THERMOMECHANICAL OPTIMIZATION OF AN INNOVATIVE LOW INERTIA MOLD WITH RECTANGULAR HEATING CHANNELS

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Abstract

In order to be able to meet industries expectations, especially aeronautical and automotive industries, in terms of production rate, aspect and structural quality for high performance composite injected parts, it is necessary to produce reactive and thermally efficient molds. The objective of this study is to lead a thermomechanical optimization on an innovative low thermal inertia mold with rectangular heating channels. The optimized structure is compared with a reference : a massive conventional mold with circular heating channels. The finite elements model setting up for this study take into account technological constraints related to pressure drop and the use of a pump for fluid circulation. Obtained results highlight the importance of taking into account these technological constraints in the mold design. Thus, according to the choosen heating technology, water or oil heating, the optimized model of the low thermal inertia mold and with rectangular heating channels allows a reduction of the heating time by a factor of 2 for water heating and by a factor of 8.5 for oil heating.

1. Introduction

Today, aerospace and automotive industries are using more and more structural composite material parts, but current technologies for processing composites, especially with thermoplastic matrix, are not sufficiently competitive in terms of cost, heating rate, and reproducibility. To meet these industries expectations, it is necessary to produce thermally reactive mold capable to absorb high production rates while ensuring structural and appearance quality of molded parts. Conventional plastic injection and composite processes involve injecting a viscous polymer into a hot and massive mold and then ejecting the part. This kind of process makes possible high heating rates by avoiding thermal cycle of the mold, but it is at the origin of defects in the molded parts: internal stresses, poor surface appearance. It is therefore essential to thermally optimize molds in order to meet heating rate expectations, while controlling energy consumption during the cycle. To improve appearance and properties of molded parts, while increasing the mold productivity through increased heating rates, it is possible to optimize two categories of parameters: parameters related to the process: nature of materials (resin and preform), injection pressure, temperature, surface treatments [1,2], and parameters related to the mold design (materials, thicknesses, channels). Parameters related to the design of the tools require thorough studies and questioning the design rules of the tools, which until now impose massive structures and straight channels created by drillings [3]. Studies have been conducted on the main parameters impacting thermal performance of molds: choice of mold material [4,5], addition of insulation to focus the heat of the molded part face, optimization of the network of heating channels [5,6] and the type of heating technology used [7–9]. Current research on thermal optimization of mold parameters is usually carried out maintaining circular section channels with expensive fluidic models or with thermal models that do not take into account technological parameters such as pressure drops. Now, with new technologies of additive manufacturing, it is possible to produce structures with low thermal inertia and rectangular conformable heating channels for better thermal performance. The interest of this concept of mold with rectangular heating channels having been numerically demonstrated [10], the objective of this paper is the thermomechanical optimization of a rectangular heating channels mold with a thermal finite element mold taking into account technological parameters: pressure drop , nature of the heat transfer fluid and the regulation of the thermoregulator's power. Methods and models used will be presented first, then the design of experiments and genetic algorithm optimization setting up for this study and finally results and discussions.

2. Methods and conventional model

The approach put in place for this study consists of:

1- Thermomechanical observations on the massive conventional mold presented in Fig. 1a.
2- Thermomechanical optimization of the rectangular heating channel mold presented in Fig. 1b.

This study is conducted on a representative bidirectional model in order to neglect edge effects and to focus on the heating zone of the mold. This work is based on a conventional plate mold made of stainless steel. To study the influence of the heat transfer fluid on thermal performances of the mold, thermal simulations are carried out initially with water, then in a second time with Therminold D12 oil [11].

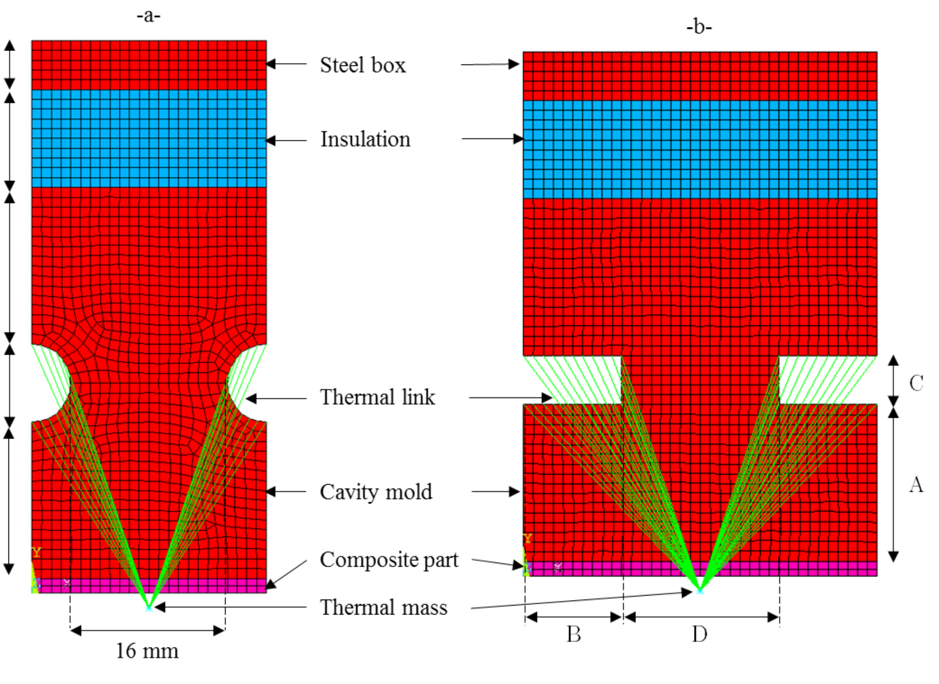


Figure 1. Finite element mold models (a) conventional: massive and (b) innovative: low thermal inertia with rectangular heating channels

A 10 mm Monolux insulating plate and a 5 mm steel sheet are fixed on the outer faces of the mold to limit thermal losses and to facilitate handling and placing in press. A carbon-epoxy composite with a thickness of 3 mm and with usual properties resulting from a homogenization is present in the cavity surface mold during thermal simulations. Mold characteristics and tehnological heating elements are presented in Table 1. Material thermal properties are considered constant over the temperature range of the study and are presented in Table 2.

Table 1. Mold characteristics

Characteristics		*Units*
Mold dimensions	570 x 570 x 110	mm^3
Mold materials	Stainless steel (1.2311)	-
Heating power	12	kW
Heat transfer fluid	Water	-
Fluid volume	16	l

Table 2. Thermal properties of materials

	Stainless steel *1.2311* [12]	Insulating *Monolux 500* [13]	Composite *Carbone-Epoxy* [14]
λ ($W.m^{-1}.K^{-1}$)	15	0.18	$\lambda_x = 2$ $\lambda_y = 0.2$
Cp ($J·kg^{-1}·K^{-1}$)	450	1130	1000
ρ ($kg.m^{-3}$)	7900	770	1800
E (MPa)	210000	3750	-
ν	0.3	0.3	-

Finite element simulations are performed using the Ansys v18.1 software. For thermal simulations, mold, composite, insulation and outer steel plate are modeled using PLANE77 quadratic thermal elements. Volume of the fluid, power of the thermoregulator and regulation are modeled with thermal mass element MASS71. The convective exchange between the thermal mass element and the wall of the mold heating channels is performed using LINK33 elements which are convective links. For mechanical simulations, tooling, insulation and the outer steel plate are modeled with PLANE183 quadratic mechanical elements. The composite is not modeled for mechanical simulations. After testing different mesh sizes, an optimal mesh size of 1 mm was chosen for thermal and mechanical simulations. The mold is considered as symmetrical at the level of the neutral fiber of the composite.

Loading conditions applied for thermal simulations are: an initial temperature of 25°C for all parts, a natural convection on the external face of the outer steel plate: T = 25°C and h = 10 $W.m^2.K^{-1}$ [15], and adiabatic surfaces on symmetry zones (lateral lines and neutral plane of the composite): heat flux = 0 W. A forced convection in mold heating channels is present and temperature is controlled by the heating of the thermal mass element with the thermoregulator power of 12 kW and the convective exchange is carried out by thermal link elements which have a convective coefficient calculated using the method presented in the study of Collomb and al. [10] and taking into account the data of the thermoregulator pump, the nature of the heat transfer fluid and the temperature. The temperature set point is 80°C. Phenomena related to the crosslinking of the resin (including exothermic) are not taken into account.

Loading conditions applied for mechanical simulations are: zero vertical displacements of the outer line of the outer steel plate, symmetries on model lateral lines, fluid circulation pressure in the channels of 3.5 bar and injection pressure on the mold cavity surface of 15 bars. The composite is not modeled for these studies.

Thermomechanical responses observed for these simulations are:

- t: heating time of the cold point of the cavity mold surface to reach 90% of the set point

- *ΔT*: maximum temperature difference on the molding surface over time
- *u*: the maximum vertical displacement of the molding surface.

For the optimization phase, heating time, temperature difference on the cavity molding surface and maximum vertical displacement of the molding surface shall be respectively: minimized, limited to 2°C during the heating phase and limited to 10 µm.

3. Design of experiment and optimization

The approach implemented to achieve optimization consists of:

1. Finite element simulations based on design of experiments (DoE)
2. Creating thermal and mechanical metamodels using the response surface methodology (RSM)
3. Thermomechanically optimization by genetic algorithm (GA).

The finite element model of the low thermal inertia mold with rectangular heating channel and its optimization variables are presented in Fig. 1b and Table 3. To avoid differential thermal expansion problems, the assumption is made that the thickness of steel above and below heating channels is identical.

Table 3. Optimization variables

	Geometric characteristics	*min*	*max*
A	Steel thickness	2 mm	15 mm
B	Half channel width	5 mm	10 mm
C	Channel height	2 mm	10 mm
D	Distance between channels	5 mm	40 mm

Construction of the response surfaces is carried out using Ellistat software and Latin Hypercube Sampling (LHD) space filling method in order to increase prediction capabilities of metamodels. The 2D finite element model is inexpensive in terms of computation time, so 100 numerical cases are generated by the LHD method. ANOVA variance analysis is carried out for the construction of metamodels by the response surface methodology.

After creating the thermal and mechanical metamodels, optimization is conducted using a genetic algorithm. The operating principle of evolutionary algorithms is to initialize a population of individuals that, generation after generation, evolve with individuals affected by: selections, crosses and mutations, which tends to improve the quality of individuals regarding to the objective function, leading to the optimal solution. Optimization parameters used for the genetic algorithm are: generation number = 500, individuals number per generation = 150, selection by tournament, individuals number per tournament = 2, tournaments probability = 0.7, crossing probability = 0.7, mutation probability = 0.03.

4. Results and discussion

Results obtained for the massive reference model for water heating are: heating time of 910 s, temperature difference in molding surface of 0.06°C. For oil heating, results are: heating time of 3659 s, temperature difference in molding surface of 0.03°C. The maximum vertical displacement is 3.99 µm. Change in thermal properties of the fluid between water heating model and oil heating causes a pressure drop increase (due to viscosity evolution), which causes a significant drop of the convective coefficient and therefore a significative thermal performance difference of the structure.

Polynomial metamodels representative of the innovative mold are constructed after having performed thermal and mechanical simulations from the design of experiment and after creating response surfaces using the ANOVA analysis. R^2_{press} coefficients, predictive correlation coefficient, are calculated for each metamodels and are from 0.977 to 0.996 for the thermal metamodels and 0.811 for the mechanical metamodel. The predictive correlation coefficient is calculated using a cross validation "leave-one-out" in order to measure the predictive quality of the metamodel [16]. Predictive correlation coefficients obtained in this study show the good quality of metamodels.

Thermal metamodels for the innovative mold for water heating are presented Eq. 1 and Eq. 2. Thermal metamodels for the innovative mold for oil heating are presented Eq. 3 and Eq. 4. The mechanical metamodel for the innovative mold is presented Eq. 5 which is independent of the chosen fluid.

$$t_{water} = 450.6 + 18.51A - 10.65B + 0.97A^2 + 0.31B^2 + 0.28C^2 + 0.04D^2 - 0.04A^3 - 0.003B^3 - 0.15AB - 0.21AC - 0.04AD + 0.24BC \quad (1)$$

$$\Delta T_{water} = -0.59 - 0.229A + 0.076B + 0.153D + 0.015A^2 - 0.002B^2 + 0.003D^2 + 0.007AC - 0.015AD - 0.002BC + 0.003BD - 0.006CD \quad (2)$$

$$t_{oil} = 2273 + 141A - 107B - 180C - 8.06D + 1.33B^2 + 6.3C^2 - 2.18AB - 1.68AC - 0.45AD + 3.67BC + 0.36BD + 0.78CD \quad (3)$$

$$\Delta T_{oil} = 1.73 - 0.59A + 0.14D + 0.054A^2 - 0.0036C^2 - 0.0086AB - 0.029AD - 0.009BD - 0.004 \quad (4)$$

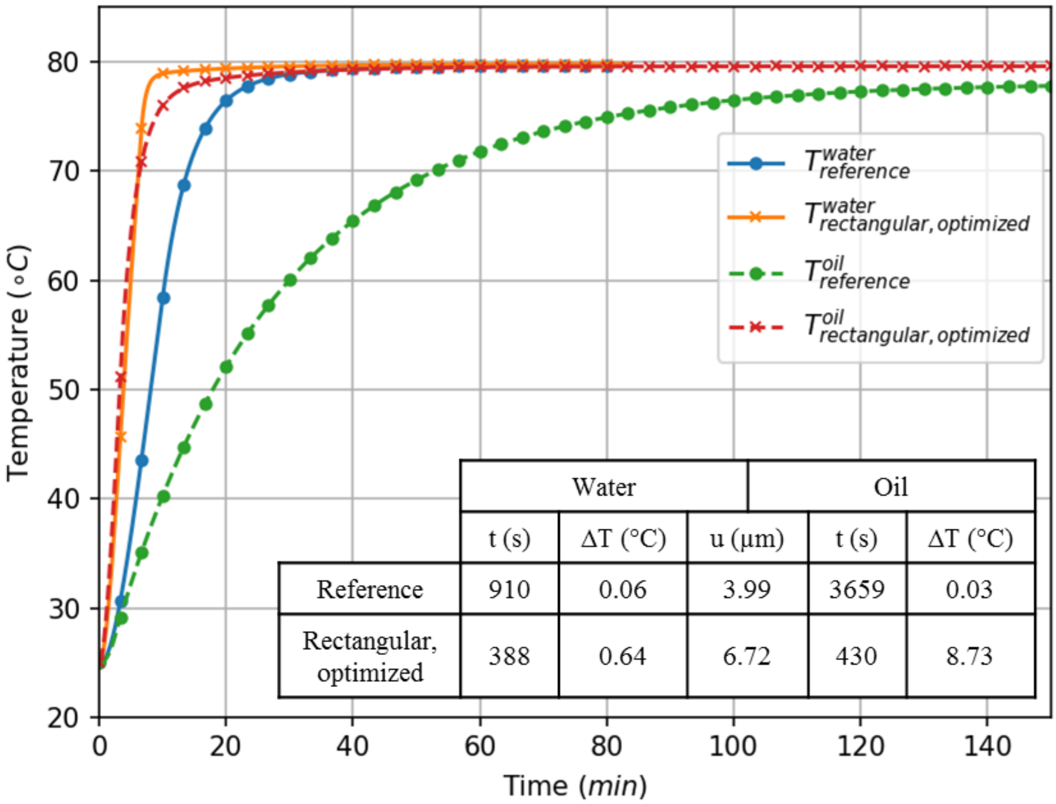
$$u_{max} = 15.86 - 5.13D + 0.615D^2 + 0.022E^2 - 0.019D^3 - 0.0002E^3 - 0.051DE \quad (5)$$

After conducting thermomechanical optimizations using genetic algorithm on the metamodels presented Eq. 1 to Eq. 5, optimal geometrical parameters presented Table 4 are obtained.

Table 4. Optimal geometrical parameters

	Parameter	*Water*	*Oil*
Circular channel mold Reference	Steel thickness	16 mm	
	Channel diameter	8 mm	
	Distance between channels	16 mm	
Rectangular channel mold Optimized	*A*	2.5 mm	5 mm
	B	18 mm	35 mm
	C	2 mm	4.5 mm
	D	5 mm	5 mm

Results on the innovative optimized model for water heating are: heating time of 388 s, temperature difference on cavity mold surface of 0.64°C and maximum vertical displacement of 6.72 μm. For oil heating, results are: heating time of 430 s, temperature difference of cavity mold surface of 8.73°C. The comparison of heating times between the reference model and optimized innovative models for water heating and oil heating is presented Fig. 2. After optimization, the shortest heating time is 388 s for water heating. Temperature fields observed at this time are presented Fig. 3a for the massive reference model and Fig. 3b for the optimized innovative mold. The shortest heating time is 430 s for oil heating, temperature fields observed at this time are presented Fig. 3c for the massive reference model and Fig. 3d for the optimized innovative mold.



	Water			Oil	
	t (s)	ΔT (°C)	u (µm)	t (s)	ΔT (°C)
Reference	910	0.06	3.99	3659	0.03
Rectangular, optimized	388	0.64	6.72	430	8.73

Figure 2. Comparison of heating times between the reference model and the optimized innovative model for water heating and oil heating

Optimization highlights the importance of taking into account technological aspects related to heating technologies for the mold design. Indeed, nature of the fluid, channels geometry, length of the fluid network and the pump associated with the thermoregulator are parameters having influence on pressure drop and therefore on the convection coefficient. Optimization on the rectangular channel model, shows that the constrain on the temperature difference of the molding surface is not influential. Thus, the geometric optimization tends to minimize the mass to be heated of the structure, while ensuring a significant convective exchange (by limiting the pressure losses) and ensuring sufficient mechanical stiffness. Therefore, transition from a water heater to an oil heater causes an increase in channels dimensions in order to limit pressure drop, requiring a steel thickness for a mechanical stiffness. Gains obtained on heating times after optimization of rectangular channel models compared to the massive reference model are 57% and 88% respectively for water heating and for oil heating.

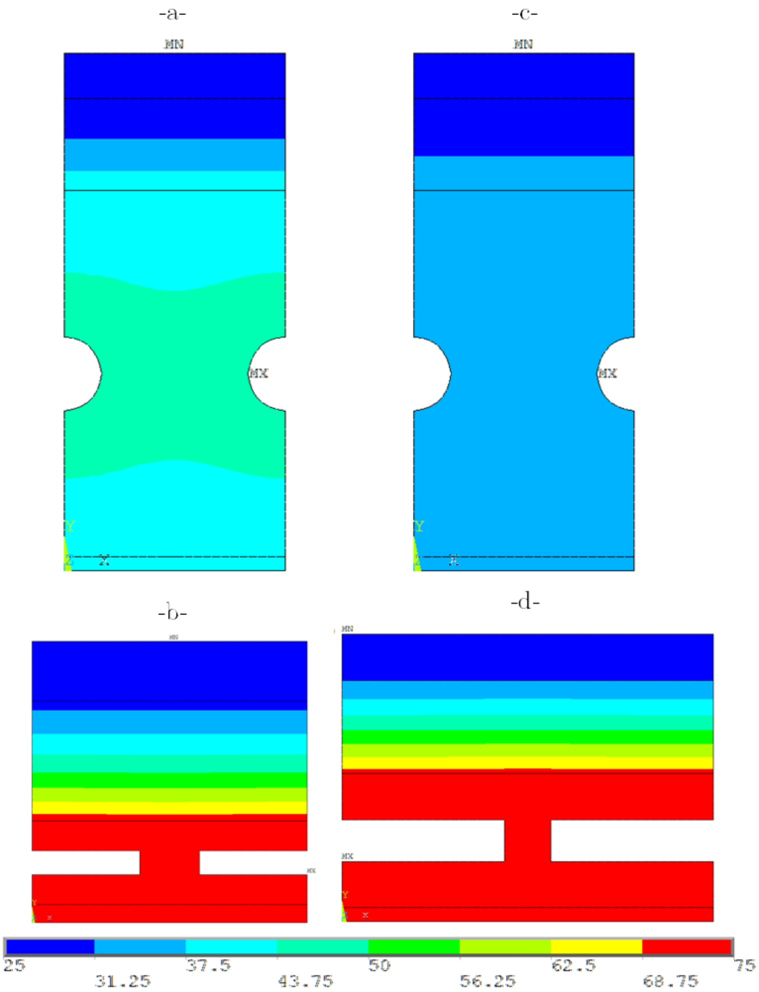


Figure 3. Temperature field comparison between the reference model and the optimized innovative model for water heating (a, b) and for oil heating (c, d)

5. Conclusion

This work was carried out for a mold and for heating technologies fixed in order to study the influence of main geometrical parameters related to thermal performance of molds. To improve thermal performances of molds, a thermomechanical optimization, which take into account technological parameters related to the circulation of the fluid, was carried out on a concept of low inertia mold with rectangular heating channels and a numerical confrontation was done with a massive reference mold with circular heating channels.

It appears that it is possible to achieve gains in terms of heating time from 57 to 88% regarding to a massive conventional mold, while controlling the temperature field on the cavity mold surface and while having sufficient rigidity. For this, it is essential when designing mold to take into account the technological aspects related to the heating system (fluid, pump, pressure drop) in order to find the optimum between: minimization of steel thickness in order to reduce heated mass, adequate channel geometry for a large convective coefficient and sufficient steel thickness to obtain a sufficient molding surface temperature field and stiffness. These heating rate gains are significant on an industrial scale since repeated on the heating and cooling phases for a very large number of cycles.

To conclude, this study confirms the strong interest of mold with low thermal inertia for obtaining better thermal performance in terms of heating rate, the need to take into account the heating technologies during the design of the mold and the interest of rectangular heating channels mold concept to promote the reduction of the mass to be heated and the control of the temperature field at the surface of the composite.

Acknowledgments

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