Cost and Temperature Homogeneity Optimization of the Heating System for Composite Materials Air Press Molding

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ABSTRACT

Due to their high strength to weight ratio, composites materials have been historically used in high performance applications. Nowadays, they are no longer considered elitist materials due to the decrease of manufacturing costs reached thanks to innovative process processes such as Liquid Composite Molding (LCM) or pre-preg molding. The latter is suitable for structural parts, but its use is limited to simple geometry components without undercuts due to the rigid counter mold. Thus, a method called Air Press Molding (APM) has been developed. It exploits an inflatable counter mold to compact the laminate on the mold. This paper presents a Multi-Objective optimization approach for minimizing cost and temperature inhomogeneity of the heating system of the APM process. By using Genetic Algorithms and the Response Surface Methodology, the authors redesigned a 1250 [kg] aluminum mold, reaching a cost saving of 15 % and reducing the temperature variance of 77 %.

Keywords: Multi-Objective Optimization, Composite Materials, Mold Heating, OOA Processes
DOI: https://doi.org/10.14733/cadaps.2019.1084-1097

1 INTRODUCTION

Advanced composite materials, especially those based on carbon fiber, have been gaining considerable attention in the last years due to their high performance and lightness. Special interest is posed by stakeholders coming from the automotive sector where the research about lightweight materials represents a key aspect for reducing emissions and for increasing vehicle autonomy [13]. Moreover, thanks to the advance on the field of composite manufacturing, their commercial price is constantly decreasing [10].

The system composed by carbon fiber and epoxy resin is recognized as the best choice for producing high-performance components [1]. The classical manufacturing process of CFRP (Carbon Fiber Reinforced Polymer) automotive parts is based on pre-impregnated laminates stacked in a mold and cured in autoclave. However, this process does not allow a high production rate typical of the automotive sector. Indeed, it is a manual process that leads to long cycle time for the hand lay-up of the prepreg in the mold, especially for large and complex products. Moreover, it is characterized by long processing time in the autoclave for the complete polymerization of the resin system, contributing to increase the already high cost of CFRP. For these reasons, several researches have been conducted to overcome these issues.

In this framework, OOA (Out-Of-Autoclave) processes have been identified as the most promising to overcome the limitations of the traditional manufacturing approaches [11]. They can be divided in two main groups: one based on prepregs and the other based on dry fibers. The latter is commonly known as RTM (Resin Transfer Molding) and, in face of high investment costs, it can be used for producing high performance components with a reduced lead time. In this closed mold technology, once the dry fibers are stacked in the mold cavity, the resin is injected, and it flows into the preform. The curing of the resin is obtained increasing the temperature of the mold via conduction, induction or IR [12]. The OOA methods based on prepreg technology exploit closed mold systems and presses to replicate the same compaction behavior of the autoclave. However, these methods are limited in presence of undercuts due to the rigid counter mold. Moreover, it is economically viable only in case of large orders and high production rates (i.e. mass production). To overcome these issues, an Italian company has developed a method based on an inflatable counter mold, which requires lower investment and maintenance costs. This innovative process, named *"Air Press Molding"* (APM), exploits a flexible counter mold made of rubber and a metallic mold where the prepreg is hand laminated.

APM is based on three main steps: hand lay-up of the prepreg over the metallic mold, positioning and inflating of the flexible counter mold between 0.2-1 [MPa], compaction and curing of the resin in a press. The cure cycle is a characteristic of the chosen matrix system and can take up to 4 hours for the complete polymerization of the resin. During this time, the pressure must be maintained steady. A specific ramp must be respected during the heating process in order to avoid matrix degradation or voids growing [1]. A typical heating ramp (4 [°C/min]) is reported in Figure 1.

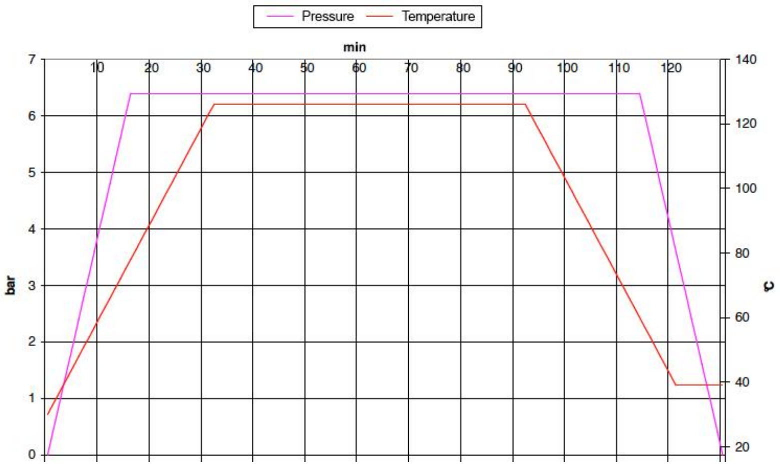

Figure 1: Typical heating ramp of a prepreg system.

To guarantee the correct polymerization of the matrix and the minimization of the cycle time, every part of the mold cavity must follow the same heating ramp. An efficient heating of the mold is essential for producing high performance and cost-effective CFRP components.

Differently from the RTM process where the heat flow is conducted also by the metallic counter mold, in the APM process this cannot be exploited due to the low thermal conductivity of the rubber. Thus, to achieve temperature homogenization of the mold surface, additional heaters must be provided inside the mold. Therefore, special attention must be paid in the design of this heating system.

Numerical modeling, thanks to the great advancement in computer technologies and algorithms, has become an efficient tool to investigate and understand real products behavior and it has been playing a crucial role in the design and optimization of complex products/systems. Moreover, companies can experience great advantages in integrating and using methods and tools for Multi Objective Optimization (MOO) to reduce computational time/cost of numerical simulations. DoE (Design of Experiment) technique [3] is a widely known method that allows engineers to reduce the number of experiments exploring the entire problem domain. It is a useful approach when a Multi-Objective Optimization (MOO) with multiple variables is involved. After DoE analysis is carried out, RSM (Response Surface Methodology) [5] and GAs (Genetic Algorithms) [8] can be exploited to easily analyze several alternatives and to find the optimal one.

Much research in recent years has been focused on the design and optimization of conduction heating of metal molds. Xi-Ping li et al. [17] used a combination of thermal simulations, RSM and GAs to design a mold for plastic injection with the aim of reducing the cycle time and homogenizing the surface temperature. Similarly, by the same authors, other studies have been conducted concerning the optimization of the heating channel in plastic injection [15], [16]. Abdalrahman et al. [2] analyzed and optimized the fluid heating system of a tool for producing composite parts. They performed numerical simulations to compare different layouts of the heating channels with the aim to limit the uneven temperature distribution on the mold surface. They found the optimum layout through Taguchi’s optimization algorithm. In a similar way, Collomb et al. [7] studied the influence of the heating channel geometries on the cycle time and on the temperature distribution. In this study, they performed structural-thermal simulations to guarantee compliance with the prescribed stress safety factor of the tool.

Although these studies improved performances of molds heating, they do not take into consideration cost as a variable during the optimization process. Numerical simulations allow only to evaluate the heating behavior without providing direct information about energetic, manufacturing and purchasing costs. However, especially if the tool has a long lifespan, the costs related to the heating process can be very high. Moreover, no research studies are present about the optimization of a mold for press molding under flexible tool. For these reasons, the authors developed a multi-objective optimization strategy for supporting the engineers during the design of heating system for the APM process, considering heating and mechanical performances and costs.

2 PROBLEM PRESENTATION

The problem faced in this research study is the optimization of an aluminum mold to produce a CFRP front bumper for a supercar. The bumper is 1720 [mm] long and weights 3.7 [Kg]. This mold weights 1250 [Kg] with a length of 2200 [mm], height of 642 [mm] and width of 728 [mm]. It is produced by milling a block of aluminum. The production rate is 4 bumpers per day for 3 years.

The press for performing the APM process is a 120 [ton] hydraulic press with hot plates for heating molds. These steel hot plates have size of 2000 x 3000 [mm] and present a total of 6 internal cartridge heaters for a total of 36 [kW]. Moreover, due to the significant size of this bumper, additional cartridge heaters are designed inside the mold for obtaining a rapid and efficient heating. A scheme of the APM equipment is reported in Figure 2.

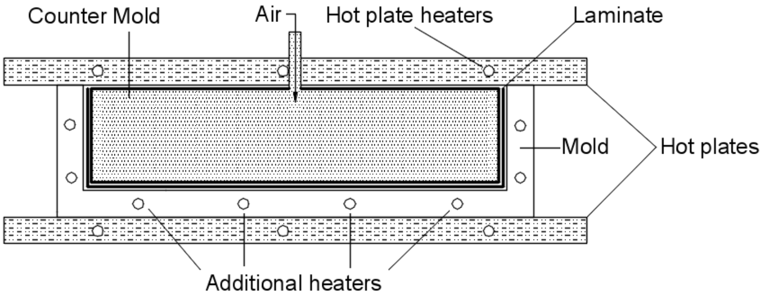

Figure 2: Representation of the APM equipment.

The cure conditions imposed by the resin system are reported in Table 1. along with the main specifications of the mold and hot plates.

Mold and hot plates specifications	
Mold dimensions	2200 x 642 x 728 [mm]
Molds weights	1250 [kg]
Mold material	aluminum
Hydraulic press force	120 [ton]
Hot plates dimensions	2000 x 3000 [mm]
Hot plates material	steel
Hot plates heaters	6 x 6 [kW]
Curing process conditions	
Consolidation pressure	0.6÷0.8 [MPa]
Heating ramp rate	1÷2 [°C/min]
Curing cycle	60 [min] @ 120 [°C]
Cooling rate	2÷3 [°C/min]

Table 1: Mold and hot plates specification and cure conditions of the resin system.

The curing temperature of 120 [°C] should be reached in 1 hour in order to minimize the cycle time. The compliance of the heating ramp and curing cycle are fundamental aspects for avoiding uncured components. For this reason, special attention must be paid for guaranteeing that every part of the mold cavity respects the cure conditions. The position and heating capacity of the additional cartridge heaters and the thermal inertia of the hot plates play a crucial role in reaching optimal conditions for the curing process. In particular, the thermal inertia of the hot plates has a great influence on the heating process due to their relevant mass. The thermal inertia of the hot plates can be managed by changing the thickness. Past company experience led to the conclusion that, in order to have a proper polymerization of the all component, the temperature gradient in the mold cavity should not exceed ±5 % with respect to the curing temperature. This means that the cure condition can be reached between 57÷63 [min] and the cure temperature can vary between 114÷126 [°C].

The costs of the heating process can be divided in two main groups: costs related to the additional heaters and costs related to the hot plates. These costs take into consideration manufacturing, purchasing and operating costs.

3 METHOD

The research approach exploited in this work is based on a previous study conducted by the same authors [6]. They developed a method for the multi-objective optimization of mechanical products in order to achieve the right trade-off between costs and performances. Their approach was based on three blocks: numerical simulation, costs estimation and design optimization. They used a DfC (Design for Cost) software for the manufacturing costs estimation and a FEM software for the numerical simulation. An optimization tool integrates, in a unique framework, the previous mentioned software, and automatically drives the optimization process by combining RSM [5] and GAs [8].

The next sections present the thermal and structural analysis, the cost model and the optimization process.

3.1 Thermal and structural analysis

The heating uniformity of the mold cavity during an APM curing process is analyzed through a transient thermal simulation performed using ANSYS© software suite. Moreover, based on the results of the thermal analysis, thermal-structural simulation was carried out to investigate the mold structural strength.

Since the mold symmetry, it is possible to simplify the finite element model considering only half part of the cavity (shown in Figure 3.). The mold is made by milling an aluminum alloy which ensures not only excellent thermo-mechanical characteristics but also lightness and high thermal conductivity. Table 2. summarizes aluminum and steel materials properties.

Aluminum properties		**Young modulus**	**Yield strength**	**Thermal conductivity**	**Thermal expansion**
Density ρ =2700 [kg/m^3]	T [°C]	E [GPa]	σ [MPa]	k [W/mK]	$\alpha 10^{-6}$ [1/K]
Poisson coefficient ν=0.35	20	69.3	503	178	22.7
c_p= 890 [J/kgK]	100	65.6	434	180.73	22.8
	200	59.2	110	185.16	23.5
Steel properties		**Young modulus**	**Yield strength**	**Thermal conductivity**	**Thermal expansion**
Density ρ =7850 [kg/m^3]	T [°C]	E [GPa]	σ [MPa]	k [W/mK]	$\alpha 10^{-6}$ [1/K]
Poisson coefficient ν=0.3	20	210	566	57.5	12.1
c_p= 461 [J/kgK]	100	210	566	54.8	12.5
	200	189	549	51.5	13.0

Table 2: Aluminum and steel properties.

3.1.1 FEA theory of transient thermo-structural analysis

The numerical calculations were performed according to the general equation based on the first law of thermodynamics that states that thermal energy is conserved:

$$\rho c\left(\frac{\partial T}{\partial t}+\{v\}^T\{L\}T\right)+\{L\}^T\{q\}=\ddot{q} \tag{3.1}$$

where ρ is density, *c* is specific heat, *T is* temperature, *t* time, $\{L\} = \begin{Bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{Bmatrix}$ is vector operator, $\{v\} = \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix}$ is velocity vector for mass transport of heat, $\{q\}$ is heat flux vector and $\{\ddot{q}\}$ is heat generation rate per unit volume.

Fourier's law was exploited to correlate the heat flux vector to the thermal gradients:

$$\{q\} = -[D]\{L\}T \tag{3.2}$$

where $[D] = \begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix}$ is conductivity matrix with K_{xx}, K_{yy}, K_{zz} conductivity in the element x, y and z directions respectively.

The temperature variation can produce the structural deformation of the object, including thermal expansion and contraction. In this study, to solve the thermo-structural problem, a relationship between the temperature field and the stresses field was set. The coupled thermo-elastic constitutive equations were established:

$$\{\sigma\} = [D]\{\varepsilon\} - \{\beta\}\Delta T \tag{3.3}$$

$$Q = T_0\{\beta\}^T\{\varepsilon\} + \rho c_v \Delta T \tag{3.4}$$

where $\{\beta\} = [D]\{\alpha\}$ is the vector of thermo-elastic coefficients and c_v is the specific heat at constant volume.

The element instantaneous total strain energy U_t in static and transient thermo-elastic analyses was calculated as:

$$U_t = \frac{1}{2}\iiint \{\sigma\}^T\{\varepsilon\} dV \tag{3.5}$$

3.1.2 Boundary conditions and basic assumptions

The starting temperature of the mold is assumed to be uniform and equal to 22 [°C], corresponding to the air temperature in the workshop. On the external lateral surfaces is imposed free air convection condition with a value for the film coefficient of 15 [W/(m^2°C)]. The symmetry plane of the model is loaded with adiabatic condition. The inner surfaces of the mold as well as the plate outer surfaces are also loaded with adiabatic condition because they can be considered well insulated. The initial temperature of the heating plates is assumed to be 170 [°C]. On the surfaces of internal heaters is imposed a heat flow of maximum magnitude W_h equal to 1000 [W]. The heating time considered has been of 7200 [s] with a time step of 100 [s]. An on-off controller is used to manage both the plates and the heaters. The on-off controller is implemented using the APDL language. The temperature set-point of the controller is set to 120 [°C] with a tolerance of ± 5 [°C].

The initial heating of the hot plates (from the ambient temperature to the reference temperature) was not took into consideration in this analysis. The energy required by this phase has been estimated to be negligible compared to that needed by the entire mold life cycle (<3%). Moreover, also the energy consumed by the plates, between the end of a curing process and the begin of the subsequent one, was considered irrelevant. The plates, waiting for a new curing process, are brought into contact with each other and the thermal dispersion is minimal.

During the curing process, the mold inner surface will be subjected to high pressure. Therefore, with the aim to reduce the surface deformation and enhance its durability, the mold must be strong enough. The geometrical arrangement of the heaters has a great influence not only on the thermal behavior but also on the structural strength. Indeed, although locating the heating channels close to the mold surface can improve the heating performance, it decreases the mechanical strength. In addition, irregular thermal expansion of the cavity may lead to stress concentration and large thermal stress.

For the structural analysis, the inner surface of the cavity is loaded with a uniform pressure of 1 [MPa]. Fixed supports, blocking all the freedom degrees of the entities, are imposed on the hot plates outer surfaces as well as on the mold lateral surfaces and on the symmetrical plane. The contacts between the mold and the plates are modeled as bonded: surfaces are fixed each other so, no gaps can open and no sliding can take place.

Numerical models have been validated through experimental test. The maximum error in the simulations of the heating process and mechanical response is less than 5%.

3.2 Cost analysis

One of the goal of this study is the cost optimization of the molding, reducing the energy consumed during the curing process. Indeed, in case of energy-intensive tools with a long service life, this reduction can lead to great economic savings. Castorani et al. [6] in their optimization method proposed to use a commercial software for costs evaluation. However, for this study, using a cost evaluation tool, such as LeanCost© by Hyperlean©, is out of purpose. Definitely, this software is able to calculate only the manufacturing cost of a product while it is not able to calculate its operating cost.

In this case, the life cycle mold cost C_m can be calculated as following:

$$\begin{cases} C_m = C_e + C_{p,p} + [C_{p,h} + C_d + C_i] \cdot F_h \\ C_{p,p} = V_p \cdot C_{u,p} \\ C_{p,h} = n_h \cdot C_{u,h} \\ C_d = n_h \cdot C_{h,d} \\ C_i = n_p \cdot n_h \cdot C_{h,i} \\ C_e = n_p \cdot (C_{s,e} \cdot E_c) \cdot F_e \\ C_{h,x} = (T_{h,x} \cdot CU_{h,x}) \cdot F_{h,x} \end{cases} \tag{3.6}$$

C_m has been modeled as a function of:

- cost for the consumed energy C_e [€],
- hot plates purchasing cost $C_{p,p}$ [€],
- heaters purchasing cost $C_{p,h}$ [€],
- cost for the drilling operation of the heating channels C_d [€],
- installation cost of the heaters C_i [€]
- corrective factor F_h.

The purchasing cost of the hot plates is modeled as a function of the plates volume V_p and the cost per unit of volume $C_{u,p}$ [€/m^3] of an aluminum block obtained per milling. The cost related to the heaters has to be increased of a corrective factor F_h (dependent on the kind of heater) to take into consideration maintenance cost (component substitution, as a result of breakage, and related labor). The heaters purchasing cost as well as the drilling cost is achieved multiplying the number of internal heaters n_h respectively for the unitary purchasing cost $C_{u,h}$ and for the cost of one drilling operation $C_{h,d}$. $C_{u,p}$ (unitary cost) is retrieved from a database of commercial components. The installation cost is multiplied, besides by the number of heaters, by the number of part to be produced n_p since they have to be removed from the mold at the end of each curing process for safety reasons. The specific energy prize $C_{s,e}$ [€/kWh] is found on the Europe's Energy Portal (https://www.energy.eu). The amount of energy consumed during a curing process E_c [kWh] is calculated from the thermal simulation results. It is important to highlight that it is necessary to consider the increase in energy prices over time with an over-head factor F_e. The installation and drilling cost is a multiplication between the hourly rate of a worker $CU_{h,x}$ [€/h] and the time required for these operation $T_{h,x}$ [h] with a corrective factor $F_{h,x}$. $T_{h,x}$ [h] values are retrieved from a database of standard times, developed by measuring the installation phase of the various kind of heaters. $F_{h,x}$ is a value to acknowledge the cost of the accessory material used for the installation, this cost depends on the kind of heater. The manufacturing cost of the mold is not accounted as it does not vary during the optimization of the heating channels layout.

The proposed cost model has been validated through the confrontation with real data: the cost estimation error is less than 5 %.

3.3 Optimization

The numerical models, describing the functional relationship between layout, peak power of the heaters Wh [W] and plates thickness t with respect to temperature distribution and structural strength of the mold, have been achieved exploiting Design of Experiments - DoE techniques [3] and Response Surface Methodology - RSM [5]. Then, these models have been explored to retrieve the optimal mold configuration thanks to MOGA-II genetic algorithm [8]. ModeFrontier® optimization platform has been used to integrates, in a unique framework, the tools for the thermo-structural evaluation and cost calculation, and to automatically drive the optimization process.

3.3.1 Design optimization theory

The first step of an optimization process consists in a proper definition of the optimization problem. Optimization problem definition is achieved through the following three steps:

1. choice of the variables to parametrize the design problem: design variables and their bounds;
2. definition of the quantity to minimize or maximize: objective functions;
3. formulation of the conditions to satisfy: design constraints.

Once the optimization problem is formulated, in order to speed-up the optimum research, DoE techniques along with RSM and genetic algorithms GAs can be exploited.

The DoE [3] is a statistical tool that can be employed in several industrial problems. It deals with engineering problem-solving and enables designers to evaluate the effects that the simultaneous variations of design variables have on response variables (objective functions). Synthetically, it is exploited to find the cause-effect relationships with the least consumption of resources; i.e. with the minimum amount of experiments. This knowledge is necessary to manage the optimization of a product design. DoE can determine meaningful interactions that may be missed when the traditional one-factor-at-a-time OFAT approach is used as experimenting strategy. Numerous DoE strategies have been reported in scientific literature.

The Response Surface Methodology – RSM [5] is a collection of mathematical and statistical techniques exploited to build a mathematical correlation between design variables and responses. It enables engineers to run numerous design evaluations in a limited time, speeding-up the optimization process. It can be well applied when a response/s are influenced by several design variables. RSM is able to exploit a limited set of data (coming from the DoE plan) with an agile utilization of the computational resources. Traditionally, the most common forms of the mathematical approximation are low-order polynomials (first or second-order):

$$y = f(x_1, x_2, \dots, x_n) + \epsilon \tag{3.7}$$

where y is the response, f is the response function, x_1, x_2, . . ., x_n are the design variables, *n* is the number of the design variables and finally ϵ is the statistical error.

The generated response surface can be efficiently explored through a suitable optimization algorithm to identify the optimal solution.

Genetic algorithms - GAs [7] are very general optimization algorithms that have been successfully applied to a wide variety of complex industrial problems. They can be used to solve all different type of problems: continuous, discrete, non-differentiable. The attractiveness of these methods is their simplicity to use and program and capability to reach global optimum solutions. GAs are inspired by the Darwin's theory of natural evolution: "survival of the fittest". The process begins with a sets of individuals (population) randomly generated. Fitness functions have to be defined. These functions are needed to determine how fit an individual is. A fitness score is assigned to each individual. The chance of an individual to be picked for the reproduction phase depends on its fitness score. A new population is generated through a random process from the picked subset of individuals. The probability to have more fit individuals in the next sets is greater with the generation of new populations. This process is iterated till convergence criterion are reached.

3.3.2 APM heating system optimization

The geometrical layout of the heating channels can be defined by the following entities (as shown in Figure 3.): number of channels n_c, distance from the axes starting point of the channels to the mold surface d_s, distance between two adjacent channels d_c and diameter of the channels D.

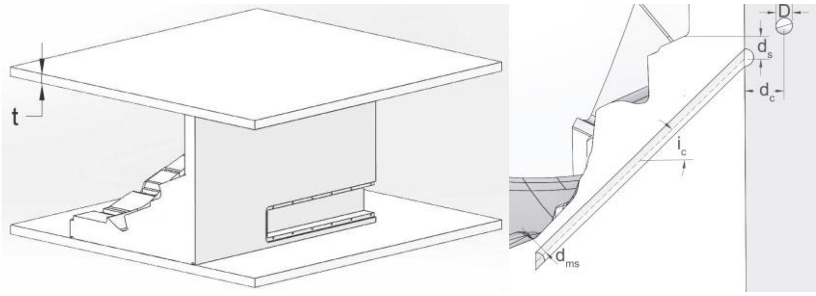

Figure 3: Investigated mold (on the left) and main geometrical entity of the channels layout (on the right).

The optimization process starts from these assumptions. The channels are equidistant from each other and d_s is the same for each channel. One kind of heater is used during the curing process, whose geometry is independent of the peak power. Therefore, D is constant and set at 20 [mm]. All the internal cartridge heaters have the same peak power W_h. The channels must reach a distance of 100 [mm] from the center of the mold. Moreover, the minimum distance between the axes of the channels and the mold surface d_{ms} must be at least greater than D. The maximum temperature on the mold surface $T_{max,s}$ in the time interval from the beginning of heating to 3600 [s] have to be less or equal to 120 [°C]. This mold has been designed to produce 3000 CFRP parts. The hot plates have the same thickness t.

Table 3. reports the variables to be optimized with their relatives investigated range, the goals to achieve and the constrains to satisfy.

Variables	***Range***
n_c [# of heating channels]	[19÷24]
d_s [mm]	[25÷50]
W_h [W]	[700÷1000]
Heating channel inclination i_c [°]	[0÷60]
t [mm]	[30÷70]
Goals	***Kind***
C_m [€]	minimize
ΔT [°C]	minimize
Constraints	
Safety factor	≥ 1.5
d_{ms} [mm]	> D
$T_{max,s}(t)\ \forall t \in [0,3600\ s]$	≤120 [°C]

$T_{ave,s}$(3600 s)	=120 [°C] ± 5%

Table 3: Variables, goals and constraints of the optimization problem.

Figure 4. shows the optimization workflow reached using ModeFrontier® optimization platform. The geometric variables have been managed and modified according to the scheduled DoE by means of a parametric CAD tool: Catia® V5. The Latin Hypercube sequence has been chosen as DoE. A script has been developed to define the arrangement of the heaters along the mold and, thanks to the Ansys® suite, thermal and structural simulations have been performed. At this stage, the variables inherent to the heaters capacity can be analyzed. Finally, the manufacturing and operating costs are evaluated through a script implementing the developed cost model.

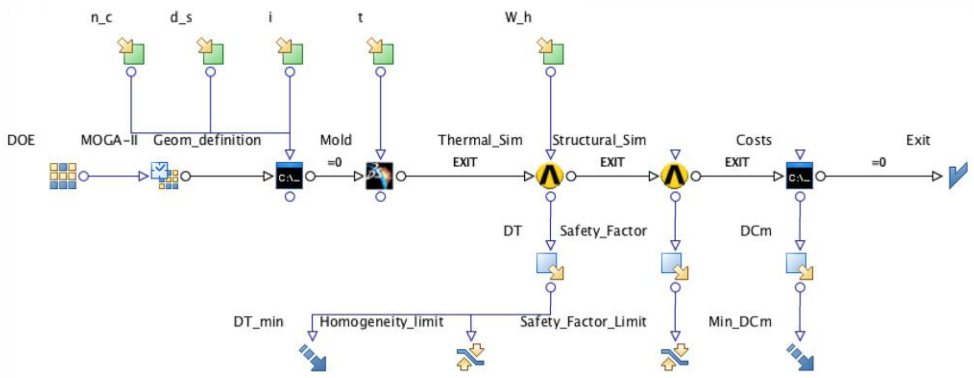

Figure 4: Workflow of the optimization process.

4 RESULTS

The paper presented the design optimization of the heating system of a mold for the production of CFRP components using the innovative APM process. In the first attempt design, the metallic mold is heated by conduction from two hot plates with a thickness of 50 [mm] and from 20 cartridge heaters (1000 [W] each) equally spaced along the mold. However, with this initial design configuration, there was an unequal temperature distribution on the mold cavity, with a variation of ±15% respect the heating ramp of the matrix system. This first configuration has been reached in a traditional way, exploiting the past experience of the designers, without the aid of any CAE/DfC software tools.

The authors were able to achieve the required temperature homogeneity on the mold cavity for guaranteeing the correct matrix polymerization. The heating ramp of 2 [°C/min] has been respected. Figure 5. shows the temperature mold distribution of the optimal configuration at 3600 [s]. The maximum and the minimum temperature on the mold surface are respectively 124.6 [°C] and 114.9 [°C], which means +3.8 % and -4.3 %. Due to the confidentiality of the data, they cavity surface has to be hidden and the mold cost is reported as delta cost with respect the initial design and cost breakdown is presented in percentage.

Figure 6. displays the solution analyzed through MOGA-II algorithm. The i_c and d_s variables are not showed in Figure 6. to increase its readability as they have a minimal influence on the objective functions. Different solutions achieved the goal of minimizing the temperature variation while respecting structural constraints. However, not all these configurations allowed to reduce the cost (respect to the first design).

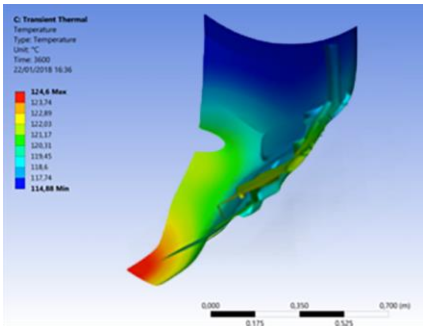

Figure 5: Temperature distribution of the mold cavity at 3600 [s].

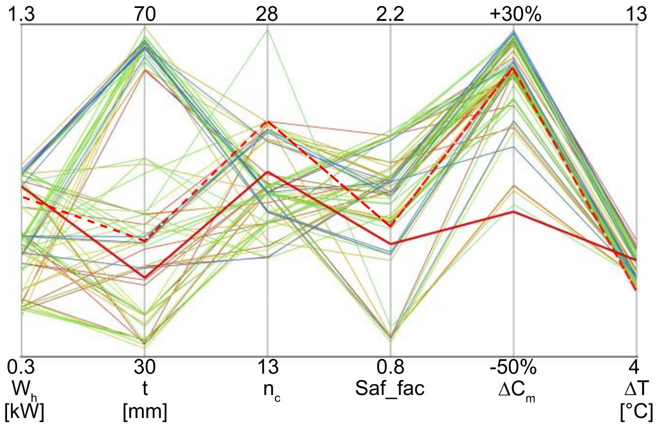

Figure 6: Spaghetti graph of the analyzed configurations. The red line shows the optimal configuration while the dashed one the optimal configuration not considering the cost minimization as optimization objective.

Figure 7a and Figure 7b illustrate the response surface respectively of the delta cost and of the average temperature variation over the time as function of heaters number and capacity. The delta cost, in most cases, decreases with the heaters number and increases with the heat capacity. The average temperature variation rises with the heaters capacity and is nearly independent (slight growth) with the heaters number. The heaters number does not influence directly the cost but plays a fundamental role in guaranteeing the homogeneity of the temperature of the mold cavity.

The average variance of the temperature on the surface of the optimized mold over time is equal to an average value of 7.6 [°C]. It was possible to reduce the average temperature variance by a 77 % (from 33.4 [°C] to 7.6 [°C]). During the initial heating phase, it is noted a greater inhomogeneity, which tends to disappear as the curing process proceeds. At the time 720 [s], it is recorded the maximum temperature variance of 32.3 [°C]. While, the minimum value is reported at 3300 [s] with a value of 4.85 [°C].

A trade-off between the two objectives was needed to identify the optimal solution. The cost minimization was chosen to be the priority of this research study. Therefore, the solution that allowed the most important cost reduction (Figure 7a.) was chosen as the optimal one (red line in Figure 6.). The configuration that minimize the cost presents 21 heaters with 900 [W], ic of 30° and ds of 28 [mm]. This result, even if it did not minimize the temperature variance (Figure 7b.), respected the thermal and structural constraints. This solution presents hot platens with a thickness of 39 [mm].

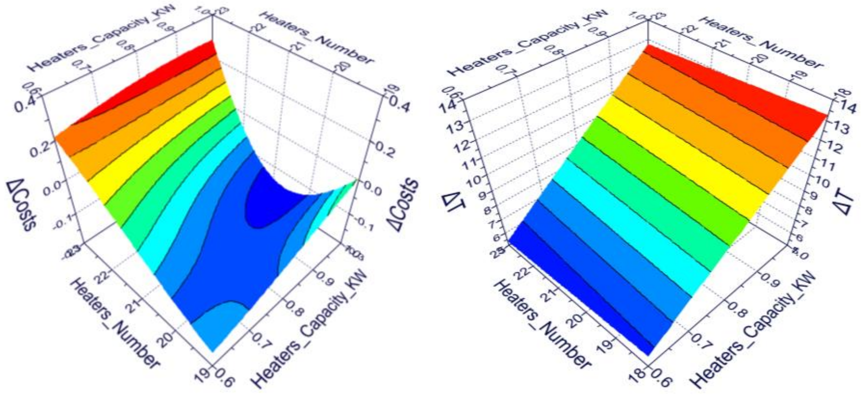

Figure 7: Response surface: a) delta cost; b) average temperature variation.

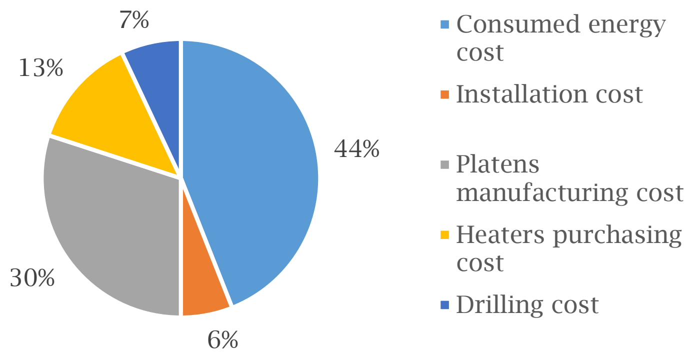

Figure 8: Cost breakdown of the optimal solution.

As highlighted in Figure 8, the consumed energy is the predominant cost item due to the long-life span of the system. The second major effect is related to the hot platens. This is due to the high acquisition and manufacturing cost of these steel parts. The installation cost of the heaters, even if is an operation repeated numerous times, is the minor cost item. A cost saving of 15 % has been obtained considering the production of 3500 CFRP parts.

One of the novelty of the proposed paper is to take into consideration the cost as one of the objective functions. If the cost is neglected in the optimum research a different solution is found: the dashed red line in Figure 6: Spaghetti graph of the analyzed configurations. The red line shows the optimal configuration while the dashed one the optimal configuration not considering the cost minimization as optimization objective. Figure 6. represents the achieved configuration considering only the temperature homogenization as optimization objective. This solution presents 27 heaters with 850 [W], ic of 35° and ds of 31 [mm]. It would lead to a temperature inhomogeneity of 5 [°C] with a cost increment of about 20 % respecting all the thermal and structural constraints. This solution presents hot platens with a thickness of 39 [mm].

5 CONCLUSIONS AND FUTURE WORKS

In this paper, a multi-objective optimization of the heating system of Air Press Molding has been presented. The optimization strategy of this innovative manufacturing process of CFRP components is based on the use of genetic algorithms and response surface methodology. The variables optimized during this process were the position and the heating capacity of the heaters inside the mold and the thermal inertia of the hot plates. The constraints that must be respected are the uniformity of the temperature on the mold surface and the heating ramp prescribed by the resin system. Moreover, structural constrains are considered in order to guarantee the strength requirements. The objectives to be reached are the minimization of the cost (manufacturing, purchasing and operating cost) and the temperature inhomogeneity on the mold surface.

The heating behavior of the mold has been analyzed exploiting a dedicated CAE software while the evaluation of the costs has been conducted using formalized rules. The optimization process has been performed using a dedicated software tool able to drive and integrate the CAE software and the formalized rules. 48 different configurations have been automatically analyzed for a total computational time of 254 hours. Designers' effort was marginal once the process has been set. Indeed, the use of the DoE techniques and Response Surface Methodology guarantee a strong reduction of the optimization time. The time required to test the same number of configurations, if this optimization process was done manually, was estimated in 350 [hours] (+38 %). Moreover, the use of genetic algorithms favored the research of the optimal solution.

It was possible to reduce the average temperature variance, compared to the first mold design, by a 77 % (from 33.4 [°C] to 7.6 [°C]) respecting the heating ramp of the matrix system and the structural strength of the mold. Moreover, a cost saving of 15 % has been obtained considering the production of 3500 CFRP parts.

Future works should focus on develop a less constrained optimization process eliminating some of the assumptions made. For example, it would be interesting to analyze the effects of different peak power W_h among the heaters or to investigate the possibility of a non-regular layout.

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