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DESIGN OF COMPOSITE FORMING TOOL WITH HIGH THERMAL DYNAMIC THROUGH THE USE OF LATTICE STRUCTURES

Matthis Balthazar^{1,2}, Nicolas Baudin¹, Jérôme Soto^{1,3}, Denis Edelin^{1,3}, Sébastien Guéroult², Vincent Sobotka¹

¹ Nantes Université, CNRS, Laboratoire de thermique et énergie de Nantes, LTEn, UMR 6607, F-44000, Nantes, France

² Institut de Recherche Technologique Jules Verne, 44340, Bouguenais, France

³ Institut Catholique d'Arts et Métiers de Nantes, Carquefou 44470, France

ABSTRACT

Thermal management is a critical factor in the composite manufacturing processes, as it directly affects the quality of the produced parts. Controlling the temperature field on the surface of the tooling both spatially and temporally is crucial to minimize defects and achieve the desired mechanical properties of the composite parts. The use of lattice structures in which a fluid circulates, makes it possible to improve and control heat transfer. This system also allows reducing the thermal inertia of tools and consequently process energy consumption related to thermal cycles.

1. INTRODUCTION

The use of composite materials continues to increase, particularly in the transport sector. Manufacturing of these components remains a real challenge because the properties depend on numerous parameters. Among them, thermal management during the manufacturing cycle is one of the most important as the quality of the part requires a controlled supply and release of heat in the part while allowing maximum productivity. Inadequate thermal management can result in various defects within the component, including warpage, shrinkage, thermal residual stresses, and sink marks [1] [2]. Moreover, productivity of the process is largely dependent on the cooling time of the molded part. Thus, in the case of thermoforming or injection molding processes, more than 50% of the cycle time is dedicated to part cooling [3], [4]. The efficiency of cooling systems directly impacts then both productivity and energy consumption of the manufacturing process.

Traditionally, thermal management is ensured by circulating a fluid, generally water or oil at imposed temperature and flow rate in circular channels, straight or conformal. However, the distance between the channels and the surface of the tool is limited by two factors: the mechanical strength of the tooling and the thermal non-uniformity on its surface, known as thermal marking. The thermal response time of the mold is then constrained by this distance.

An alternative to these approaches is the use of lattice structures in which the regulating fluid circulates. Lattice structures are a distinct type of porous material distinguished from foams by the ordered and repetitive arrangement of their unit cells. These porous structures can be integrated into the tooling as close as possible to the surface because they provide structural reinforcement and prevent thermal marking through fluid flow in sheet form (figure 1).

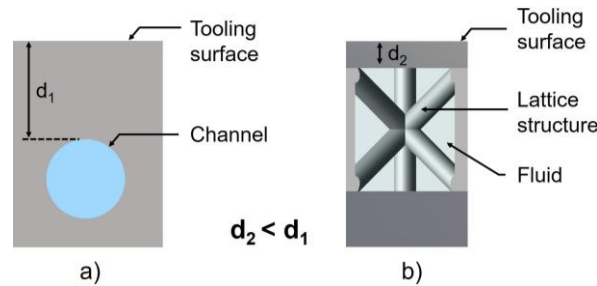


Figure 1: a) Straight or conformal cooling, b) Proposed system with the lattice structure

Moreover, additive manufacturing enables the creation of this type of complex architected 3D designs thanks to its high design freedom [5] [6].

The objective of this experimental study is to assess and analyze the potential benefits of incorporating lattice structures to improve and control heat transfer for composite forming tool. The experimental setup developed aims to visualize the time evolution of the temperature field during heating and cooling cycles at the tooling surface to compare an empty channel to a channel with the lattice structure.

2. EXPERIMENTATION

The experimental setup developed allows a circulation of water at controlled temperature and mass flow rate inside a rectangular channel of 200 mm long by 20 mm wide. Lattice structure can be integrated or removed of the channel to compare temperature evolution of the tooling surface between these two configurations. To perform heating and cooling cycles, circulation of hot water ($T_h = 70\text{ }^\circ\text{C}$) and cold water ($T_c = 20\text{ }^\circ\text{C}$) is alternated. The experimental setup is shown in figure 2. The circulation of cold and hot water is controlled by solenoid valves (SV) to have cycles of circulation of cold water during 60 seconds and alternating with the hot one during 60 seconds. Above the channel, a stainless-steel plate of 5 mm thickness is positioned, so as to represent the tooling skin. The upper surface of this plate represents the surface in contact with the forming composite part: the tooling surface. This is this surface (indicated in red on the figure 2) which is observed using an infrared camera during cycles to analyze the temperature evolution over time. The stainless-steel plate is thermally insulated on its lateral surfaces thanks to the polycarbonate upper part. Finally, the lattice structure used is made of polymer.

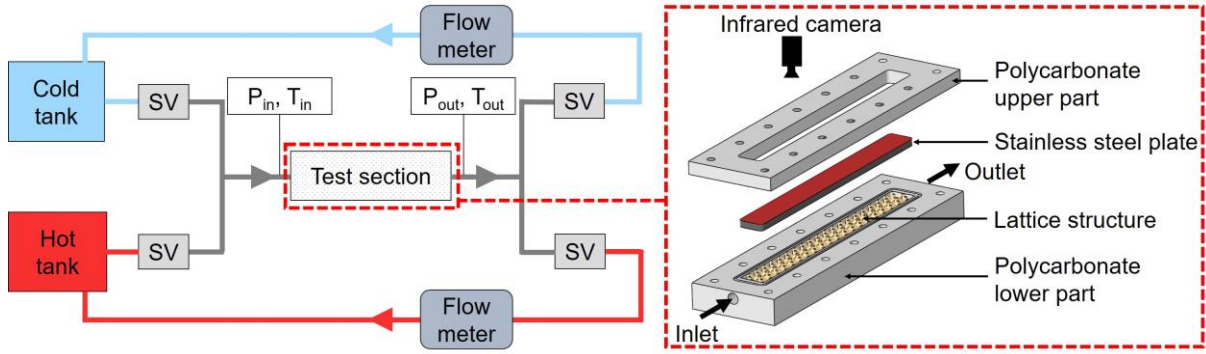


Figure 2: Schematic of the experimental setup

Experimentally, two study cases are investigated: the first one with a lattice structure of constant porosity in order to obtain a uniform temperature, and the second one with a local variation of the porosity to locally increase heat transfer and thus reduce local temperatures for composites with thickness variation for example.

a. Configuration 1: constant porosity

Figure 3 presents temporal evolution of the mean temperature (in solid line) and standard deviation Std (dashed line) of the temperature at the upper surface of the stainless-steel plate: the tooling surface. The temperature evolution is faster with the lattice structure, and the standard deviation lower during the transition phase. Thermal inertia of the tool skin is characterized by the thermal time constant τ , the time to reach 63.2% of the temperature amplitude of the observed surface. This results in $\tau_{\text{lattice,channel}} = 7.7\text{s}$ and $\tau_{\text{empty,channel}} = 12.5\text{s}$. This difference is due to the higher global heat transfer coefficient in the lattice structure ($h=4200\text{ W}\cdot\text{m}^{-2}\cdot\text{m}^{-1}$) than in the empty channel ($h=1230\text{ W}\cdot\text{m}^{-2}\cdot\text{m}^{-1}$). The time to obtain the steady state is reduced by 38% in this configuration thanks to the lattice structure. Moreover, a

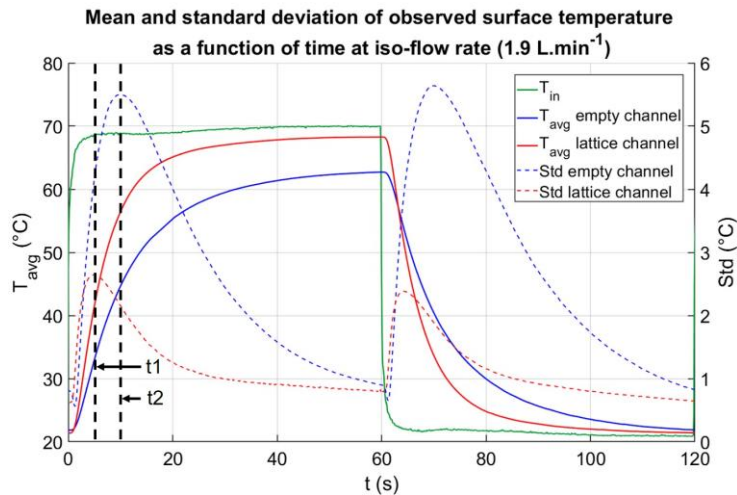
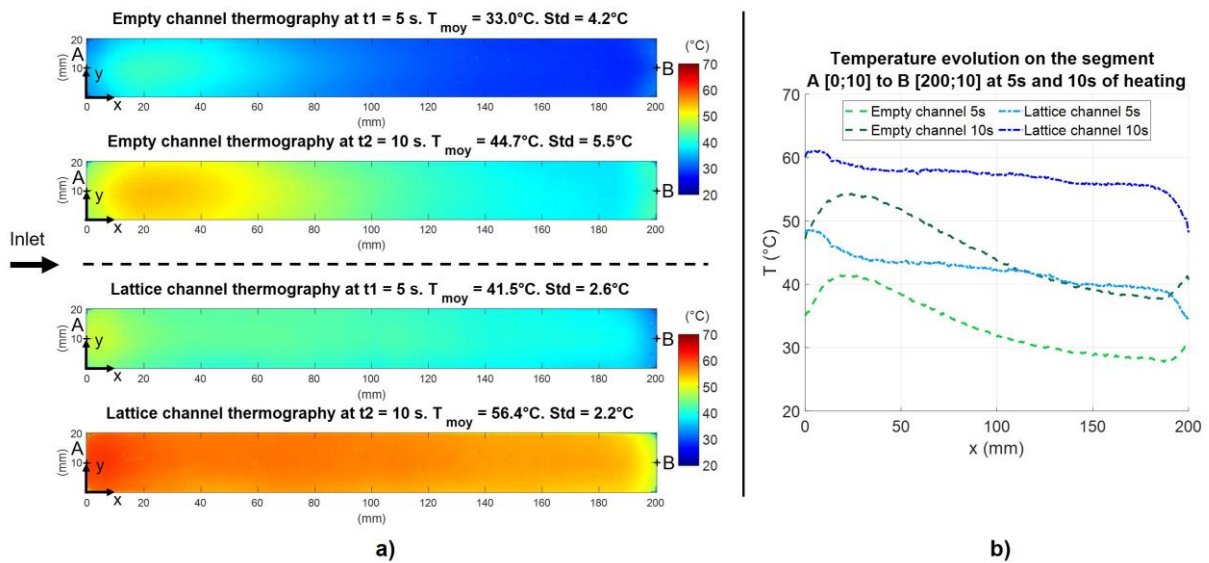


Figure 3: Temporal evolution of the mean and standard deviation of the temperature on the observed surface

conduction model allows to predict this time as a function of the lattice properties, and thus to help the design of the tool.

Figure 4 shows on the left side the temperature field of the tooling surface when the channel is empty and when the lattice structure is positioned inside at 5 and 10 seconds of heating. On the right side, the temperature evolution along the x axis at the tooling surface is presented. On these thermographies, the improvement of the thermal homogeneity during the thermal transition phases is observable. The graph confirms that the temperature gradient is lower in the fluid flow direction with the lattice structure.



b. Configuration 2: graded porosity

Another advantage of lattice structures is that the porosity ϵ can be locally modified to control heat transfer. Yun & al [7] have shown that by decreasing porosity, the heat transfers are increased. As the porosity decreases, vortices inside the lattice channel become more prominent, and near-wall flow velocities are intensified, causing larger disturbance of the thermal boundary layer. These two phenomena improve convective heat transfers.

Figure 5 presents the used configuration of the graded porosity. Cells porosity denoted as ϵ is fixed at $\epsilon = 0.8$ at the beginning of the channel (10 cells), then, $\epsilon = 0.5$ (4 cells) and finally $\epsilon = 0.8$ (6 cells). Controlling the porosity means locally controlling the heat transfer coefficient. In this configuration temperature can be locally decreased by 5°C at the tooling surface after 5 seconds of cooling (corresponding at 65 seconds in figure 3). This means that it is possible to locally control the temperature distribution at the tooling surface by adapting lattice structure porosity in space. This is of interest for forming composite parts with thickness variations where thicker zones require better heating or cooling.

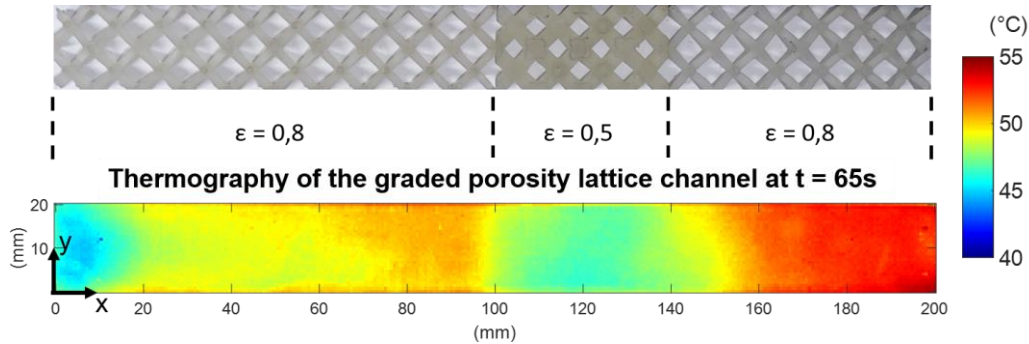


Figure 5: Graded porosity lattice channel at 5 seconds of cooling

4. CONCLUSIONS

This experimental work shows that the lattice structure allows to obtain rapid temperature variations with good temperature uniformity on the tooling surface during the thermal dynamic phases. The time constant can be predicted and is reduced of 38% by using the lattice structure compared to the empty channel in this configuration. Compared to the conformal cooling, thermal inertia can be greatly reduced thanks to the lattice structure which allows the circulation of the fluid as close as possible to the surface of the tool without thermal marking, resulting in lower energy consumption and lower cycle times. It is also possible to concentrate heat transfers by adapting porosity of the lattice structure in order to have local temperature variations, which is useful for the manufacturing of composite part with thickness variation for example.

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