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RESEARCH CONCERNING RESIN TRANSFER MOLDING PROCESS UNDER ELECTROMAGNETIC FIELD

Constantin OPRAN[1], Doru Andrei BALOTĂ[1]
[1]University POLITEHNICA of Bucharest, Production Engineering Department, Bucharest, Romania,
constantin.opran@ltpc.pub.ro, doru.balota@ltpc.pub.ro

Abstract: *Resin Transfer Molding (RTM) is a widely-used process in which a charge of resin is placed in a transfer pot and is injected into a closed mould. The method allows the resin to be finally prepared and then transferred fast and accurately into the mould, in which the required reinforcement has already been placed, in suitable form. Heat can be applied to the mould before the finished part is removed in order to shorten the cure-time and high quality of finished products. The surface of the mould is rapidly heated using electromagnetic induction and allows two different temperatures, one for the resin injection and another for the curing phase. Electromagnetic induction is referring at the phenomenon by which electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. Induction heating has made it easier to set the heating parameters without the need of an additional external power source. This paper aims towards to a study of heating adaptation for the Resin Transfer Molding of composite industry defined "Resin Transfer Molding under Electromagnetic field" (RTM-EF).*
Keywords: *electromagnetic field, resin transfer molding, induction heating, process parameters, composite industry.*

1. INTRODUCTION

Advanced composite materials offer an exciting and diverse alternative to classic materials. Their high strength and stiffness-to-weight ratios allowed them to be a popular material in performance-driven areas such as aerospace and sports industries. Resin Transfer Molding (RTM) is a closed mold process for making composite materials. RTM involves the injection of a liquid resin into closed moulds which contain the reinforcement in the form of a dry fiber preform, the resin wets out the preform, fills the mould and is then cured in situ. It is a method which offers good repeatability combined with low costs and the ability to produce complex components which would otherwise be impractical [12]. Heat can be applied to the mould to shorten the cure-time. The surface of the mould is rapidly heated using electromagnetic induction and allows two different temperatures, one for the resin injection and another for the curing phase [10]. Electromagnetic induction is referring at the phenomenon by which electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. Induction heating has made it easier to set the heating parameters without the need of an additional external power source [8]. Control and monitoring systems have been developed, so that RTM is now emerging as one of the most important processes for molding composite parts to high levels of quality and reproduceability. Operating at low pressure, it uses lower-cost machinery and moulds and offers an economic means of medium volume production of high quality parts [10].

2. RESIN TRANSFER MOLDING PROCESS

2.1. Classic Resin Transfer Molding Process

Thermoset polymeric composites with continuous fiber reinforcements can be produced by injection of reactive liquids into molds with preplaced fiber mats. One process used increasingly in industry is Resin Transfer Molding (RTM). In the RTM process, a stack of fiber mats or woven rovings is preplaced in the mold cavity, then the mold is sealed and resin is injected. The resin and the mold can be heated before injection in order to accelerate mold filling by dimishing the viscosity of the resin. However, proper care must be given so that the

resin polymerization is not completely filled. It is necessary to analyze the heat transfer phenomenon in order to control the temperature distribution of the resin during the filling process [5].
The main phenomena governing composites production are flow through porous media, conduction heat transfer and exothermic curing reaction:
Flow through porous media occurs during impregnation in liquid molding and pultrusion and during consolidation in autoclaving and filament winding and it governs:
- the duration of the impregnation or consolidation stage;
- the formation of voids;
- the creation of macroscopic dry spots.
Heat conduction and the exothermic reaction take place during the curing stage of all processes, usually after flow completion or in some cases alongside with flow and they control:
- the duration of the curing stage;
- the uniformity of final degree of cure;
- the existence of thermal gradients during the cure which subsequently governs the built up of residual stresses
- the extent of exothermic phenomena which can give rise to degradation [1].

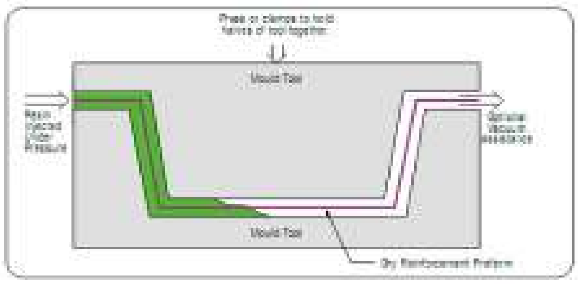

Figure 1: Classic Resin Transfer Molding Process

Factors in the modelling of resin injection and cure processes:
- calculation of the flow front shape, speed and position with time for an arbitrary geometry, arbitrary gating and arbitrary V_f (volume fiber fraction);
- calculation of tow and fiber wet-out rates;
- calculation of cure time, demould time, peak mould and component temperatures at any and all positions in the tool and component
- calculation of resin expansion and shrinkage effects during heat up to cure [11].

2.2. Resin Transfer Molding Process under Electromagnetic field (RTM-EF)

Resin Transfer Molding method allows the resin to be finally prepared and then transferred fast and accurately into the mould, in which the required reinforcement has already been placed, in suitable form. Heat can be applied to the mould before the finished part is removed in order to shorten the cure-time and high quality of finished products. The surface of the mould is rapidly heated using electromagnetic induction and allows two different temperatures, one for the resin injection and another for the curing phase [10]. To optimize the process and reduce its cost, a correct knowledge of mold filling becomes highly necessary. The key issue in mold filling concerns the resin flow through the preform and the heat transfer phenomenon occuring between the resin and the fiber reinforcement [5].

Induction heating employs magnetic fields to induce eddy currents into the molding as it moves through an induction coil. When an electrical current alternates in a work coil, it produces an alternating magnetic field in and around the work coil. If an electrically conductive part is placed within the magnetic field, a current is developed in that part. The work coil may be considered as the primary winding of a transformer and the workpiece as a short circuit secondary winding. The induced current in the part flows against the resistivity of the material and generates heat. All conductive materials heat up in a magnetic due to eddy current heating. A typical induction heating system includes an AC power supply, a remote workhead and a water-cooled copper coil. The coil size and shape are dependent on the size and geometry of the component being heated. An optional temperature-measuring system can be easily integrated into the system to provide temperature feedback to the power supply for precise temperature control of the metal. The coil is designed to deliver the most efficient heat to the metal, and is dependent on the speed at which the part travels through the coil in addition to the shape and magnetic properties of the part. When the workpiece is placed in the coil, the magnetic induces eddy currents in the workpiece, generating precise amounts of clean, localized heat without any physical contact with the workpiece. The different variables to be considered when selecting an induction heating system are operating frequency, power supply sizing and coil design.

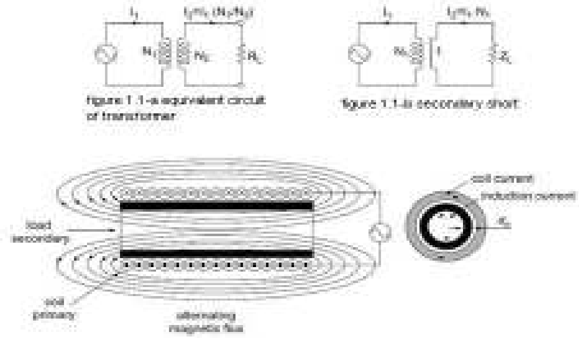

Figure 2 : Basics of Electromagnetic field

Operating frequency: induction heating energy produced in the metal as a result of the induced eddy currents is produced within a certain distance from the surface. This depth of penetration of heat is called the "skin depth". The density of heat energy produced is greatest on the surface and drops off exponentially at the skin depth. There is a relationship between the frequency of the alternating current and the depth of penetration in the workpiece. Low frequencies of 5 to 30 kHz are effective for thicker materials, delivering deeper heat penetration, while higher frequencies greater than 50 kHz are effective for heating smaller or thinner parts or heating the surface of parts. Higher frequencies also have a higher efficiency of heat transfer into the parts. A good analogy is the act of rubbing your hands together (representing a higher frequency), with the same amount of contact pressure, the more warmth you produce. In terms of aluminum and steel trim, steel heats more efficiently than aluminum trim. Magnetic materials are easier to heat than non-magnetic materials, due to the added effects of hysteresis heating. Magnetic materials naturally resist the rapidly changing magnetic fields within the induction coil. The resulting friction produces its own additional heat-hysteresis heating- in addition to eddy current heating. Steel trim is easier to heat than aluminum trim when using induction heating.

Power Level Required: several variables must be considered to determine the amount of heat energy required for heating a particular trim material. The mass flow rate, the specific heat of the material being heated and the rise in temperature required determine the amount of energy required in the material to raise its temperature from ambient to the desired final temperature. In addition, thermal losses due to conduction of heat into workpiece and convection losses must also be considered.

Efficient Coil Design: the induction coil, typically made of copper tubing, is normally cooled with water. The shape of the copper tube is dependent on the current and water flow required for the application and can vary from round to rectangular. The size and type of the coil-single or multiple turn, helical, round or square, internal or external is selected based on the properties of the metal trim being heated and the processing speeds required. The coil is designed to deliver energy at the best coupling efficiency. Coupling refers to the proportional relationship between the distance between the workpiece and the coil. Close coupling generally increases the flow of current and therefore increases the amount of heat produced in the workpiece. With a good coil design, the proper heat pattern is achieved and the efficiency of the induction heating power supply is maximized. Each coil needs a non-conductive liner inside to electrically insulate the trim from the coil as it travels through the coil. Glass, ceramic or plastic is generally used as insulating material. Induction heating provides fast, reliable, repeatable, non-contact, energy-efficient heat [8].

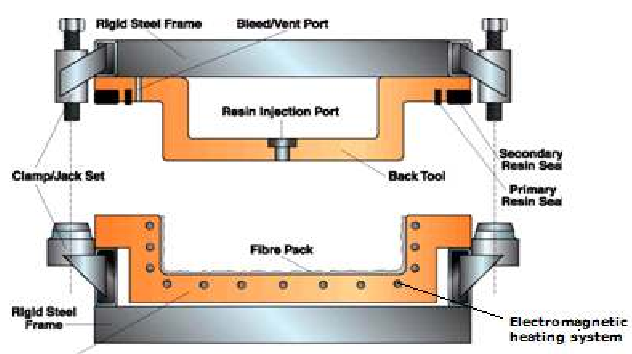

Figure 3 : Resin Transfer Molding under Electromagnetic field

2.3. Monitoring of Resin Transfer Molding under Electromagnetic field

The mould filling process, which can take a number of minutes, is critical to obtain a good quality part. The resin must fully wet out the preform so that the part contains no voids or dry spots. Any voids present can result in a defect that can diminish the strength and quality of the cured part. Knowledge of how the resin fills the mould can aid in the optimization of the RTM process and result in faster process development and more consistent, high quality parts [7]. Process monitoring plays a crucial role in the RTM process as it significantly affects the repeatability of the process cycle and the quality of parts produced. Monitoring the resin flow allows engineers to detect whether the flow front propagates as it was designed to or not, and hence if any undesired void (dry spot) remains within the mold cavity. Monitoring the cure of the polymer allows engineers to decide when to de-mold the part (open the mold and remove the part) which ends the production cycle. For these two monitoring purposes, the most frequently used sensors are SMART weave, pressure transducer, thermocouple, dielectric, ultrasonic, fiber optic, and point- and lineal-voltage sensors. Thermocouples can be used to detect the key events of moulding cycle such as resin arrival and resin exotherm. However the effectiveness of the monitoring depends upon the relationship between the type of process which is operated and the nature and position of the thermocouples. The requirements of slower processes such as polyester RTM may be satisfied by using tool-mounted thermocouples with relatively long time constants. When instrumenting a mould cavity for monitoring and control purposes the minimum requirement is usually to install one thermocouple at or close to the injection gate and another at the vent or mould periphery, or any area which is judged likely to be the last area to fill. These positions should be independent of any instrumentation used for control of mould heating, since the objective is to measure temperatures on the surface or at the mid-plane of the part rather than those within the mould body. Twisted pair thermocouples provide the shortest response times and can be laid inside the preform during process development work but technique is time consuming and the thermocouples is sacrificed with each molding. Surface mounted thermocouples can be used within the mould body but since the through thickness temperature gradient is very high it is usually desirable to measure temperatures as close as possible to the laminate mid-plane. The response of the thermocouples is extremely important in determining absolute temperatures and heating and cooling rates [2].

Thermal monitoring is the simplest monitoring technique to implement. Every mould control system makes use of thermocouples and in some cases the presence of an exothermic is considered empirically as an indication of the progress of the reaction. However, thermal monitoring has a lower level of sophistication in comparison with the rest of the cure monitoring techniques, since its results are not related with a cure progress dependent property. In order to derive cure monitoring results, thermal monitoring should be combined with accurate chemical cure kinetics and themorheology models. Methods for appropriate modelling of the curing reaction are available, but batch to batch variations of the raw materials and the extensive experimental effort required to produce a representative cure kinetics model that limit the range of uses of such an approach. Consequently the, mainstream current research on composites manufacturing does not consider the measurement of temperature as being within the context of cure monitoring. Monitoring based on heat flux signals measured using a variety of combinations of temperature sensors has been presented in the research literature [1].

2.4. Modelling of heat transfer and curing at Resin Transfer Molding under Electromagnetic field

Heat transfer modelling is performed by the application of an energy balance in an appropriate form [1]. The general form of energy balance as it arises from the first law of thermodynamics for an incompressible medium is:

$$\rho c_p \frac{dT}{dt} = \rho c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T\right) = S_i - \nabla \cdot (\vec{q}_{cd} + \vec{q}_r) \qquad (2.1)$$

The left side of Eq. 2.1 represents the time derivative of specific enthalpy (ρ is the density, c_p the specific heat capacity, T the temperature and $\vec{u}$ the velocity). The right side is the sum of the powers per unit volume generated within the material (S_i is the heat generated per unit volume per unit time) and crossing a surface element ($\vec{q}_{cd}$ is the heat conduction through a surface per unit area per unit time and $\vec{q}_r$ is the heat radiation through a surface per unit area per unit time). As shown in Eq. 2.1 the time derivative of temperature can be analyzed further in the variation of temperature with time at a fixed position, represented by $\frac{\partial T}{\partial t}$, and the variation of temperature with time of a material element followed during its motion, represented by $\vec{u} \cdot \nabla T$.

The conduction heat flux can be expressed by Fourier's law as follows:

$$\vec{q}_{cd} = -K\nabla T \qquad (2.2)$$

where K denotes the thermal conductivity tensor.

Consequently Eq. 2.1 becomes:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T\right) = S_i + \nabla \cdot (K\nabla T) \qquad (2.3)$$

In the case of liquid composite molding, heat transfer occurs during both impregnation and curing. When the impregnation takes place at a constant temperature which is lower than the onset of reaction, the filling can be considered isothermal and heat transfer phenomena can be ignored. In contrast, when the filling takes place at a temperature where the resin is reactive or under non-isothermal conditions, i.e. when the temperature of the tool is different than that of the liquid thermoset or when there are significant temperature variations across the tool, heat transfer should be coupled with the flow models. During the curing stage a heat transfer model coupled with a cure model operates independently, since forced convection does not take place. The implementation of heat transfer models varies according to the stage of the process (filling or curing) they simulate. In filling stage simulations which do not consider the reaction, assuming that although the filling stage is non-isothermal the reaction is very slow, the form of the heat balance used is:

$$\rho c_p \frac{dT}{dt} + \rho_r c_{pr} \vec{u} \cdot \nabla T = K \nabla^2 T \tag{2.4}$$

where ρ_r is the resin density and c_{pr} the resin specific heat capacity.
In cases where the reaction plays a role in impregnation, Eq. 2.3 becomes:

$$\rho c_p \frac{dT}{dt} + \rho_r c_{pr} \vec{u} \cdot \nabla T = K \nabla^2 T + (1 - v_f) \rho_r H_{tot} \frac{d\alpha}{dt} \tag{2.5}$$

where H_{tot} is the total heat of reaction.
Here the conductivity tensor has been considered isotropic and independent of temperature. Typical boundary conditions complementing such models are:
- temperature at the inlet is equal to resin temperature prior to injection;
- temperature on the mould wall is equal to a prescribed value;
- temperature on the flow front is equal to the preform temperature;
- heat gained due to the flow progress is equal to the heat flux on the flow front boundary.

In order to solve this model coupled with a Darcy flow model, finite elements are used, and the analysis is decoupled in each time step. The temperature distribution is calculated using the impregnated domain as resulted from the flow model. Then the result of the heat transfer is used for the calculation of viscosity in order to update the finite elements representation for the next time step of the flow model. These representations of the heat transfer problem assume a local thermal equilibrium which enables the local averaging of temperature, in order to treat the filling composite as a uniform material. In microscopic terms that means that the heat exchange through the resin-reinforcement interface rapidly erases any difference between the resin and reinforcement temperatures. If the process is very fast, e.g. in structure reaction injection molding, or when the heat exchange is very slow; there might be some differences between the temperatures of the two phases. In that case a separate energy balance should be formed for each of them. The resulting equations include some unexpected terms and some difficult to determine coefficients. In practice, the only term used in models is the one representing the heat exchange. The corresponding formulation is:

For the liquid phase:

$$\rho c_p \frac{\partial T}{\partial t} + \frac{1}{(1 - v_f)} \rho_r c_{cp} \vec{u} \cdot \nabla T_r = \nabla \cdot K_r \nabla T_r + \rho_r H_{tot} \frac{d\alpha}{dt} + h_v (T_f - T_r) \tag{2.6}$$

For solid phase:

$$v_f \rho_f c_{pf} \frac{\partial T_f}{\partial t} = v_f \nabla \cdot K_f \nabla T_f + (1 - v_f) h_v (T_r - T_f) \tag{2.7}$$

where T_r, T_f are the resin and fiber temperatures, K_r, K_f the resin and fiber thermal conductivities and h_v the heat transfer exchange coefficient. Another phenomenon that may affect heat transfer during impregnation is dispersion. It occurs when microscopic velocities are different from their average values. This results in significant mechanical mixing which contributes to the transfer of heat by convection and can override diffusion. Thus, a term which acts similarly to conductivity should be included in the energy balance which is modified as follows:

$$\rho c_p \frac{\partial T}{\partial t} + \rho_r c_{pr} \vec{u} \cdot \nabla T = \nabla \cdot (K + K_D) \nabla T + (1 - v_f) \rho_r H_{tot} \frac{d\alpha}{dt} \tag{2.8}$$

where $K_D \nabla T$ is the dispersion contribution to the heat flux.
The heat transfer modelling of the curing stage of liquid molding is based on the same principles as the modelling of impregnation. The energy balance is simplified in that case, since no convective terms are included and there is no need to allow for two phase modelling or to account for dispersion effects. The appropriate expression of the energy balance becomes:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot [K] \nabla T + (1 - v_f) \rho_r H_{tot} \frac{d\alpha}{dt} \tag{2.9}$$

The curing stage of liquid molding has received much less attention than the impregnation stage up to now. Only one dimensional models aiming at modelling the whole curing cycle in the RTM have been developed using 1-D finite differences representations of Eq. 2.9.
Some of the kinetic modelling methods described before have been used to incorporate resin cure kinetics in the models. For the incorporation of thermal properties in heat transfer models for both impregnation and curing, all the previously mentioned studies use constant values throughout the filling and cure cycle, which is an extreme

simplification considering the changes, like gelation and vitrification, that the resin undergoes. Some models incorporate relations in order to obtain the composite material properties from its constituents values:

$$\rho = \frac{\rho_r \rho_f}{w_f \rho_r + (1 - w_f)\rho_f} \tag{2.10}$$

$$c_p = w_f c_{pf} + (1 - w_f) c_{pr} \tag{2.11}$$

$$K = \frac{K_r K_f}{w_f K_r + (1 - w_f) K_f} \tag{2.12}$$

where w_f is the fiber weight fraction.

3. CONCLUSION

This paper shows the advantages of a less conventional heating technique. As was explained throughout this document, the primary advantage of induction heating is that the heat is generated within the material to be heated. This results in a very quick response, good efficiency and local heating possibilities.

Resin Transfer Molding under Electromagnetic field are the fooling advantages:

- meets tight production tolerances with precise localized heat to small areas creating pinpoint accuracy;
- increased production rates with faster heating cycles;
- reduce defect rates with repeatable, reliable heat;
- eliminate variability from operator-to-operator, shift to shift;
- use less energy-immediate heating;
- non-contact heating;
- generate heat only where needed;
- does not contaminate material being heated;
- integrates well into production cells;
- uses compact work-head, optimizing workspace;
- integrates with automated control systems (analog & digital I/O);
- user-friendly adjustable tap settings, interchangeable coils;
- environmentally friendly – creates clean, pleasant operating environment.

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