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Procedia Manufacturing 47 (2020) 1117–1122

Procedia MANUFACTURING

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23rd International Conference on Material Forming (ESAFORM 2020)

Design for Additive Manufacturing: Thermoforming Mold Optimization via Conformal Cooling Channel Technology

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Abstract

The cooling system of thermoplastic mold plays a critical role during the production process because it not only affects part quality but also its cycle time. Traditionally, due to the limitations of conventional drilling methods, the cooling system of the thermoforming mold usually consists of simple paralleled straight channels that results in a lack of performance to cool complex shapes. Nowadays thanks to the evolution of additive manufacturing technique (AM) characterized by an increase of shape complexity it is possible to design a complex cooling system conformal to the mold geometry (conformal cooling). However conformal cooling respect to others AM design improvements, as topology optimization, is still under development and specific rules that define how to better design cooling channels still do not exist.
In this paper, to enlarge the knowledge about this methodology, the authors simulated the performance of three different conformal geometries (serpentine, rectangular and tank) and compared the results with the traditional geometry in terms of cooling performance. Results highlight how serpentine geometry is able to improve process performance imposing a cooling curve characterized by a higher slope respect to the traditional shape.

Keywords: Additive Manufacturing; Conformal cooling channel; Thermoforming process

1. Introduction

The additive manufacturing (AM) technologies include all the processes that realize components by adding material layer by layer. These technologies can be classified into seven categories: vat photo polymerization, material extrusion, material jetting, binder jetting, powder bed fusion, direct energy deposition, sheet lamination. Together the AM, it has been developed the "Design for Additive Manufacturing" (DFAM), a guidelines collection that assists the designer to make the best use of these technologies. Indeed, the AM differs from the traditional subtractive processes thanks to four main capabilities: shape complexity, material complexity, hierarchical complexity, functional complexity. These abilities can be applied in different areas, according to the 3D printing technology employed: biomedical parts, vehicle components, finish products for example can be redesigned and realized with new and better properties. However, the AM capabilities allow to re-think even the tools used in the manufacturing process. Nowadays, the redesign of the moulds is getting great interest because with a most performing mould it is possible to obtain better products or improve the entire production cycle. In the thermoforming processes, for example, the moulds need an optimum cooling system to ensure high quality of the part and to reduce the cycle time. Due to the limitations of conventional drilling methods, the cooling system of the mould usually consists of simple paralleled straight channels that results in a lack of performance to cool complex shapes. Thanks to the evolution of AM, characterized by an increase of the shape complexity, it is possible to design a complex cooling system conformal to the mould geometry (conformal cooling). In the literature, the researches about this technique focused their

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10.1016/j.promfg.2020.04.128

attention on the optimization of the thermoforming process and injection moulding. A studied made by A.B.M. Saifullah and S.H. Masood [1] reveals that the conformal cooling channels can greatly improve the injection molding process, reducing the mold temperature of 9°C and the cycle time of 20%. Another studied made by Brooks and Bridgen [2] analyzed the use of the lattice structures together the conformal cooling. The lattice structures work as supports for the cooling channels. By this way, the motion of the refrigerant fluid becomes turbulent, optimizing the cooling process (cooling time reduced of 26%). Other researches provide some guidelines for the design of the cooling channels. In the study of Eva Voynova [3] for example, it has been suggested to place the channels near the hottest zones, choose their optimum section, realize an optimum distribution of the channels around the shape of the mold and not compromise the stiffness and the resistance of the mold. Another study, made by Yung Wa et al. [4], proposed an automatic method for the design of the cooling channels. Emmanuel Sachs et al. [5] used a particular 3DP technique to realize the molds with the conformal cooling channel. Thanks to this technology, a powder bad of stainless steel was spread and a binder material was used to selectively bided the powder particles. After this, the not bind powder was removed and an infiltration process with cooper alloy was performed to fill the porosity of the mold and to obtain a fully dense part. Altaf k. et al. [6] compared the results of profiled cross section of the conformal cooling channel (PCCC) with circular one. Both channels were designed with 78,5mm cross-sectional areas and normal water at 25°C as a coolant. The thermal distribution in both the CCCs was simulated using ANSYS. Result showed that 14,6% increase of heat flow with PCCC. Muhammad Khan et al. [7] designed different types of cooling channels, namely, conventional cooling channels (CCC), series conformal cooling channel (SCC), parallel conformal cooling channel (PCC), and conformal cooling channel with additive cooling lines (CCAL) for cooling of a food container and compared the results using Autodesk Moldflow Advisor 2013. Simulation results have shown that CCAL lines gave better cooling as compared to conventional cooling lines.

However conformal cooling respect to others AM design improvements, as topology optimization, is still under development and specific rules that define how to better design cooling channels still do not exist. Thus in this research, to enlarge the knowledge about this methodology, it has been carried out an optimization of a thermoforming mold cooling system. Three new geometries of the cooling channels were tested and compared with the traditional one in terms of cooling performance. In this way, it has been deduced what cross section and what cooling path allow to make the most of the conformal cooling technique and improve the cooling system. This study is based on a numerical investigation: every test was a virtual experiment, performed in Altair Acusolve, a CFD simulation software.

2. Materials and methods

The thermoforming process studied in this paper is shown in figure 1: a plastic sheet is deposited on the frame of the mold and is heated by a heating plate till the formed temperature (this value of temperature varies according to the used material), then a vacuum pump withdraws the air. The plastic sheet adheres to the mold and the finished part is obtained. Removed the part, the refrigerant fluid goes through the cooling channels and reduces the temperature of the mold. After this, the process can start again. The main problem of this process is due to the heating step. Indeed, the repetitive heating cycles overheat the surfaces of the mold in contact with the clamps. Due to the limitations of the traditional cooling system, the overheating forces to stop the thermoforming machine, in order to allow the refrigerant fluid to cool the mold. By redesigning the cooling channels, it is possible to improve the cooling phase and avoid this machine stops, enhancing the productivity.

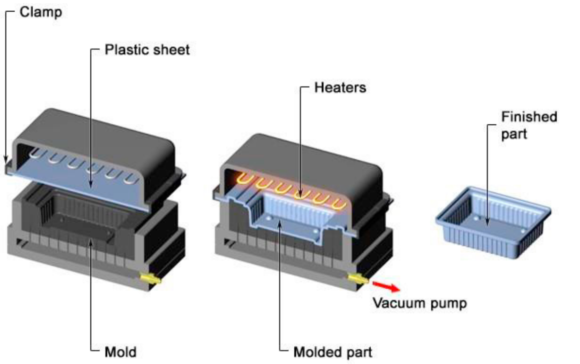

Fig. 1. representation of a thermoforming process.

The mold, object of this research, is composed by three different parts, shown in figure 2. A description of the parts is given below:

- the base: it contained the cooler and the matrix and connected the mold to the thermoforming machine. The plastic sheet was placed on the frame of the base and the heating plate applied here the heat to obtain the thermoformed piece;
- the cooler: placed inside the base, the cooler had a central hole, concentric with a hole in the base, for the generation of vacuum in the mold. The cooler was the main responsible of the cooling of the entire mold;
- the matrix: this part gave the shape to the plastic sheet. It contained a lot of holes to withdraw the air. It was fixed to the cooler through four screws.

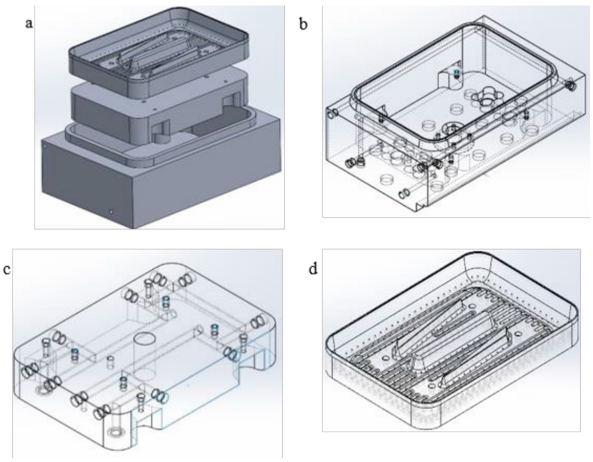

Fig. 2. (a) exploded view of the mould; (b) base of the mould; (c) cooler; (d) matrix.

In table 1, the materials selected for this research are reported. The ABS material and its properties came from literature while the aluminium material was selected from the material library of the software used to carry out the simulations. This library did not specify the aluminium alloy.

The main parameters of the thermoforming process are listed below:

- Initial temperature of the mold: 30 °C;
- Cooling fluid temperature: 20 °C;
- Input fluid velocity: 0,15 m/s;
- Heat flux: 100 W/m^2;
- Time duration of the process: 600 s;

Table 1. materials of the mold.

Component	Material
Base	Al
Cooler	ABS
Matrix	Al

Table 2 shows the density and the two main thermal properties of the materials used in the research.

Table 2. properties of the materials utilized.

Material	Density [kg/m^3]	Specific heat [J/kg-k]	Conductivity [W/m-k]
Aluminum	2702	908	237
ABS	1050	2050	0,189

The heat flux was applied to the contact surface between the heating plate and the mold (the white surface in figure 3a) and it acted as a step function (figure 3b): 30 seconds ON (when there is contact between the plate and the mold), 30 seconds OFF (because during the cooling phase there is no contact between the two areas).

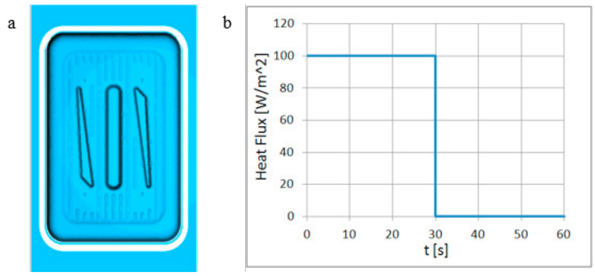

Fig. 3. (a) surface where the heat flux is applied, (b) step function that described how the heat flux acts on the mould surface.

In order to study the cooling process, it has been performed four simulations in the commercial software Altair AcuSolve, a software used for the simulation and analysis of heat exchanges between fluids and bodies. In every simulation, it has been set the parameters of the standard process (shown before), to accurately replicate the real conditions. Then, it has been defined the surfaces of heat exchange, the adiabatic ones and the input and output points of the refrigerant fluid. The white surface described in figure 3a has been defined as a surface of heat exchange due to heat flux here applied. This heat flux influenced the inner and outer surfaces of the three parts of the mold, thus all of them has been set as surfaces of heat exchange. Moreover, the refrigerant fluid absorbed heat from the surfaces of the cooling channels, so these areas has been defined as surfaces of heat exchange too. The input and output points of the fluid were the same for all simulations.

The optimization of the cooling process was reached by redesigning the geometry of the cooling channels placed inside the cooler. In figure 4, it can be seen the new geometries of the cooling channels of the cooler. A brief description of the new geometries is here reported:

- Serpentine geometry: the cooling path across the cooler was a serpentine with a circular section with a diameter of 7 mm;
- Rectangular: the path had a rectangular section with dimensions of 25x5 mm;
- Tank: it has been removed the material inside of the cooler, in order to obtain an empty part.

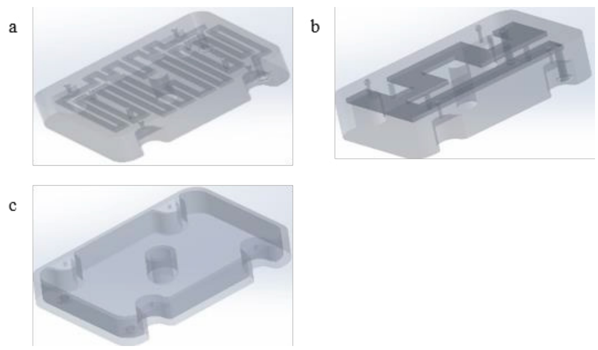

Fig. 4. (a) serpentine geometry; (b) rectangular geometry; (c) section view of the tank geometry.

As it can be seen, it has been used three different sections for the cooling channels of the cooler in order to evaluate how these sections influenced the cooling process.

To understand which cooling geometry of the cooler was the best, three simulations have been performed, one for each geometry (serpentine, rectangular, tank). The results have been compared using thermal maps. The molds were analyzed from two different views:

- top view of the cooler;
- middle section view: a horizontal plane (figure 5a) cut the mold at a distance of 53,4 mm from the bottom of the base. By this way, the plane divided the cooling channels into two equal parts.

The traditional geometry of the cooling channel and the best of those redesign has been compared utilizing both thermal maps (as shown before) and a quantitative approach: two nodes located in the red circles of figure 5b (point 1 was placed on the frame of the base, point 2 on the matrix) have been selected to study the temperature variation during the 600 s simulated.

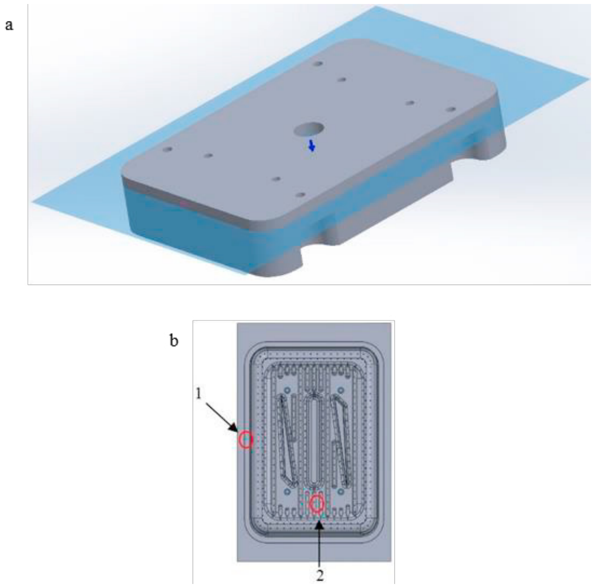

Fig. 5. (a) horizontal plane used for the section view of the cooler; (b) the two nodes selected for the quantitative analysis.

3. Results and discussion

The next sections are organized as follows: in section 3.1 the three new geometries (serpentine, rectangular and tank) are compared with each other to understand which has been the best to cool the mold. In section 3.2 the best of these three geometries is compared with the traditional one, to verify if there have been real improvements in cooling performance.

3.1. Simulations of the redesigned cooler cooling systems

In this section the results of the three simulation performed for the redesigned cooler cooling systems are shown. In figure 6, the top views of the coolers highlighted that the serpentine geometry was the best: here the lowest reached temperature is between 21,3°C and 22,6°C while the rectangular and tank geometry brought to higher values, between 27,5°C and 28,6°C. Moreover, thanks to the serpentine path, it has been possible to perform a more uniform cooling of the cooler. Indeed, in figure 6a, it can be seen that more than the 80% of the surface of the cooler reached a temperature lower than 30°C (the initial temperature of the mold), while in figure 6b and 6c this percentage was much smaller.

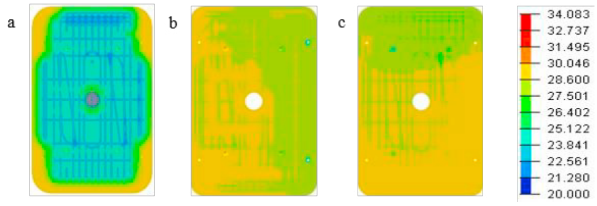

Fig. 6. top views of the cooler. (a) serpentine; (b) rectangular; (c) tank

The section views of figure 7 confirmed the serpentine geometry was the best. This cooling channel allowed to obtain a more uniform cooling than the other ones. Indeed, a large part of the cooler reached a temperature value between 20°C and 21,3°C, while in the simulations with the rectangular geometry, this temperature has been detected only along the path of the cooling channel. The simulation with the tank cooling system highlighted some problems during the filling of the cooler. Indeed, the cooling took place only in the part of the mold near to the input point of the fluid.

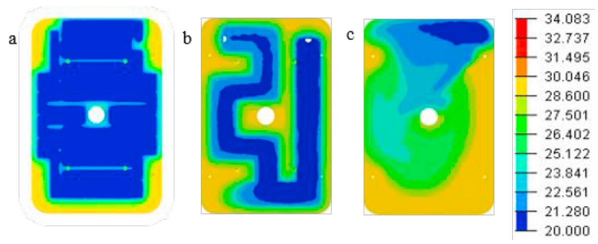

Fig. 7. Section views of the moulds. (a) serpentine; (b) rectangular; (c) tank

The three simulations revealed that the serpentine cooling system was the best to cool the mold. Indeed, its cooling path has been made very complex in order to cover almost the entire area of the cooler. This great complexity has been possible thanks to the circular section with a diameter of 7 mm. Using a bigger section, as the rectangular one, the cooling path had to be simpler not to self-intersect. With a channel section too big, as the tank cooling system, the refrigerant fluid could not follow a precise path, generating problems during the filling of the cooler.

In the next section, it has been compared the serpentine geometry and the original one, to understand if the redesign cooling system was better than the traditional one.

3.2. Comparison of serpentine and original cooling system

After having understand the serpentine geometry was the best to cool the mold, the cooling channel of the base was redesigned (figure 8) and used together with the new cooler. By this way, it has been possible to obtain an optimal cooling even on the frame of the base, where the heat flux was applied.

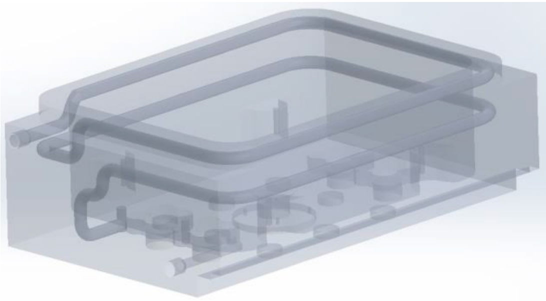

Fig. 8. redesigned cooling channel of the base.

Two simulations were performed, one for the original cooling system and one for the redesigned one, that had the serpentine geometry for the cooler and the modified cooling channel in the base. The results of these simulations were compared using both thermal maps and a quantitative approach, as described in section 2. In figure 9, it can be seen the top views of the molds.

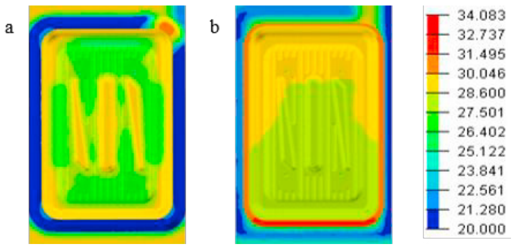

Fig. 9. top views of the moulds. (a) serpentine; (b) original

The serpentine geometry performed a better cooling, shown by the lower values of temperature of the matrix. Indeed, the top view of case a) highlighted that more than 75% of the matrix reached a temperature of 27,5°C. On the other areas of the matrix, the detected temperature never overcame the 29°C. The matrix of the original geometry was divided into two different areas: in the yellow one, the detected temperature was between 28,6 and 30,1°C; in the green one, the temperature was between 27,5 and 28,6°C. The frame of the base underlined the better cooling of the serpentine geometry. Here, the temperature reached in casa a) was between 20 and 21,3°C while in case b) it was reached the maximum value of 31,5°C.

The section views confirmed the improvement given by the serpentine cooling system. Figure 10 showed how the redesign geometry allowed to obtain a more uniform cooling and a low temperature (20-21,3°C) has been reached in large part of the cooler. The original geometry instead focused its cooling along the channel path, while the other areas maintained high temperatures (28,6-30,1°C).

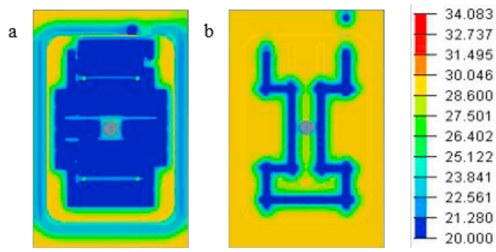

Fig. 10. section views of the mould. (a) serpentine; (b) rectangular.

In order to better understand the different cooling performance of the serpentine and the original geometry, a quantitative approach was used for the analysis of the cooling process. In figure 11, it has been shown the temperature variation in point 1 for both cooling system: the serpentine geometry turned down the temperature from a maximum value of 30,3°C to a minimum of 20,8°C, while with the original cooling path the maximum reached temperature was 31,5°C and the minimum 29,9°C. The graphic showed fluctuations of temperature for both cooling system because on the frame of the base (where point 1 was located) the heat flux acted as step function. At the end of the 600 s, the temperature detected in point 1 for the original cooling system was 30,3°C, with an increment of 1% compared to the 30°C, while for the redesigned cooling system, the temperature was 21,1°C, with a reduction of 29,7% (compared to the 30°C).

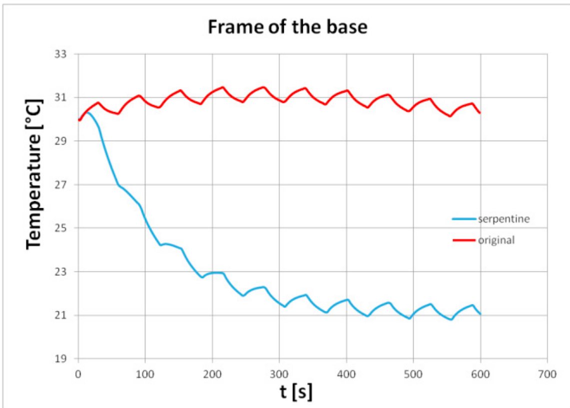

Fig. 11. temperature variation in point 1, on the frame of the base.

Analyzing the point 2 (located on the matrix), it can be seen the serpentine geometry brought to a lower temperature. Indeed, the redesign geometry reduced the temperature till a minimum value of 27,3 °C while the original one to a value of 28,6°C. Besides the advantage of this redesign cooling channel leads to a reduction of temperature equal to 4,5%, it must be remembered that the mold works only ten minutes while actually it is used for 8 consecutive hours.

Figure 12 shows the variation of temperature in point 2 for both cooling system. It is important to underline the different slope of the two curves: original one a slope of 0,003 while the serpentine has a slope of 0,007 with an increment of 233,3%.

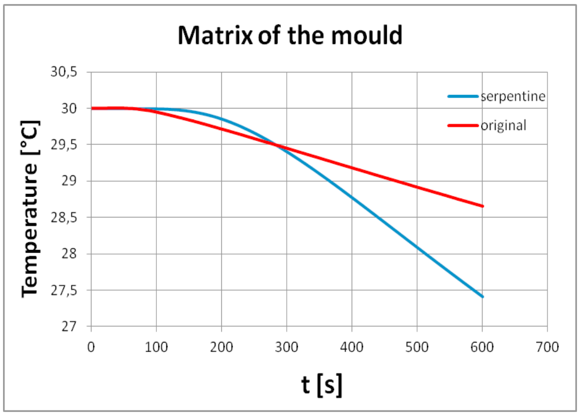

Fig. 12. temperature variation in point 2.

The graphic just showed confirmed that the serpentine geometry performed better cooling than the traditional one.

4. Conclusions

The conformal cooling technique can strongly improve the cooling phase of a manufacturing process. In this paper, it can be seen that the geometry of the cooling channel greatly affects the performance of the whole cooling system. Indeed, the simulations reveals that to perform an optimum cooling process, the section of a cooling channel should be circular and the cooling path should be a serpentine. This configuration allows the refrigerant fluid to follow a precise path and to reach almost every point of the cooler. By this way there are no problems during the filling of the cooling channel and the cooling of the mold is more uniform.

Future experiments about the conformal cooling technique could be concern the mold used in process different from the thermoforming and injection molding process.

Acknowledgements

The authors would like to thank the Mondini s.p.a. for providing the geometry of the original mold and for the willingness showed during the whole period of the research.

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