Title:

Cost and Thermo-Structural Optimization of a Mold Used for Manufacturing CFRP Components with an Out-Of-Autoclave Process

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Introduction:

Advanced composite materials, especially those based on carbon fiber, have been attracting the interest of many automotive companies for producing light and high-performance components. Weight reduction is one of the main goal for automobile manufacturers since it allows to produce more efficient cars with low emissions and with extended autonomy.

The costs and the long cycle times for producing CFRP (Carbon Fiber Reinforced Polymer) components are often prohibitive for the typical mass production of the automotive sector. For these reasons, CFRP parts producers devoted a lot of effort to develop innovative methods for manufacturing components in a more efficient way. OOA (Out-Of-Autoclave) methods have been recognized as the most promising processes for obtaining high productivity and cost reduction. One of these methods is press molding under flexible tool [1]. This is a closed-mold manufacturing process that uses a metal mold and a flexible rubber counter-mold for the application of external pressure. In this process, a pre-impregnated carbon fiber layup is placed on the open mold cavity and then the upper mold is inflated between 0,2-1 [MPa] for consolidating the preform. The pressure is maintained steady throughout all the cure cycle (1-4 hours depending on the matrix system). The efficient heating of the mold is a key aspect to reduce the cycle time of this process. Moreover, a specified heating ramp need to be respected to avoid matrix degradation or void growing [7]. Another important issue equipment designers must face off is the temperature homogenization of the mold surface to obtain a constant component curing and prevent over-curing of the matrix system. Typically, mold heating can be obtained through hot plates, internal heaters or fluids, induction or IR-heating [8].

Much research in recent years has focused on the design and optimization of conduction heating of metal molds. Xi-Ping li et al. [11] used a combination of thermal simulations, RSM (Response Surface Methodology) and GAs (genetic algorithms) 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 [9], [10]. Abdalrahman et al. [1] 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. [5] studied the influence of the heating channel geometries on the cycle time and on the temperature

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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 purpose of this study is the design optimization of a tool for manufacturing composite parts, through the press molding under flexible tool process, considering both heating and mechanical performances and costs.

Main idea:

The research approach exploited in this work is based on a previous study conducted by the same authors [4]**.** 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 is 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 structural evaluation. An optimization tool that integrates, in a unique framework, the previous mentioned software, automatically drives the optimization process, by combining RSM [3] and GAs [6].

In this paper, an aluminum mold (1250 [Kg]) for producing a CFRP component for the automotive sector has been optimized. It is heated by conduction from two hot plates and from 20 cartridge heaters (1000 [W] each) equally spaced along the mold. However, with this first attempt 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 analysis has been carried out with the collaboration of an Italian company that is one of the world leaders in the production of CFRP parts.

Thermal, structural and cost analysis:

In order to analyze the heating uniformity of the mold cavity during a typical OOA curing process, transient thermal simulation was performed by the use of ANSYS© software suite. Moreover, based on the results of the thermal analysis, transient thermal-structural simulation was carried out to investigate the mold structural strength.

Since the mold symmetry, it is reasonable to simplify the finite element model considering only half part of the cavity (shown in Fig. 1). The mold is made by milling an aluminum alloy of Ergal family (7075), which ensures not only excellent thermo-mechanical characteristics but also lightness and high thermal conductivity.

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 130 [°C] with a tolerance of ± 5[°C].

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.

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. [4] 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:

$$\begin{cases} C_m = C_e + [C_p + C_d + C_i] \cdot F_h \\ C_p = n_h \cdot C_{u,p} \\ C_d = n_h \cdot C_{h,d} \\ C_i = n_p \cdot n_h \cdot C_{h,i} \\ C_e = n_p \cdot (C_{s,e} \cdot E_c) \cdot F_e \\ C_{h,x} = (T_{h,x} \cdot CU_{h,x}) \cdot F_{h,x} \end{cases} \qquad \text{(Eq. 1)}$$

C_m has been modeled as a function of: cost for the consumed energy C_e [€], heaters purchasing cost C_p [€], cost for the drilling operation of the heating channels C_d [€], installation cost of the heaters C_i [€] and a corrective factor F_h. 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 purchasing cost as well as the drilling cost is achieved multiplying the number of internal heaters n_h respectively for the unitary purchasing cost $C_{u,p}$ and for the cost of one drilling operation $C_{h,d}$. The purchasing cost of the heaters (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.

Optimization:

In order to investigate the functional relationship of the layout and peak power of the heaters W_h [W] with respect to the temperature distribution and structural strength of the mold, the Response Surface Methodology [3] has been exploited to achieve the corresponding numerical model. Then, this model has been explored to retrieve the optimal mold configuration thanks to MOGA-II algorithm [6].

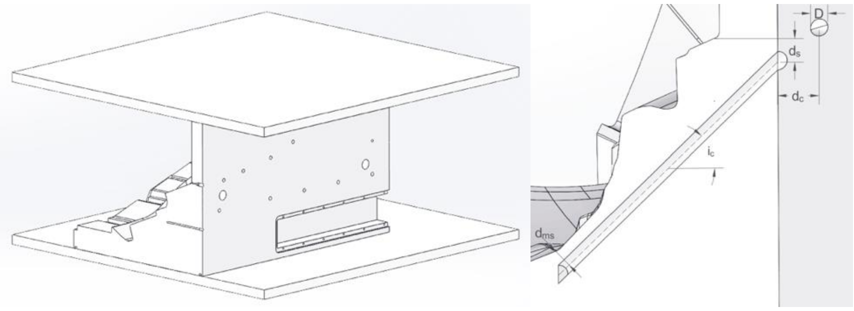

Fig. 1: Investigated mold (on the left) and main geometrical entity of the channels layout (on the right).

The geometrical layout of the heating channels can be defined by the following entities: 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.

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]. 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 130 [°C]. This mold has been designed to produce 3000 CFRP parts.

Tab. 1 reports the variables to be optimized with their relatives investigated range, the goals to achieve and the constrains to satisfy.

Variables	***Range***
n_c	[19÷24]
d_s [mm]	[25÷50]
W_h [W]	[700÷1000]
Heating channel inclination i_c [°]	[0÷60]
Goals	***Kind***
C_m [€]	minimize
ΔT [°C]	minimize
Constraints	
Safety factor	≥ 1,5
d_{ms} [mm]	> D
$T_{max,s}(t)\ \forall t \in [0,3600\ s]$	≤130 [°C]
$T_{ave,s}(3600\ s)$	=130 [°C] ± 5%

Tab. 1: Variables, goals and constraints of the optimization problem.

Results and conclusion:

The paper presented the design optimization of the heating channels layout of a mold for the production of CFRP components in OOA processes. The authors were able to achieve an excellent temperature uniformity on the mold cavity, while minimizing the costs. At the same time, the mechanical strength of the structure was ensured through the respect of the safety factor. Fig. 2 shows the temperature distribution at 3600 [s] and the cost breakdown of the optimal configuration.

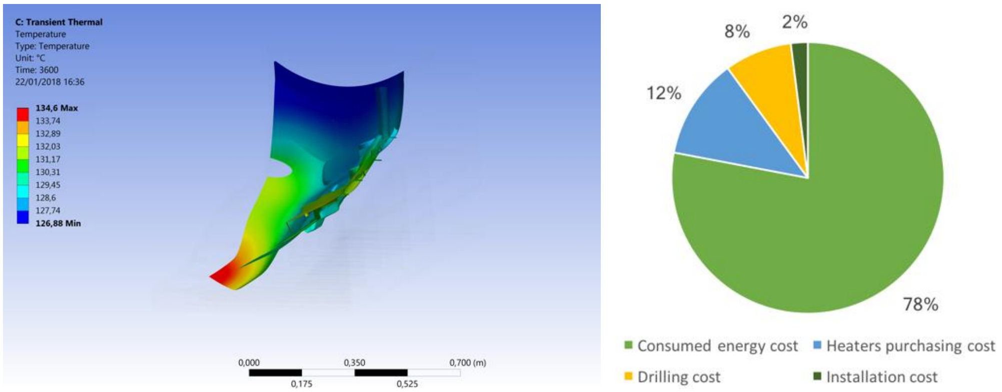

Fig. 2: Temperature distribution at 3600 [s] (on the left) and life-cycle cost breakdown (on the right) of the mold optimized configuration.

Due to the confidentiality of the data, they cavity surface has to be hidden and the cost breakdown is presented in percentage.

The variance of the average temperature on the surface of the optimized mold over time is equal to an average value of 7,25 [°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].

The authors were able to simulate and analyze 40 different configurations of the channels layout for a total simulation time of 250 [hours]. Designers' effort was marginal once set the simulation model. Indeed, the use of the Response Surface Methodology guarantees 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 315 [hours] (+26 %). Moreover, the use of genetic algorithms favored the research of the optimal solution. Thus, it was possible to reduce the average temperature variance 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, compared with the first design of the heating channels, a cost saving of 15 % has been obtained considering the production of 3000 CFRP parts.

Future works should focus on considering the possibility to use heaters with different peak power that can be placed with a greater geometric flexibility on the mold.

References:

[1] Abdalrahman, R.; Grove, S.; Kyte, A.; Rizvi, M. J.: Numerical simulation and design optimisation of an integrally-heated tool for composite manufacturing, Materials and Design, 64, 2014, 477-489. http://dx.doi.org/10.1016/j.matdes.2014.07.019

[2] Brent Strong, A.: Fundamentals of Composites Manufacturing: Materials, Methods and Applications, Society of Manufacturing Engineers, 2008.

[3] Box, G. E. P.; Draper, N.: Response Surfaces, Mixtures, and Ridge Analyses, John Wiley & Sons, Hoboken, NJ, 2007. http://dx.doi.org/10.1002/0470072768

[4] Castorani, V.; Vita, A.; Mandolini, M.; Germani, M.: A CAD-based method for multi-objectives optimization of mechanical products, Computer-Aided Design and Applications, 14(5), 2017, 563-571. https://doi.org/10.1080/16864360.2016.1274528

[5] Collomb, J.; Balland, P.; Francescato, P.; Gardet, Y.; Leh, D.; Saffré, S.: Thermo-mechanical simulations for the comparison of heating channels geometries for composite material injection tools, Applied Thermal Engineering, 126, 2017, 204-211. http://dx.doi.org/10.1016/j.applthermaleng.2017.07.125

[6] Goldberg, D.E.: Genetic Algorithms in Search Optimization and Machine Learning, Addison- Wesley Longman Publishing Co. Inc., Boston, MA, 1989.

[7] Hernández, S.; Sket, F.; Molina-Aldareguìa, J.M.; González; C., LLorca; J.: Effect of curing cycle on void distribution and interlaminar shear strength in polymer-matrix composites, Composites Science and Technology, 71(10), 2011, 1331-1341. https://doi.org/10.1016/j.compscitech.2011.05.002

[8] Oppelt, T.; Schulze, J.; Stein, H.; Platzer, B.: Comparison of methods for mould surface heating - Part 2: Examples, Gummi Fasern Kunststoffe, 65(9), 2012, 578-586.

[9] Wang, G.; Zhao, G.; Li, H.; Guan, Y.: Multi-objective optimization design of the heating/cooling channels of the steam-heating rapid thermal response mold using particle swarm optimization, International Journal of Thermal Sciences, 50(5), 2011, 790-802. https://doi.org/10.1016/j.ijthermalsci.2011.01.005

[10] Wang, G.; Zhao, G.; Li, H.; Guan, Y.: Research on optimization design of the heating/cooling channels for rapid heat cycle molding based on response surface methodology and constrained particle swarm optimization, Expert Systems with Applications, 38(6), 2011, 6705-6719. https://doi.org/10.1016/j.eswa.2010.11.063

[11] Xi-Ping, L.; Guo-Qun, Z.; Yan-Jin, G.; Ming-Xing Ma: Optimal design of heating channels for rapid heating cycle injection mold based on response surface and genetic algorithm, Materials & Design, 30(10), 2009, 4317-4323. https://doi.org/10.1016/j.matdes.2009.04.016

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