Available online at www.sciencedirect.com

ScienceDirect

Materials Today: Proceedings XX (2016) XXX–XXX

materialstoday: PROCEEDINGS

www.materialstoday.com/proceedings

PMME 2016

Comparative study of cooling systems for vacuum forming tool☆

B.I.Hussain[a]*, M.Safiulla[b]

[a]*Dept. of Mech. Engg., Bapatla Engg. College, Bapatla-522101, Guntur Dt., Andhra Pradesh, India*
[b]*R&D section, Dept. of Mech. Engg., Ghousia College of Engg., Ramanagaram-562159, Karnataka, India*

Abstract

Vacuum forming is one of the simplest manufacturing processes that is inexpensive when compared to other moulding and forming techniques used in the plastic industry. In this paper an attempt is made in evaluating the available cooling techniques that affect the cooling time of the mould in manufacturing a plastic part. The three different methodologies considered for cooling the vacuum forming tool are chill plate attachment method, straight cooling channels within the mould and conformal cooling channels within the mould. The best possible alternative which minimizes the cooling time is suggested to the industry

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

Keywords: Vacuum forming; cooling time; plastic part; manufacturing process; chill plate; cooling channels

1. Introduction

Amongst the several manufacturing processes available, the one which is suitable for moulding the required shape for a plastic sheet material is vacuum forming, wherein a plastic sheet is heated to a moulding temperature with an electric heater and the shape is obtained by creating a vacuum between the mould and sheet. Numerous applications like blister packing, skin tight packing, disposable trays and cups, material handling trays etc. are originated from vacuum forming. The most important factor that is urging any manufacturing process in general and vacuum forming process in particular is cooling time of mould which determines the speed of the manufacturing process and

* Corresponding author. Tel.: +919966673866; fax: +918643224246.
E-mail address: iftekharhussainb@gmail.com

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

its applicability. The total cycle time obviously has a considerable economic impact on the effective production. This cycle time can be reduced by decreasing the cooling time of the part. Ultimately, the decrease of cooling time leads to several advantages like producing quality product with least possible time which enhances the productivity of the enterprise.

2. Related work

Several researchers have made contributions to cooling methods and conformal cooling channels etc. in injection moulding processes in one or the other direction. Lin and Chou had designed the Cooling Channels in Nonrectangular Plastic Flat Injection Mold [1]. D.E.Dimla *et. al.* had made contributions to determine an optimum and efficient design for conformal cooling channels in the configuration of an injection moulding tool[2]. H.Hassan et al. had made efforts to determine the temperature profile along the cavity wall to improve the cooling system design in injection moulding [3]. H.Hassan et al. had studied the effect of the cooling system design on the solidification and heat transfer of polymer by injection molding[4]. Researchers had proposed an automatic method for designing conformal cooling circuits that affects the quality and timing for products fabricated by rapid tooling concept [5]. G.Kovács and B.Sikló had investigated an injection molding analysis of the heat flow developed at corners in injection molds [6]. A.B.M.Saifullah, S.H.Masood & I.Sbarski had carried out investigation on bi-metallic conformal cooling channel with high thermal conductive copper tube insert for injection moulds [7].

Majority of the research work carried out during the past decade in cooling methods of mould using rapid tooling technology is confined to injection molding process. Any such work on cooling methods of vacuum forming tool is not reported in the literature. The present investigation is aimed at carrying out the possible cooling methodologies of the mould used in vacuum forming process and selection of the best strategy to cool the mould evenly in order to optimize the process.

3. Research Methodology

3.1 CAD Modeling

In order to study and optimize the cooling methodology, a plastic part made of polystyrene is taken into consideration. It is a disposable, flat and rectangular cup to hold solid or liquid foodstuff in functions for a small period of time. The CAD model of the cup modeled in commercially available PLM software, NX 8.0 is shown in Figure1. The maximum dimensions of the part are 100 mm x 90 mm (including canopy to hold it) with internal dimensions of 85 mm x 81 mm, filleted on four corners and bottom with radii of 15 mm and 3mm respectively. The depth of the part is 30 mm. Because the container is used for a short duration of time and made of small thickness (0.2 mm), a mesh of grooves is designed for the purpose of strength in the structure.

3.2 Tool Design with cooling mechanism

The tool for producing the plastic part using vacuum forming is made of Aluminum HA30 (industrial grade). The cooling channels allow water to flow through the mold walls and cool the hot plastic part. The removal of heat by circulating coolant through the mould cooling channel would arrest the rise of mould temperature upon continuous production [8]. The tool design for this study is based on [1] with cooling channels of 10 mm diameter and mould dimensions of 130 mm x 130 mm with a height of 50 mm. The gap between the cavity and cooling channels is 10 mm.

3.3 Mould cooling methods

In vacuum forming process, the cooling of mould is often ignored for producing a small quantity of output. In the entire vacuum forming cycle, cooling stage is the dominant component, and generally accounts for 50% to 70% of the cycle time. In order to cool the mould to produce accurate parts with minimum time, it is imperative to have cooling channels inscribed in it. The complexity involved in designing and manufacturing the cooling channels is hampering the developments in optimizing the parameters like cooling time, strength etc. Thanks to the advent of technologies like rapid tooling wherein any complex mould can be easily built in a couple of hour's time.

The three basic types of cooling methodologies employed for mould cooling are,

a. Chill plate attached at the bottom of the mould.

b. Straight drilled cooling channels in the mould with baffles and plugs.
c. Conformal cooling channels according to shape of the part to be produced.

These three methodologies are studied in detail for selecting the best amongst them in the industry.

3.3.1 Chill plate method of cooling the mould

The most widely used method of cooling the mould in the industry is to attach a chill plate at the bottom of the mould to dissipate the heat from the mould through conduction. Even though scientifically not proven to be the best, it is widely used because of its simplicity and adoptability to any mould. The same chill plate is used multiple number of times for producing different parts on different moulds. The chill plate in turn will have its own channels of cooling and is connected to the chiller plant or a form of refrigerator in order to supply the cool water (or any suitable fluid) continuously. The chill plate method of cooling does not have any sort of cooling channels within the mould and hence is simple to construct the mould with CNC milling or any other allied processing operations. Figure 2 shows the concept of chill plate method of cooling.

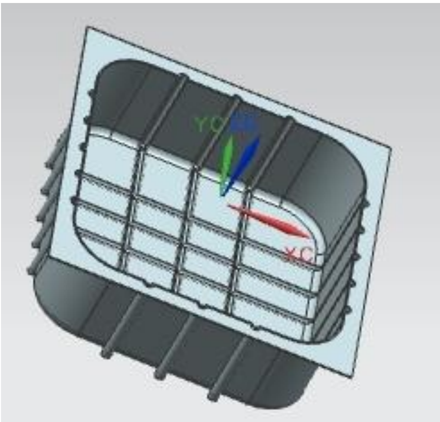

Fig 1. 3D CAD Model of disposable container

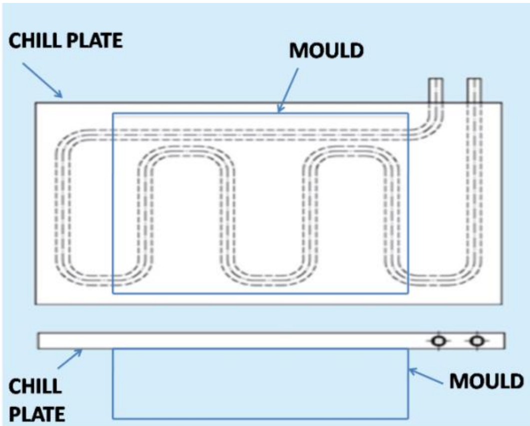

Fig 2. Chill plate attached to the mould for cooling

3.3.2 Straight drilled cooling channels

Until recently if at all any cooling channel has to be incorporated in the mould, it used to be straight drilled cooling channels with baffles and plugs inserted inside it. Figure 3 illustrates a straight drilled cooling channel inside a mould immaterial of the part shape to be produced, but that best fits for rectangular part without any fillets or contours in it. The manufacturing technologies available and the cost restrict to have the cooling channels along the straight line path. If the part to be produced is having contours like elliptical shape or filleted with a larger radius, the straight drilled cooling channels will yield with non uniform cooling of the mould as illustrated in Figure 4 with different distances of x, y and z from the mould to part. The CAD model with straight drilled cooling channel for such a case (present investigation) is illustrated in Figure 5.

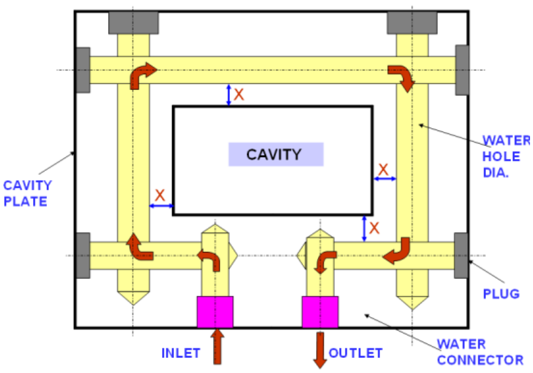

Fig 3. Straight cooling channel equidistant from part [9]

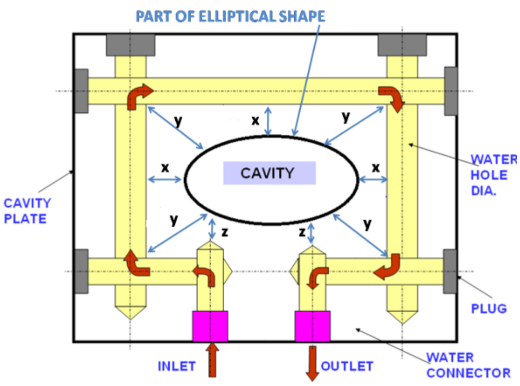

Fig 4. Straight channel for contoured part with uneven cooling

3.3.3 Conformal cooling channels

Conformal cooling channels can be employed today to make the mould with the technologies available like additive manufacturing. The cooling channels take the shape of the part to be produced to have uniform cooling throughout the mould in the manufacturing process to enhance the fatigue life and part quality with minimized rejections. The additive manufacturing technologies available today can be used to make any complicated mould with any number of cooling channels of any shape as long as it can be modelled in modelling software. Further the time required to make a mould of any complex shape is limited to couple of hours. The model of mould taken for the present study with conformal cooling channel is depicted in figure 6.

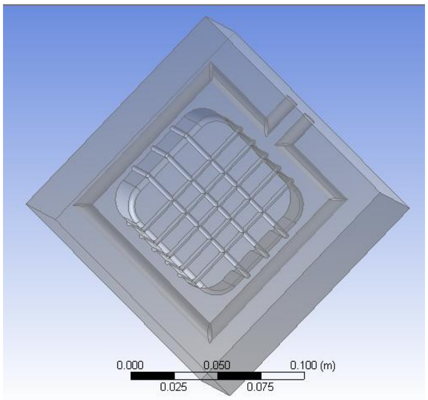

Fig 5. Straight drilled cooling channel

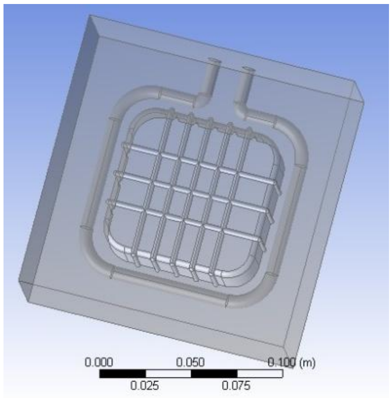

Fig 6. Conformal cooling channel in the mould

4. Analysis

As the model considered is complicated to study and derive the heat transfer between mould and part with cooling method, finite element analysis (FEA) is carried out to derive the approximate numerical results based on which conclusions are drawn. Furthermore it is proved by many researchers that for complex numerical calculations in this area, FEA is one of the few methods available to perform analysis. It is reported that an accurate prediction of the mould flow pattern, pressure distribution, temperature and cooling profile of the resin using simulation techniques allow one to optimize the process and hence to improve the final properties of the manufactured part [10].

FEA is carried out using commercially available software ANSYS Workbench 15.0. Solid 87 is used as element that is suitable to model irregular meshes produced from various CAD/CAM systems and is applicable for conducting transient thermal analysis. Free mesh is carried out on the entire mould and it is refined at the place of part contact and cooling side. The meshed model is shown in figure 7. The conduction between the mould surface (where heated part comes in contact) and the cooling channel/chill plate is studied. The radiation from outside surface of the mould to atmosphere is neglected. The convection within the cooling medium (water) is also not considered. A transient thermal analysis is carried out for the mould with three cooling methodologies considered. The mechanical properties of the mould material used for analysis are presented in Table 1. The parameters used to perform analysis are tabulated in Table 2. The properties for analysis were taken from [11]. For chill plate method of cooling, the bottom surface of the mould is applied with a cooling temperature of 20^0C and forming temperature applied in cavity with side walls of the mould constrained. For cooling channels inscribed within the mould, the bottom surface accompanied with side walls of the mould are constrained and coolant temperature of 20^0C is applied within cooling channels followed with forming temperature applied inside the mould surface where the part sticks to the mould. Heat flux is the heat energy absorbed per unit area. The heat flux results are procured from the analysis.

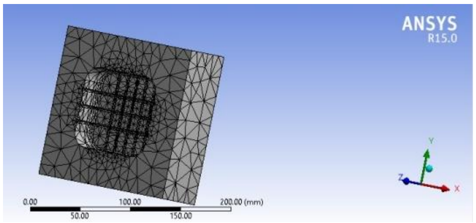

Fig 7. Meshed model in ANSYS

Table 1. Properties of the mould material

Mould Material	Aluminium HA30 industrial grade
Modulus of Elasticity	71000 MPa
Density	2770 Kg/m^3
Poisson's ratio	0.33
Coefficient of thermal expansion	2.3 x 10^{-5} m/^{0}C
Specific Heat	875 J/Kg ^{0}C
Thermal Conductivity (at forming temperature)	170 W/m ^{o}C

Table 2. Parameters for analysis

Analysis Type	Transient thermal analysis
Ambient Temperature	25^{0}C
Chilled Coolant (Water) Temperature	20^{0}C
Forming Temperature	150^{0}C
Time for analysis	20 seconds

5. Results and Discussion

The heat flux results at a side corner for 20 seconds of cycle time divided into several fragments of milliseconds is obtained from analysis. The results of heat flux at the end of the cycle, i.e. after 20 seconds for three categories of cooling the mould viz. Chill; Straight cooling channel and Conformal cooling channels are depicted in Figures 8, 9 and 10 respectively. The maximum heat flux obtained after 20 seconds for each of the cases is tabulated in Table 3. The variation of heat flux with time for these three cooling methods is represented in figure 11. (The reader is advised to view the web version of this article for clear visualization of results). By comparing the three cases studied individually, as depicted in figures 8, 9 and 10, it is observed that the least of the maximum heat flux values recorded are from chill plate method of cooling and the highest from the conformal cooling channel method of cooling the mould. The maximum heat flux for straight drilled cooling channel method is in between these two cases. This indicates that a good amount of heat is absorbed by the conformal cooling channel method when compared to the other two methods. However the entire set of heat flux values recorded are depicted in graph (figure 11) which shows that at the initial stage of mould cooling not much variation exists for starting 2 to 3 seconds for all the cases. With gradual increase of time and coolant flow, the maximum heat flux values are varying for each of the cases thereafter. After a cycle time of 20 seconds, the conformal cooling method shows highest amongst all thereby giving an indication of more heat dissipation from the mould to the coolant.

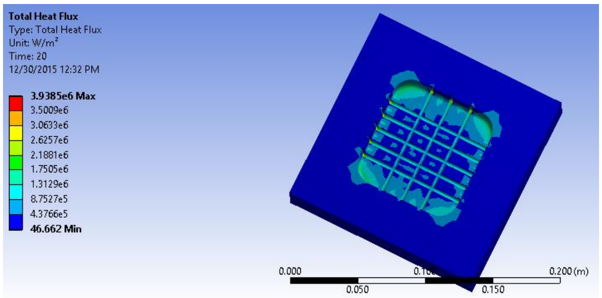

Fig 8. Heat flux after 20 sec when chilled plate at 20°C is attached

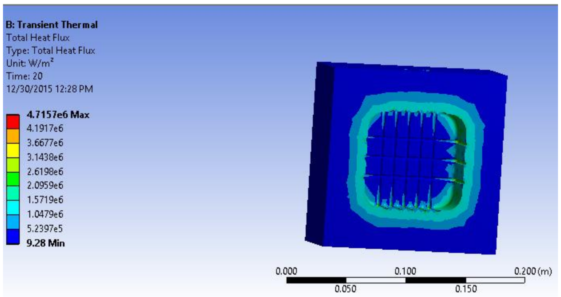

Fig 9. Heat flux for Straight cooling channels after 20 sec

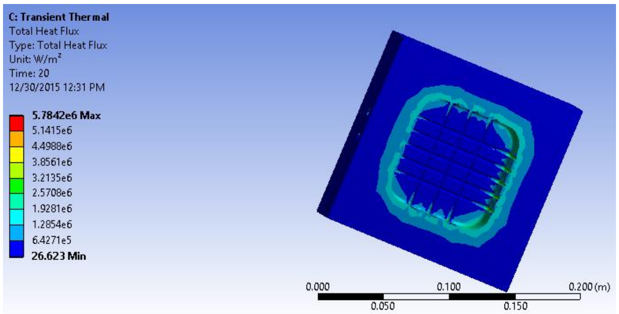

Fig 10. Heat flux for conformal cooling channels after 20 sec

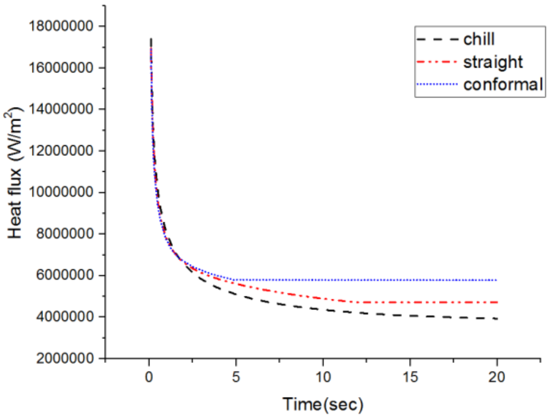

Fig 11. Comparison of Heat flux for different cooling methods

It is reported in the literature that CAE based software programs can be applied for any traditional manufacturing company involved in plastic producing parts [12]. Further it is reported that the interplay of part design, tool design, material properties, production conditions, and part quality is extremely complex and involves a matrix of many variables. It is not reasonable to expect a team of engineers to deal with these complex interactions and optimize forming processes without the use of modern finite element methods. Also the system of nonlinear partial differential equations representing the phenomena taking place during processing can only be solved using numerical techniques such as the finite-element method [13]. This gave the confidence that the results can be truly accepted as no such work is reported in literature on application of vacuum forming through rapid tooling concept and its heat transfer behavior.

Table 3. Maximum heat flux for three cases after 20 sec

Cooling method	Maximum heat flux (W/m^2)
Chilled plate	3.9385×10^6
Straight cooling channels	4.7157×10^6
Conformal cooling channels	5.7842×10^6

6. Experimental validation

Experiment is conducted to evaluate the cooling time for chill plate method and straight cooling channels method of mould. After four hours of continuous production using aforementioned cooling methods separately on the same machine for the same part with different moulds, temperature is recorded using k-type thermocouple at the corner point of the cavity wall. The temperature for chill plate method of mould is found to be 56^0C whereas for mould with straight drilled cooling channels, the temperature is found to be 47^0C. These results of cooling time have shown that the mould with straight cooling channels is cooler than the mould with chill plate attachment after the same period of production time. This depicted an improvement of cooling system in straight cooling channel when compared with chill plate attachment.

7. Conclusion

The heat flux results have shown that the values are decreasing with respect to time as the difference of temperature between the mould and cooling channels is decreasing. Further it is observed that the heat flux results are in ascending order for chilled plate method of cooling, straight drilled cooling channels and conformal cooling channels. Hence it is concluded that the conformal cooling channels are the best form of cooling methodology to be adopted as more heat is ejected from the mould and transferred to the coolant. The experimental results have shown an improvement of cooling system by 16% from a temperature of 56^0C for chill plate method of cooling to 47^0C for straight cooling channel method of cooling. The work can be further extended by conducting a series of experiments to evaluate the model in different directions like change in parameters for existing cooling system and rapid tooling based conformal cooling channels of the mould.

References

[1] Lin.Z and M.Chou, Design of the Cooling Channels in Nonrectangular Plastic Flat Injection Mold, *Journal of Manufacturing Systems*, 2002, 21/ 3.

[2] Dimla D.E et al., Design and optimisation of conformal cooling channels in injection moulding tools, *Journal of Materials Processing Technology* 164–165 (2005) 1294–1300.

[3] Hassan.H et al., Effect of cooling system on the polymer temperature and solidification during injection molding, *Applied Thermal Engineering* 29 (2009) 1786–1791.

[4] Hassan.H et al., 3D study of cooling system effect on the heat transfer during polymer injection molding, *International Journal of Thermal Sciences* 49 (2010) 161–169.

[5] Wang.Y et al., Automatic design of conformal cooling circuits for rapid tooling, *Computer-Aided Design*, 43 (2011) 1001–1010.

[6] Kovács.J.G, and B.Sikló, Investigation of cooling effect at corners in injection molding, *Int. Communications in Heat and Mass Transfer* 38 (2011) 1330–1334.

[7] Saifullah.A.B.M et al., Thermal–structural analysis of bi-metallic conformal cooling for injection moulds, *Int J Adv Manuf Technol*, Dec 2011.

[8] Bolur.P.C, *A Guide to Injection Moulding of Plastics,* Mangalore, 2000.

[9] Prabhakar Purushothaman, browsed from web page of Wikipedia, https://en.wikipedia.org/wiki/File:Cavity_plate_cooling.png

[10] Mathew.A and S.H.Masood, Part optimisation using gate location analysis in injection moulding, Int. Conf. On Computer Aided Engineering, (CAE 2007), IIT Madras.

[11] MatWeb. The Online Material Information Resource Homepage. http://www.matweb.com

[12] Vinod.S, et al., Mould analysis: an enabler of agility in mould design, Int. Conf. On Computer Aided Engineering, (CAE 2007), IIT Madras.

[13] Salloum, Gorges. "Process Modeling", in Hilton.P, *Rapid Tooling: Technologies and Industrial Applications,* Marcel Dekker, Inc., New York, 2000.