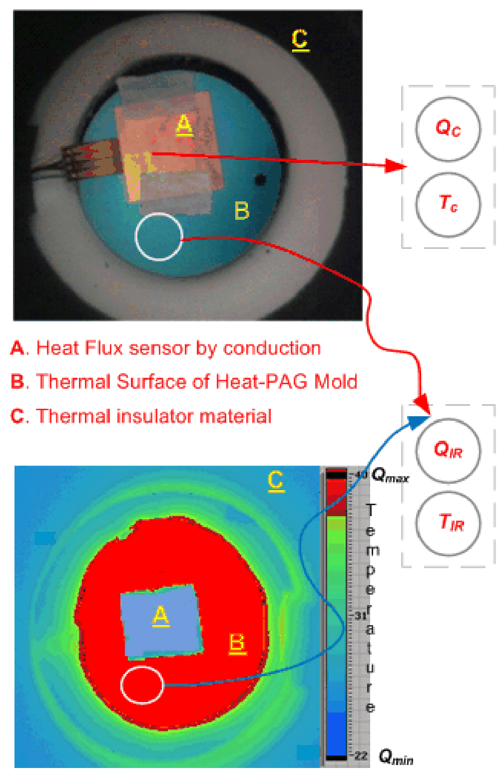

Fig. 4. Setup of the experiment. Thermal Photo in an instant time.

As shown in Fig. 4 the square labeled *A*, is the heat flux sensor on the *Heat-PAG Mold* surface, labeled *B* is the thermal surface in the *Heat PAG Mold* and labeled *C* is a thermal isolator material which drives the thermal flow for going to the thermal camera direction.

3.1 Software and hardware integration

It treats of custom software developed in graphical programming (*LabVIEW*) as shown in the Fig 5. This custom software to control and monitor manages the data flow from **PC** to the actuators, the power supply and the fan of the peltier cell as well the electric radiator that control the room temperature. This PC collects the information in real time from the thermal camera at 10 frames per second, conductive sensor at 30 samples per second, as also the temperature in the IR calorimeter and the room temperature. A schematic of the connection of all the components is shown in Fig 5.

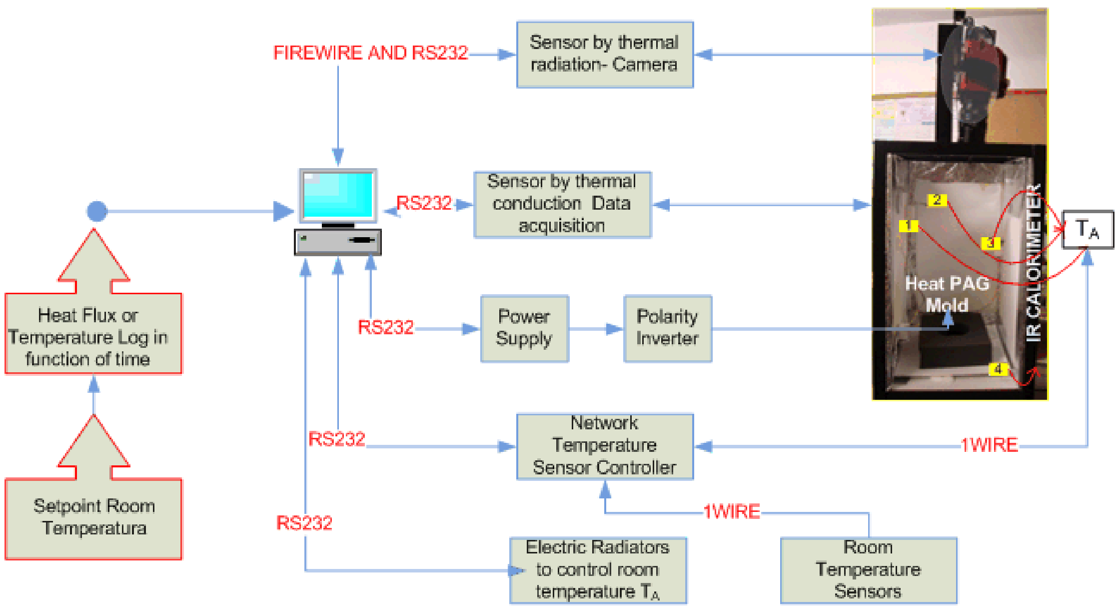

Fig. 5. Software and Hardware as integration tools for studying cure stage by Heat PAG Mold.

3.2 In situ thermal camera calibration

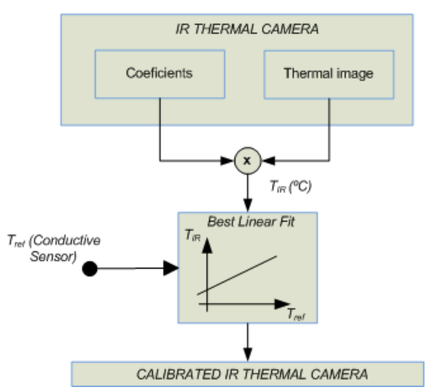

Fig. 6 In situ Thermal Camera calibration

Previously to the use of the thermal camera for the temperature measurements, it is necessary to calibrate it.

The procedure for the thermal camera calibration is depicted in Fig. 6.

First of all, IR camera gives an image where the information of each pixel is not a temperature. That information is a proportional amount of infrared energy but it is not calibrated. Therefore, IR camera delivers some coefficients which the camera computes as initial calibration in function on the ambient conditions but it is not always reliable due the environment and temperature changes in thermal transient process as the exothermal. By operation of these coefficients with the pixels values, it is possible to obtain the temperature of the pixel for steady-state conditions. In the cases where the surface conditions changes, for thermal transient-state, a in situ thermal camera calibration is used, [6-8;11]. In particular, in the present work and in situ thermal calibration proposed in [8]is used. This method uses a temperature sensor located on the surface and uses this temperature evolution itself and the temperature measured by the camera in order to fit a straight line that relates both parameters. In our case, it is programmed in the Heat PAG Mold a heating ramp, slope of 0.05ºC/s, room temperature at 25ºC.

4 Experimentation

Two tests were performed: Both tests are based on a subroutine programmed where Heat-PAG mold behaves as the test of the manufactured part in [3]. In that work, an unsaturated polyester resin mixed with catalyst (MECKP 2 wt%). In [3] that resin was injected to glass fiber. Therefore, the log reference for Heat-PAG Mold is the surface temperature registered in the experiments documented in [3].

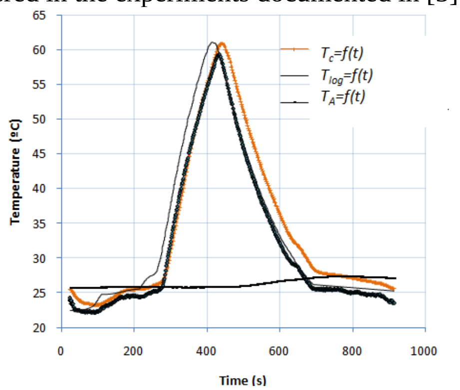

Fig. 7 T_{log} is Reference Temperature (log) VS T_c temperature in the conductive sensor and, T_A is the ambient temperature.

In Fig. 7 it is show the temperature reference and the temperature evolution measured by the conductive sensor. Also in this figure is showing the ambient temperature evolution (room temperature reference is 25ºC).

In Fig. 8 it is show the temperature measured by a single pixel of the IR camera and the conductive sensor. In this figure both temperatures are shown when go up are very similar. However, T_c goes down with a small offset than T_{IR}. Therefore, It could be generated by the radiative heat transfer from the walls to the mold surface while decreases the exothermic phenomenon. The latter thing indicates us that the calibration had not in account this offset neither the rate *ºC/s* when T_c is falling down to the baseline.

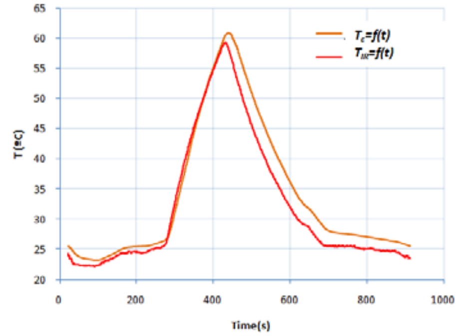

Fig. 8 IR temperature VS Conductive temperature

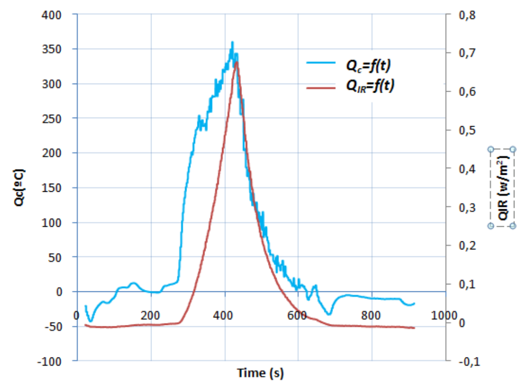

Fig. 9 Conductive heat flux VS Radiative heat flux

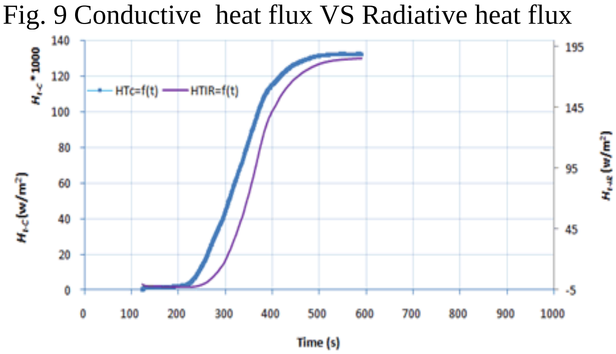

Fig. 10 Energy emitted measured by each sensor.

In Fig. 9 radiative heat flux Q_{IR} was computed by the equation (3).As we can see, the peak in Q_{IR} by the IR camera is detected with a little delayed to Q_c. It also is due to the offset abovementioned.

In Fig. 10 it is show the measured energy by the IR camera, H_{T_IR} and the energy by Conductive sensor, H_{T_C}. These energies are necessary to compute the degree of cure shown in Fig. 11, using equation (4).

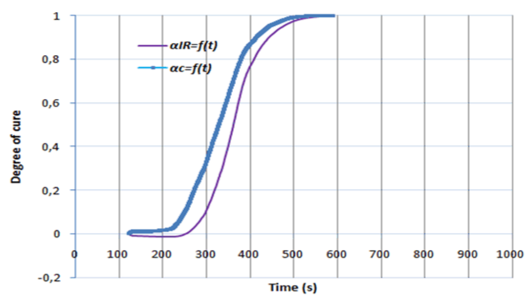

Fig. 11 Computed degree of cure measured by both sensors.

5 Conclusions

In this paper it is evaluated the ability of IR cameras for the measurement of the same parameters measured using conductive sensors. In particular, the degree of cure is computed as an example parameter. For evaluating the latter an experimental Heat Flux Programmable Artificial Generator (Heat PAG Mold) which can simulate as the heat transfer of a small part in manufacturing as well a neat resin in the DSC (Differential Scanning Calorimeter). Therefore, Heat PAG Mold in our tests simulates the manufactured part documented in [3].

It has demonstrated how non-intrusive sensors (IR thermal camera) can detect the heat transfer phenomena such as conduction heat flux sensors do it. However, IR cameras require a proper calibration in order to obtain repeatability in the measurements. It can be obtained by means of knowledge of the heat sources and heat absorbers what are present surrounding the manufacturing location because they affect the accuracy of the measured temperatures as well as the radiative heat flux measurements. The earlier will be dealt as a future work where calibration must be developed for each rate of raising or falling temperature in order to obtain a family of best linear fits of them. Heat PAG Mold will continue being a useful tool to have realistic thermal behavior without making actual manufacture.

6 Acknowledgments

This research work is financially supported by University Cardenal Herrera CEU (Valencia – Spain). The authors would like to thank J. Vicente Navarro for his help.

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