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G.N. Labeas, V.B. Watiti, Ch. V. Katsiropoulos. Thermomechanical Simulation of Infrared Heating Diaphragm Forming Process for Thermoplastic Parts. *Journal of Thermoplastic Composite Materials*, 2008, 21 (4), pp.353-370. 10.1177/0892705708089480 . hal-00570805

HAL Id: hal-00570805

<https://hal.science/hal-00570805>

Submitted on 1 Mar 2011

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Thermomechanical Simulation of Infrared Heating Diaphragm Forming Process for Thermoplastic Parts

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ABSTRACT: An innovative methodology for the thermomechanical simulation of the infrared heating diaphragm forming (DF) process is proposed. In the first section of the paper, the heat transfer mechanisms between the infrared (IR) heating lamps and the thermoplastic plate are simulated, and the effect of the various preheating parameters on the heating time and temperature distribution is investigated. In the second section, the mechanical deformation of the thermoplastic component is simulated to enable prediction of heat losses due to the plate contact with the mold. Based on the developed simulation methodology, the main process parameters – e.g., the number, location, and power of IR lamps for optimal preheating; the heat losses during plate deformation; and the minimum required mold temperature throughout the forming phase – are derived for five different thicknesses. The optimization results show that the forming parameters considered influence the heating of the plate in a complex and interactive way; in addition, it is found that with increasing plate thickness, the heating time required to reach the desired temperature also increases.

KEY WORDS: numerical model, diaphragm forming, infrared heating, thermoplastic material, process optimization.

INTRODUCTION

RECENTLY, THE AIRCRAFT industry has focused on the efficient incorporation of composite materials into commercial aircraft designs. Composite materials with thermoplastic matrices, such as carbon/PEEK

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Figures 4 and 6–12 appear in color online <http://jtc.sagepub.com>

(APC-2), carbon/PPS, glass/PPS, and carbon/PEI have the potential to offer a significant weight saving over conventional isotropic materials such as steel or aluminum. Although, manufacturing processes such as resin transfer molding (RTM), pultrusion, and autoclave are all applicable both to thermosets and thermoplastics, the diaphragm forming (DF) process has gained considerable attention primarily in the forming of preconsolidated thermoplastics, due to its capability for producing structural parts with complex geometries at high-volume rates [1].

In the conventional form of DF, the preheating stage usually involves heating of the thermoplastic plate as well as the tool using conventional heating methods. This step consumes a substantial part of the overall process time, which makes the DF process cost ineffective. Implementation of the IR heating DF technique, which is also known as 'cold' DF, includes two main steps. In the first step, the preconsolidated thermoplastic laminate is heated above melting point, while the mold is usually heated to the required temperature. In the second step, the laminate is fixed under vacuum between two thin plastically deformable diaphragm films, which are usually clamped around the edges; forming of the plate is performed over the heated tool, which achieves the desirable shape by introducing a suitable pressure gradient through the diaphragms. The formed part is removed from the tool after cooling under pressure to a suitable temperature at which material structural stability is achieved. A schematic representation of the process is shown in Figure 1.

The efficiency of heating the thermoplastic composite laminate by IR lamps arises from short heat-up times, as the laminate is heated directly and not via the tool or the surrounding media. However, the implementation of cold DF requires careful selection of the power and position of the

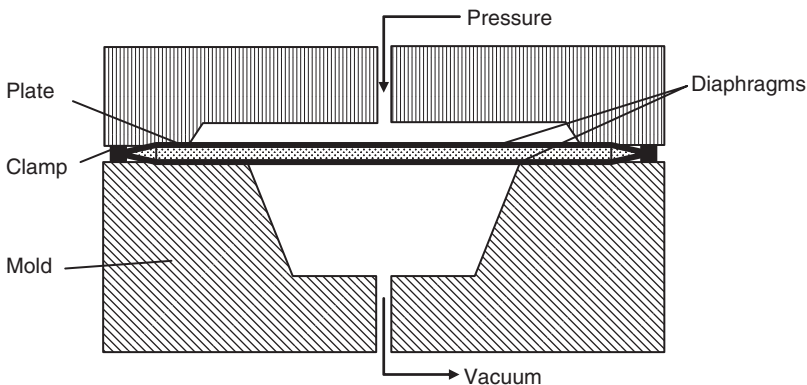


Figure 1. Schematic representation of the diaphragm forming process.

IR lamps to overcome the usual problems of this version of DF technique, including temperature differences through the thickness of the material and hot/cold spots due to nonuniform temperature distributions. Especially at high heating energy densities, the top plate surface may reach temperatures well above the required process temperature, while the rest of the material volume remains below the processing temperature; this problem becomes more significant for thick thermoplastic composite plates, leading to nonuniform part mechanical properties.

Very few researchers have proposed a method for the thermomechanical simulation of the entire IR DF process, with most of the existing numerical approaches concentrating only on the thermal analysis of the preheating stage. Sweeney et al. [2] developed a model to investigate the influence of heater position and power density on one- or two-sided IR preheating, based on an analytical approach restricted to simple plate geometry and boundary conditions. Radiant heat transfer to flat and inclined composite panels has been modeled by Cassidy et al. [3,4]. Their model takes into account the different parameters involved in the IR heating process by means of a one-dimensional finite difference numerical model, which predicts only the through-the-thickness transient temperature distribution. Turner and Ash [5] developed a model that predicts the steady-state radiant heat flux produced by single and multiple quartz heaters on a planar surface, with and without reflectors, based on analytical and statistical methods; however, no attempt is made to model transient effects and optimal conditions. The only thermomechanical simulation model relevant to the scope of the present paper is that of Hsiao and Kikuchi [6], which addresses numerical analysis and optimization of the thermoforming process of thermoplastic fabrics. This model is capable of predicting heat losses, material temperature distributions, and deformed shapes and is used to derive the optimal process parameters.

The present paper deals with a simulation methodology suitable for use in defining the optimum cold DF process conditions, as an efficient alternative to the conventional experimental trial-and-error optimization approach used in the industry. To this end, a methodology capable of carrying out thermomechanical simulation of the entire DF process of carbon/PEI plates, including the IR preheating phase, the mold post-heating step, and structural deformation, is developed. In the first part, the heat transfer mechanisms between the IR lamp(s) and the thermoplastic plate are simulated, using the finite element method, with the aim of predicting the transient temperature distribution during the IR heating preheating stage. The effect of the various forming parameters, namely, thermoplastic plate thickness, IR lamps – thermoplastic plate surface distance, and IR lamp number and power on the preheating cycle-time, is investigated. To achieve

uniform temperature distribution within the thermoplastic plate, especially during the preheating stage, optimization of heating time for each combination of the forming parameters is performed.

After the preheating stage and during the forming phase, the deformation of the thermoplastic plate is quite large and is usually accompanied by conduction temperature exchange with the tool, as well as by convection to the air. To define the part areas that progressively come in contact with the tool during forming, a mechanical simulation model of the deforming plate under the mechanical pressure load has been developed. Based on the computed contacting areas, the heat losses due to thermal contact between the thermoplastic plate and the mold are consequently predicted, for different values of mold temperature, ranging from room temperature, i.e., no mold post-heating, up to 100°C.

PREHEATING SIMULATION

The heat transfer mechanisms occurring between the IR lamps, the thermoplastic plate, and the mold during the IR preheating phase are schematically presented in Figure 2; they include radiation from the IR heaters to the thermoplastic plate, conduction through the thermoplastic plate, conduction between the thermoplastic plate and the mold, and natural convection from the top and bottom surfaces of the thermoplastic plate to the surrounding environment.

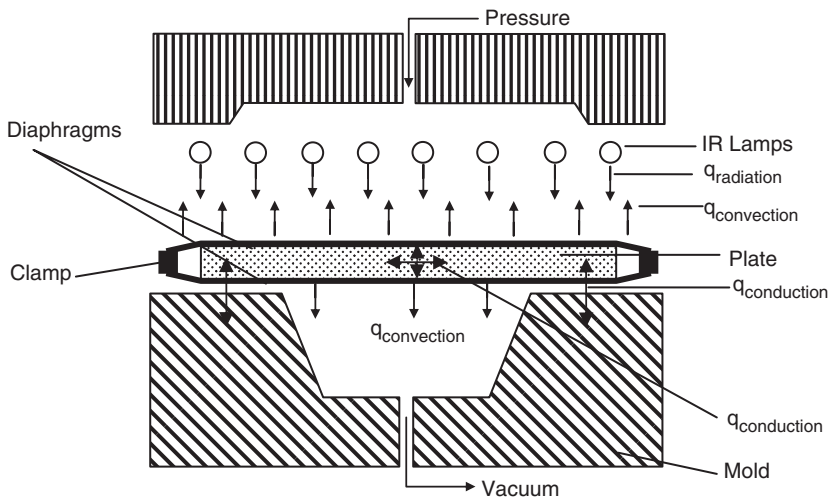


Figure 2. Schematic representation of cold DF heat transfer mechanisms.

Radiation

Heat transfer from the IR lamps to the thermoplastic plate during the preheating stage is simulated by radiation analysis of an enclosure that includes the IR lamps and the thermoplastic plate. The enclosure surfaces are assumed to follow the usual assumption [2,7–9] of being isothermal, opaque, diffuse and grey. The heat transfer due to radiation is calculated using the following equation:

$$q_r = \sigma \cdot F \cdot A \left[\varepsilon_{lamp} T_{lamp}^4 - \varepsilon_{plate} T_{plate}^4 \right] \quad (1)$$

where q is the heat flow, σ the Stefan–Boltzmann constant, F the view factor, A the surface area, ε the emissivity, and T the temperature. The subscript r refers to radiation, while $lamp$ and $plate$ refer to the IR lamp and the thermoplastic plate surfaces, respectively. The total view factor F for an enclosure including N surfaces is a geometric quantity depending on the orientation of each surface relative to the others, evaluated by the superposition rule:

$$F = \frac{A_1 F_{Lamp1 \rightarrow plate} + A_2 F_{Lamp2 \rightarrow plate} + \cdots + A_N F_{LampN \rightarrow plate}}{A_1 + A_2 + \cdots + A_N} \quad (2)$$

where A_N is the lamp surface area and $F_{lamp-plate}$ the view factor between each single lamp and the thermoplastic plate given by

$$F_{Lamp \rightarrow Plate} = 1 - \left[1 - \left(\frac{D}{s} \right)^2 \right]^{1/2} + \frac{D}{s} \tan^{-1} \left(\frac{s^2 - D^2}{D^2} \right)^{1/2} \quad (3)$$

where D is the IR lamp diameter, and s is the distance between the IR lamps.

Convection

The heat transfer between the thermoplastic plate and the surrounding environment is calculated using the following equation:

$$q_c = A \cdot h \cdot (T_{plate} - T_{air}) \quad (4)$$

where q_c is the heat flow due to convection, A is the plate surface area, h is the convection coefficient, T_{air} is the air temperature and T_{plate} is the surface temperature on the thermoplastic plate.

Conduction

The heat transfer between the thermoplastic plate and the mold, as well as within the thermoplastic plate, is calculated using the following differential equation [10]:

$$\begin{aligned} \rho \times c \times \left(\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x} \times v_x + \frac{\partial T}{\partial y} \times v_y + \frac{\partial T}{\partial z} \times v_z \right) \\ = q_{\text{cond}} + \frac{\partial}{\partial x} \left(k_x \times \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \times \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \times \frac{\partial T}{\partial z} \right) \end{aligned} \quad (5)$$

where ρ is the density, c is the specific heat capacity, T is the temperature, t is the time, v_x , v_y , v_z is the velocity of mass transport for the heat in the x , y , and z directions, respectively, q_{cond} is the heat flow due to conduction, and k_x , k_y , k_z is the conductivity of the thermoplastic plate in the x , y , and z directions, respectively.

Finite Element Model

All the heat transfer equations mentioned above are numerically solved by means of the finite element method, using the commercial FE code ANSYS [10]. The thermoplastic plate is modeled using element Shell131, which is a three-dimensional layered shell element having in-plane and through-thickness thermal conduction capability. The element has four nodes with up to 32 temperature degrees of freedom at each node. The conducting shell element is applied in a 3D transient thermal analysis. The heat transfer mechanisms during the preheating stage involve combinations of conduction, convection, and radiation. Conduction between the mold and the thermoplastic plate is simulated using contact element Conta175 and target element Targe170, positioned as shown in Figure 3.

The finite element mesh of the developed model, comprising 3426 elements and 3226 nodes, is shown in Figure 4.

Element Shell131 is also used to model the IR lamps. IR lamps used are composed of a coiled tungsten filament, contained in a quartz tubular enclosure filled with natural gas (Argon) and coated on their surface with a ceramic reflector in order to increase the heat flux received by the thermoplastic plate, as shown schematically in Figure 5.

The tungsten and quartz tube temperatures are calculated using the nonlinear equation system [11–15]:

$$P - \varepsilon_{\text{Fil}}(T_{\text{Fil}})S_{\text{Fil}}\sigma T_{\text{Fil}}^4 - 2\pi L_{\text{Qz}}k_{\text{Argon}}(T^*)\frac{T_{\text{Fil}} - T_{\text{Qz}}}{\ln(d_{\text{Qz}}/d_{\text{Fil}})} = 0, \quad (6)$$

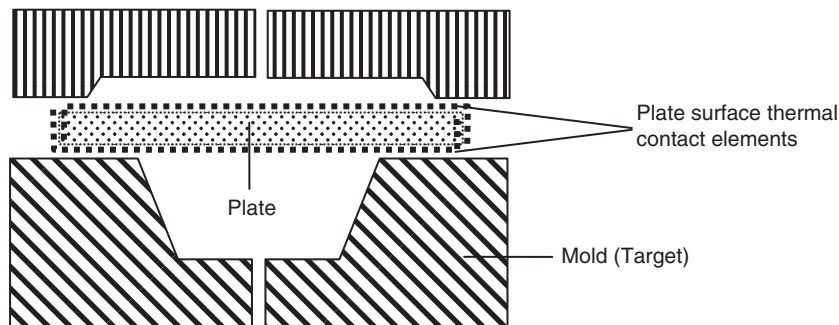


Figure 3. Contact elements applied on the thermoplastic surface.

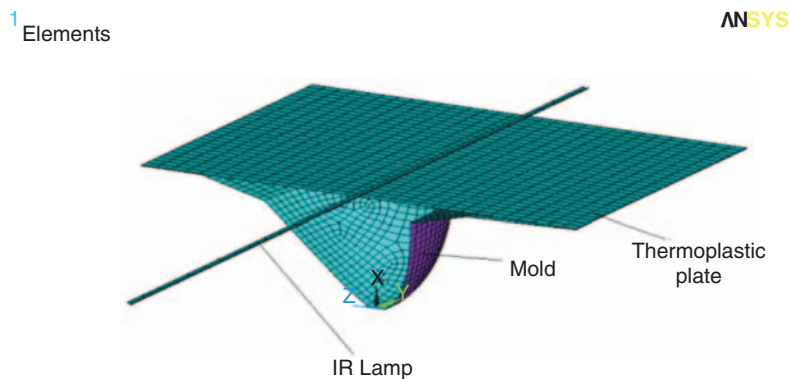


Figure 4. Finite Element mesh of the preheating model.

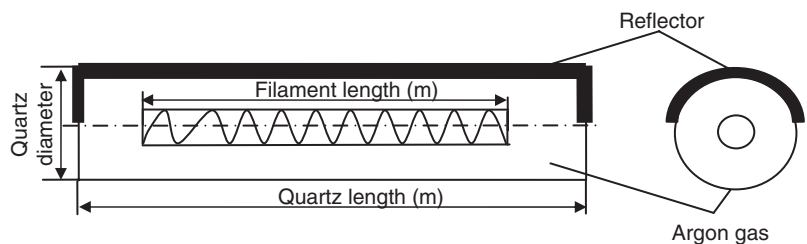


Figure 5. Schematic representation of the IR lamp components.

Table 1. IR lamp quartz temperature.

Electrical power [W]	Quartz temperature [K]
500	592
1000	730
1200	776
1400	815
1500	833
2000	913
3000	1035

$$\alpha_{Qz}(T_{Fil})\varepsilon_{Fil}(T_{Fil})S_{Fil}\sigma T_{Fil}^4 + 2\pi L_{Qz}k_{Argon}(T^*)\frac{T_{Fil} - T_{Qz}}{\ln(d_{Qz}/d_{Fil})} - \varepsilon_{Qz}S_{Qz}\sigma T_{Qz}^4 - hS_{Qz}(T_{Qz} - T) = 0 \tag{7}$$

where P is the electrical power of the IR lamp, ε is the emissivity, T is the temperature, S is the lamp area, σ is the Stefan–Boltzmann constant, L is the length of the IR lamp, k is the conductivity, d is the filament or quartz diameter, α is the absorptivity and T^* is assumed equal to $(T_{Fil} + T_{Qz})/2$. The subscripts Fil and Qz refer to the filament and quartz tube, respectively, while argon refers to argon gas in the IR lamp.

The results obtained from the solution of the nonlinear equation systems (6) and (7) for IR lamps with $d_{Qz}=0.02\text{ m}$, $d_{Fil}=0.004\text{ m}$, $L_{Qz}=0.35\text{ m}$, $S_{Fil}=0.044\text{ m}^2$, $\varepsilon_{Fil}=0.18$, $k_{argon}=0.018\text{ W/mK}$ and $\alpha_{argon}=0.125$ are shown in Table 1.

Verification of the Finite Element Model

For validation of the FE methodology, the experimental results of Cunningham et al. [7] are used. The experimental data refer to a 390 mm × 390 mm × 3 mm brass panel heated on the upper surface by IR lamps placed 200 mm above. Heating takes place in a closed oven using twelve 600 W IR lamps. The brass panel is coated with soot with an emissivity value of 0.95, a thermal conductivity of 159 W/(m K), a specific heat capacity of 380 J/(kg K), and a density of 8750 kg/m³. The center and corner temperatures are measured using thermocouples. Numerical predictions of temperature histories calculated by the developed FE simulation model are compared to the experimental data in Figure 6. The model agrees well with the experimental results throughout the heating cycle. In the steady state, the model slightly overestimates the middle node temperature by 10°C and the corner node temperature by 3°C.

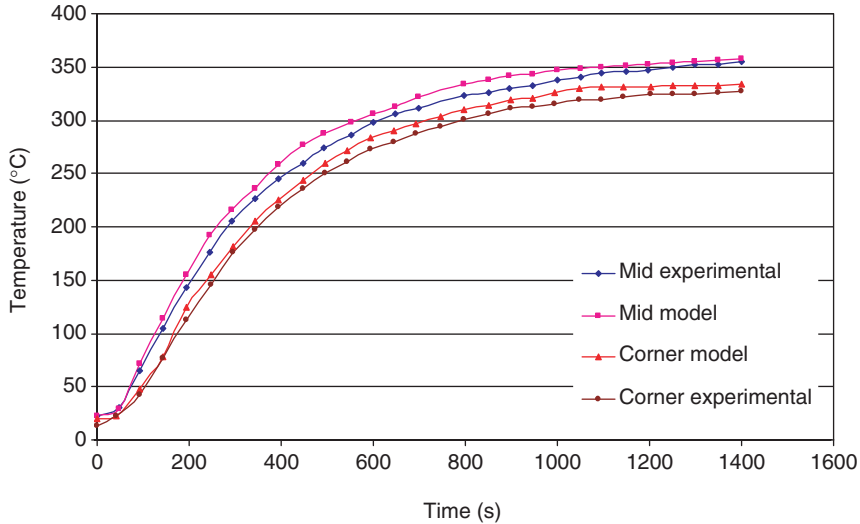


Figure 6. Comparison between computed and experimentally measured temperature histories.

It can be observed from Figure 6 that the corner nodes have lower temperature values than the middle nodes due to a higher convection rate and lower radiation energy. A slight deviation between the experimental and numerical results may be attributed to omission of the heat conduction towards the edge supports from the preheating model.

**APPLICATION OF THE DEVELOPED MODEL IN THE CASE OF
A SINGLE IR LAMP HEATING**

A parametric study of the preheating stage is carried out to investigate the maximum possible width that can be heated by one IR lamp at a specific target temperature, as a function of the plate thickness and the lamp position and power. Furthermore, the required preheating time for achieving the desired temperature values is computed, as it is an essential parameter, characterizing the cost efficiency and the productivity of the cold DF process. The plate thickness ranges between 1 and 5 mm, while the distance of the lamp from the thermoplastic (*h*) varies between 50 and 200 mm. In all cases, the IR lamp power varies between 500 and 3000 W. A preconsolidated carbon/PEI thermoplastic square laminate plate of 1.2 m edge is chosen for the study. To save CPU time, one-half of the plate is modeled, and symmetry boundary conditions are applied. The calculated

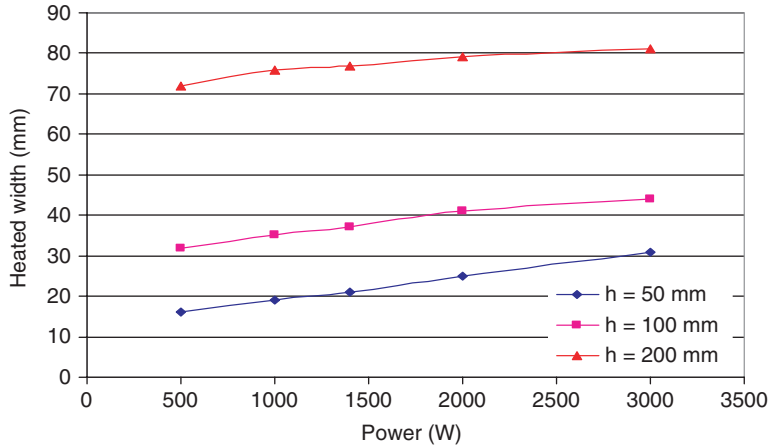


Figure 7. Heated width as a function of IR lamp power for different lamp positions over a 3-mm thickness plate.

width of the heated zone as a function of IR lamp power for different distances (h) between the lamp and the thermoplastic plate is shown in Figure 7.

In Figure 7, it can be observed that the size of the heated width increases as the IR lamp is raised: this is because the view factor increases when the lamp is placed further away from the thermoplastic plate. A similar trend is also observed for the other investigated plate thickness values.

The computed preheating temperature, as a function of plate thickness, for IR lamp power varying between 500 and 3000 W and IR lamp distance varying between 50 and 200 mm, is presented in Figure 8.

It can be observed from Figure 8 that the maximum achieved temperature value increases with decreasing plate thickness and increasing IR lamp power. In addition, increasing lamp power leads to a simultaneous increase of the heated width, due to the higher amount of radiation energy transferred to the plate material.

Consequently, the required preheating time to achieve the steady state temperature value is calculated. The simulation model predictions of the heating time as a function of thickness for IR lamp power varying between 500 and 3000 W and lamp distance varying between 50 and 200 mm, are shown in Figure 9.

It can be observed from Figure 9 that the heating time increases with increasing IR lamp distance from the thermoplastic plate, increasing plate thickness, and decreasing IR lamp power. It can be concluded from

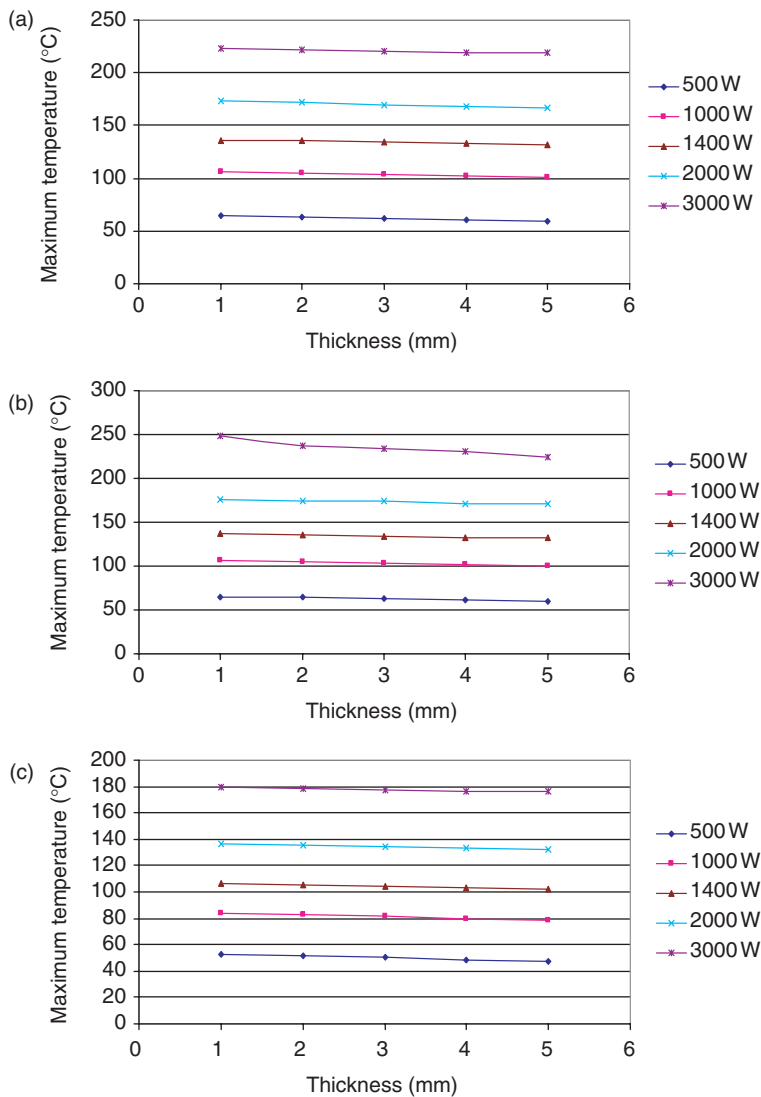


Figure 8. Predicted maximum temperature on the thermoplastic plate positioned: (a) 50 mm, (b) 100 mm, and (c) 200 mm below the IR lamp.

Figures 8 and 9 that the desired forming temperature, which is $300 \pm 15^\circ\text{C}$ for carbon/PEI, cannot be achieved using a single IR lamp. Therefore, a multi-lamp heating system is necessary to achieve the target preheating conditions.

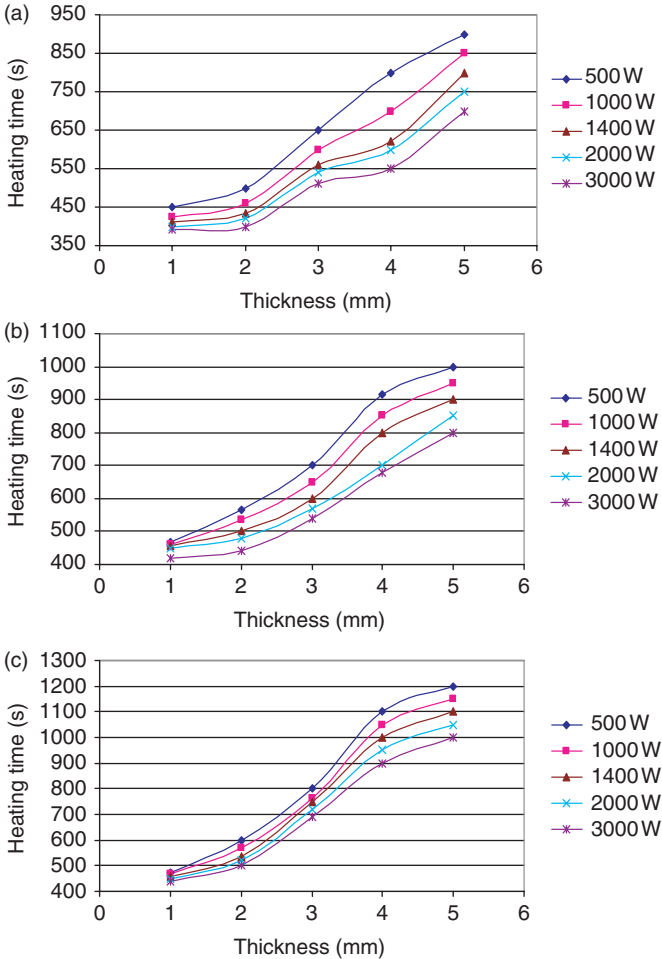


Figure 9. Predicted heating time for plate-IR lamp distance of: (a) 50 mm, (b) 100 mm, and (c) 200 mm.

INVESTIGATION OF THE PRE-HEATING STAGE USING MULTIPLE IR LAMPS

The developed FE model is extended for the case of multiple IR lamps, and an optimization study is carried out, aimed at predicting the best combination of forming parameters that will minimize deviations from the desired temperature value within the thermoplastic plate volume at the steady state. To achieve this goal, an optimization loop is executed

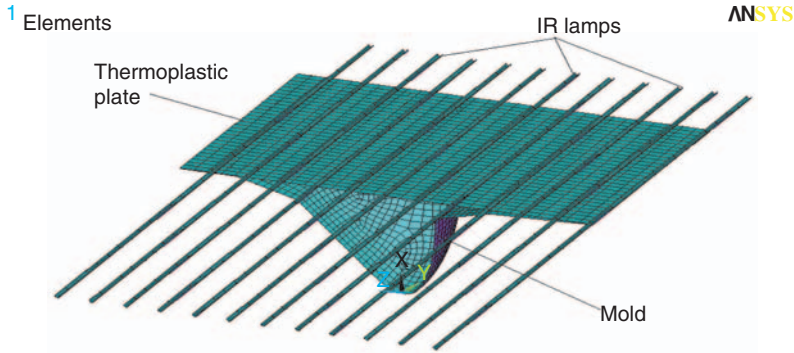


Figure 10. The FE model used in the optimization process.

until a viable solution is reached. The optimization variables of the current problem are divided into design variables, state variables, and the objective function. In the present case, the design variables are the IR lamp power varied between 450 and 2000 W, the distance of the IR lamp above the thermoplastic plate varied between 50 and 200 mm and the lamp pitch varied between 10 and 50 mm. The state variable is the steady-state temperature of any point of the plate, which is constrained to be within the limit of $300 \pm 15^\circ\text{C}$. The objective function is the difference between the maximum and minimum temperature values within the thermoplastic plate, which indicates the uniformity of the temperature distribution.

The sub-problem approximation method is used for this optimization. The sub problem approximation method is an advanced zero-order method that requires only the values of the dependent variables, and not their derivatives. The two concepts that play a key role in this method are the use of approximations for the objective function and state variables and the conversion of the constrained optimization problem to an unconstrained problem. For this method, the program establishes the relationship between the objective function and the design variables by curve fitting. This is done by calculating the objective function for several sets of design variables values (i.e., IR lamp power, distance between the plate and IR lamp and the IR lamp pitch) and performing a least squares fit between the data points. The resulting curve is called an approximation. Each optimization loop generates a new data point, and the objective function approximation is updated. It is this approximation that is minimized instead of the actual objective function. This gives the optimal solution. The FE model used in the optimization loop is shown in Figure 10.

Table 2. Optimal forming parameters for different plate thickness.

Thickness (t) [mm]	Number of lamps [–]	Power (P) [W]	IR lamp Position (h) [mm]	Top surface temperature [°C]		Bottom surface temperature [°C]		Heating time [s]
				Max	Min	Max	Min	
1	22	765	50.62	304.98	292.93	304.95	292.89	300
2	22	775	50.40	308.27	296.79	307.33	295.73	800
3	12	905	55.85	306.25	292.69	304.55	291.12	1200
4	12	710	50.47	309.15	296.78	308.15	296.12	2000
5	20	850	58.16	308.46	295.41	302.94	290.02	2500

The results of the optimization, i.e. the optimal number of lamps, IR lamp power, IR lamp–plate distance and heating time for thicknesses varying between 1 and 5 mm are presented in Table 2. In addition, the extreme temperature values calculated for each optimal solution is given in Table 2, indicating that the target temperature of $300 \pm 15^\circ\text{C}$ has been achieved.

In Table 2, the optimization results, i.e. the optimal combination of the forming parameters in order to achieve the required forming temperature, are presented. It can be observed from Table 2, that there is no specific relation between each one of the forming parameters, namely, number of lamps, lamp power and distance between lamp–plate, and plate thickness. This can be attributed to the fact that the three considered forming parameters do not act independently within the optimization loop but they are strongly inter-related, thus their combined action leads to the optimal solution.

SIMULATION OF THE FORMING PHASE

The purpose of the thermomechanical simulation of the forming phase is to determine the mold temperature which is required in order to limit the heat losses due to the progressive contact between the mold and the thermoplastic plate and to maintain the forming temperature of $300 \pm 15^\circ\text{C}$ during the entire forming phase. A mechanical analysis is initially performed by applying a pressure gradient on the top surface of the thermoplastic plate forcing it to gradually deform into the shape of the mold. The calculated deformed shapes are introduced in a consequent thermal analysis, from which the required heating temperature of the mold is computed.

Mechanical Analysis

A mechanical FE model is developed where the mold is simulated using element Targe170, which represents a 3D target segment. The thermoplastic

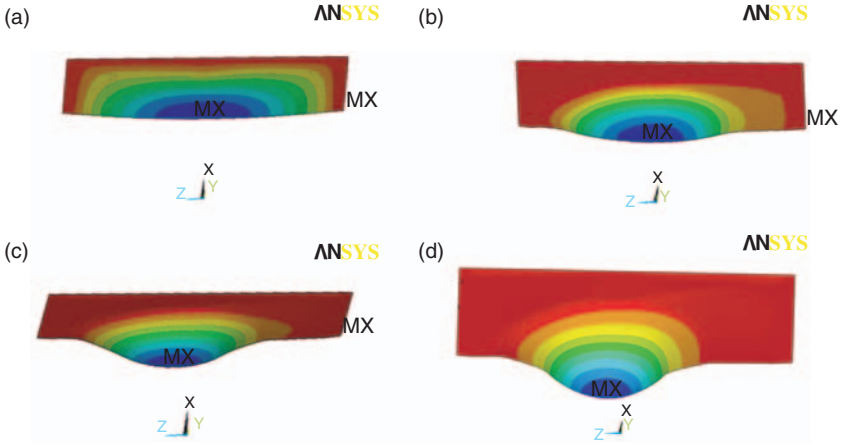


Figure 11. Deformed shapes of the thermoplastic plate: (a) 0.7 bars pressure, (b) 3 bars pressure, (c) 5 bars pressure, and (d) 7 bars pressure.

plate is simulated using element shell181, which is suitable for analyzing thin to moderately-thick shell structures, having six degrees of freedom at each node, i.e. translations and rotations in the x , y , and z -axes. The element is well-suited for linear, large rotation and/or large strain nonlinear applications.

The interface phenomenon at the contact surfaces between the plate and the mold were simulated using a sliding model with separation and friction. This involves introduction of Conta175 elements on the plate surface, which are paired with the target elements of the mold via a shared real constant set. The value of Coulomb's friction coefficient μ was assumed to be 0.03.

The Carbon/PEI considered in the current analysis has a Young's Modulus value ranging between 17 GPa and 196 GPa for the temperature range of 350°C to 25°C , respectively. A 7-bar pressure load is slowly applied, which gradually deforms the thermoplastic plate. In Figure 11, deformed shapes at various forming intervals are presented.

Plate-mold Post-heating Analysis

During the deformation stage the thermoplastic plate loses heat mainly through conduction to the mold. Heat transfer by convection is considered negligible due to the small forming time. In order to maintain the thermoplastic temperature within the desired range of $300 \pm 15^{\circ}\text{C}$, the mold has to be heated. A parametric study is carried out, whereby the mold is heated at different temperatures and the heat losses for each case

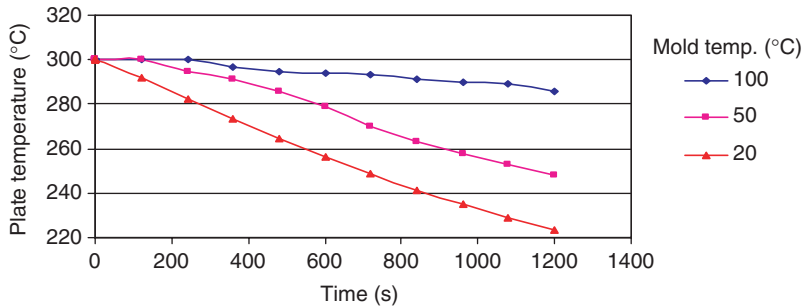


Figure 12. Temperature history of the central node of the thermoplastic plate for mold post-heating.

are calculated. The thermoplastic deformed shape is transformed from element shell181 to element shell131, which has thermal capabilities.

The temperature history of the central node of a 3-mm thermoplastic plate, for mold temperatures of 20°C, 50°C, and 100°C is presented in Figure 12.

From Figure 12, it can be observed that when the mold is not post-heated, i.e. it has the temperature of 20°C, the plate nodal temperature drops to around 230°C by the end of the forming phase, while for a mold temperature of 50°C, the plate temperature drops to around 250°C. In order to maintain the plate temperature within the desired $300 \pm 15^\circ\text{C}$ limits, the mold should be heated at 100°C.

CONCLUSIONS

1. A simulation model capable of simultaneously predicting the mechanical deformation and the thermal response during the preheating and forming phases of the “cold” DF process has been developed.
2. The simulation model has been used in the optimization of the IR preheating and forming process parameters, namely, mold temperature, IR lamp power, position and pitch, for several thicknesses of carbon/PEI thermoplastic plates.
3. The use of IR lamps in the ‘cold’ DF process has a great potential of minimizing heating times by achieving the uniform temperature distribution required to ensure the mechanical and thermal properties standards.
4. In order to minimize heat losses by conduction between the thermoplastic plate and the mold, heating of the mold is necessary; this ensures that the

forming temperature is within the acceptable limits throughout the deformation stage.

5. The proposed simulation methodology may be applied for the optimization of the DF of different geometrical configurations and various thermoplastic material systems.
6. There is no specific trend of the optimized values of each forming parameter with respect to the plate thickness, since the three considered forming parameters act in a very interrelated way and not independently.

ACKNOWLEDGEMENTS

This work was partially funded by the DINAMIT project, contract number AST3-CT-2003-5022831 of the Commission of the European Communities.

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