INVESTIGATION OF THE IMPACT OF CONFORMAL COOLING ON THE PERFORMANCE OF INJECTION MOULDS FOR THE PACKAGING INDUSTRY

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ABSTRACT

This paper discusses the results obtained from studies on the performance of different cooling layouts. The conventional method of cooling makes use of straight-line cooling channels. This simple method of cooling does not possess the capability of uniformly cooling down the part produced. In contrast, conformal cooling is a technique that makes use of cooling channels in an injection moulding tool that closely follows the geometry of the part to be produced. The paper presents some experiences gained in a comparative case study of conventional cooling vs conformal cooling using simulation, followed by an experimental validation and statistical analysis of the results.

Keywords: Injection moulding, Conformal cooling, Simulation

1. INTRODUCTION

Injection moulding is one of the most important processes used to manufacture plastic products. Today, more than one third of all thermoplastic materials are injection moulded, and more than half of all polymer processing equipment is for injection moulding. The injection-moulding process is ideally suited to manufacturing mass-produced parts of complex shapes that require precise dimensions [1]. The injection moulding process for thermoplastics comprises three major stages (Figure 1):

- Injection (filling) stage. In this stage the plastic material is first heated to the molten state and plasticised before the filling process. Under high pressure, the screw plunges forward to inject the plastic into the mould. The plastic flows through the nozzle into the spur, and then into the mould cavity. When the filling of the mould cavity is completed, more molten plastic is delivered into the cavity via high pressure to compensate for the shrinkage of the plastic, and to ensure the complete filling of the mould cavity. The packing time depends on the properties of materials being moulded [2].

- Packing stage. This stage begins after the cavity has been filled. This involves further application of pressure to the material in an attempt to pack more material into the cavity, in order to ensure uniform shrinkage, and consequently reduce component warpage.

- Cooling stage. This starts after the first rapid filling of the cavity and continues during the packing stage. The rate and uniformity at which the part is cooled affects the finished mould quality and the production cost. Mould cooling accounts for more than two-thirds of the total cycle time in the production of injection-moulded thermoplastic parts [3].

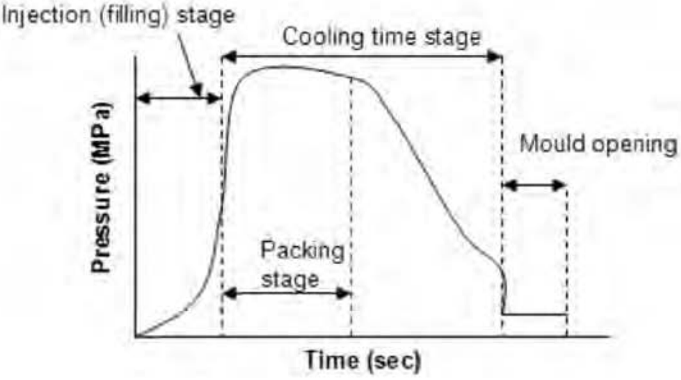


Figure 1: The injection moulding process

However, the use of analysis tools for the simulation such as Moldflow Part Adviser™ software is the ideal way to quickly check the manufacturability of a plastic part early in the design process, when the cost of any change is still at its lowest. The analysis results can be used to determine the optimum thickness of the part and gate locations, as well as to identify and eliminate cosmetic issues such as weld lines, air traps and sink marks.

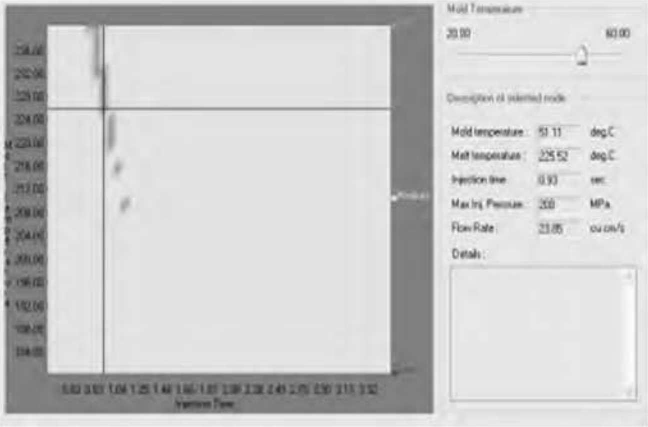
2. BACKGROUND AND OBJECTIVES

The conventional method of supplying cooling water within moulding components is to drill connecting holes to make a series of straight channels, through which the water comes into close contact with the wall of the mould cavity. This method is limited by the ability to produce straight channels only. Methods that build better cooling systems by using new fabrication technology have been reported [4, 5]. Instead of the conventional hole-drilling method to produce straight-line channels, Sachs [6] presents a method that takes the advantage of solid freeform fabrication technology to produce conformal cooling channels. The study shows no transient behaviour at the start of the moulding while at the same time a more uniform temperature is maintained in the tool during an individual moulding cycle; therefore, an accurate temperature control is possible, even for a part with a complex shape. Different layered manufacturing (LM) methods have been discussed and compared [7-13]. Thus, most existing work on the design of cooling systems of plastic injection moulding was focused on the detailed analysis of the optimisation of the cooling system and the cooling channel layouts. Based on previous studies in improving the cooling mould design system, the objective of this work is to investigate the impact of advanced conformal cooling design on the performance of the injection moulds.

3. SIMULATION MODEL

3.1. Model design

A cup of a commercially available household article was chosen as a benchmark. The solid modelling of the cup and the mould was done to check the effect of different layout cooling design channels on the component and an optimal approach to the design with respect to functionality, proportionality, core and cavity extraction, and actual dimension perspective. The cup material is a high-density polyethylene (HDPE) polymer. One of the first simulations performed is the Moulding Window Analysis using Moldflow™. This analysis result enables the user to determine the optimal injection parameters such as melt temperature, mould temperature and injection pressure (Figure 2)



Mold temperature : 51.11 deg.C
Melt temperature : 225.52 deg.C
Injection time : 0.93 sec
Max Inj. Pressure : 200 MPa
Flow Rate : 23.85 cu.cm/s

Figure 2: Moulding window results

The result of the cup analysis shows that an optimal melt temperature of 225.52°C should be used together with a mould temperature of 51.11°C.

3.1.1. Gate location

The first step after the part has been imported from a computer aided design (CAD) package is to determine the gate location. The most suitable areas for gate locations are coloured dark (blue) in Figure 3.

3.1.2. Confidence of fill

After the optimal injection location has been identified, a confidence of fill analysis needs to be performed. This is the level of confidence when the simulation program shows the probability that the part will be easy to produce. It is clear from the result in Figure 4 that the part will fill adequately with a high quality prediction.

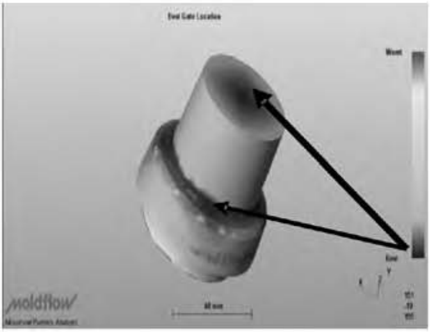


Figure 3: Best gate location

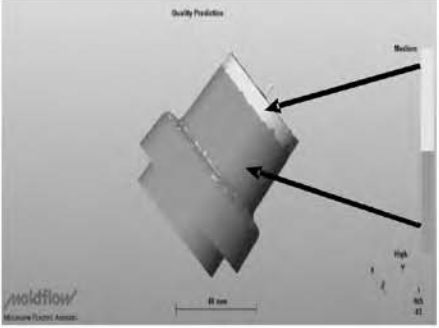


Figure 4: Confidence of fill

3.1.3. Filling time

The fill time result shows the path that the molten plastic takes through the part, and the amount of time it takes to fill. In this result, all areas of the part that are filled at the same time are given the same colour contour. The areas of the part that fill first are at 0.0 seconds, while those that fill last are at 0.90 seconds Figure 5 shows the time for each stage of the component as indicated by its colour.

3.1.4. Injection pressure

The injection pressure result is a contour plot of the pressure distribution throughout the cavity at the end of filling. The maximum value is at the injection location, which appears to be 44.68 MPa (Figure 6). The minimum is at the last point of the cavity to fill.

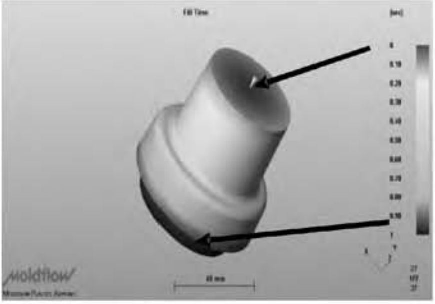


Figure 5: Fill time

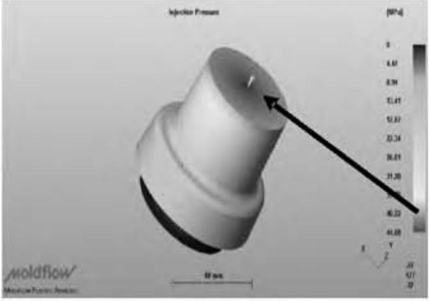


Figure 6: Injection pressure

3.1.5. Volumetric shrinkage

It can be seen in Figure 7 that the rest of the cup has very little shrinkage. The area where the cup is prone to 11.78% shrinkage is where the plastic is at its thickest. This will have no effect on the functionality of the part to open / close the container and the part will even have a good appearance.

3.1.6. Sink marks

The result in Figure 8 indicates the presence and location of sink marks. Sink marks typically occur in mouldings with thicker sections. The part examined is prone to having some sink marks, but only at a maximum depth of 0.197 mm.

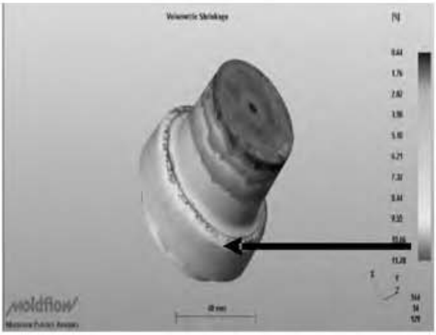


Figure 7: Volumetric shrinkage

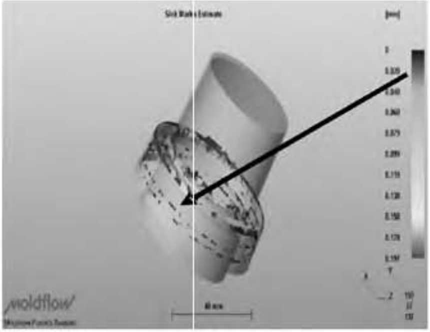


Figure 8: Sink marks

3.2. Simulation process

The simulation analysis was used for different cooling layouts: bubbler only, spiral only, bubbler with outside ring, inside spiral with outside ring and inside and outside spiral, and by applying different temperatures for mould (40, 50 and 60°C) and melt (200, 220 and 240°C). In the simulation it was assumed that the coolant consists of pure water with no added anti-freeze chemicals and that it could be chilled to a temperature of 11°C, as is the case in most of the bigger manufacturing plants.

A coolant flow rate of 7 l / minute was used for all simulations, as this was the lowest flow rate needed to exceed a Reynolds number of 10,000. The coolant flow rate is also a function of temperature, whereby the temperature of the outgoing fluid may not be more than 2 3°C warmer than the ingoing fluid. It was confirmed for all cooling layouts to be in the region of between 0.28 - 0.86°C.

3.3. Cooling channel layout

Five different cooling layouts were chosen in this study according to the needs and the ability to manufacture them, for practical implementation as well as a test for physical experimental work. The cooling layouts included:

- a bubbler on the inside of the core insert
  The reason for the selection of the bubbler cooling channel in this research is due to the fact that it is an easy and cost-effective method to implement. This section of cooling line diverts the coolant flow into the area that would normally lack cooling. Cooling channels are typically drilled through the mould core insert (Figure 9).

- a spiral helix cooling channel inside the core insert
  The aim of using this method is to obtain a uniform and therefore better cooling in order to reduce the cycle time with good quality parts. The spiral helix cooling channel is shown in Figure 10.

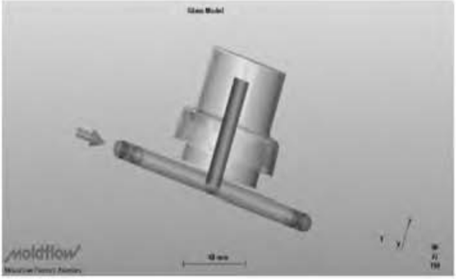


Figure 9: Bubbler cooling layout

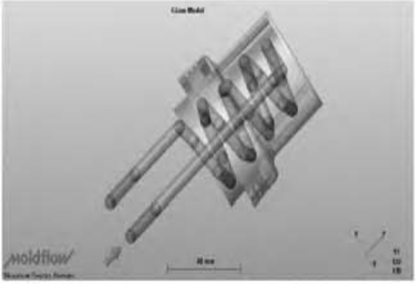


Figure 10: Inside spiral only

- A bubbler on the inside of the core insert and with an outside ring on the surface of the cavity insert

This method was designed to compare the cycle time and the quality of the part with the other layout cooling channel (Figure 11).

- A spiral helix inside of the core insert with an outside ring on the surface of the cavity insert

This type of test was designed in order to compare it with the layout of spiral cooling inside the core/cavity inserts, so that its influence on the part quality and cycle time could be investigated (Figure 12).

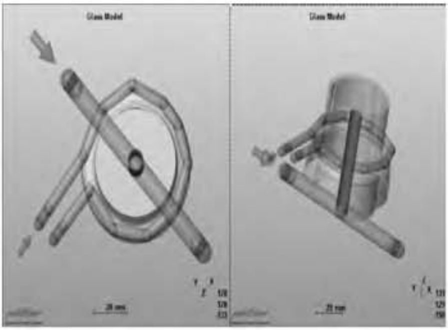


Figure 11: Bubbler with outside ring

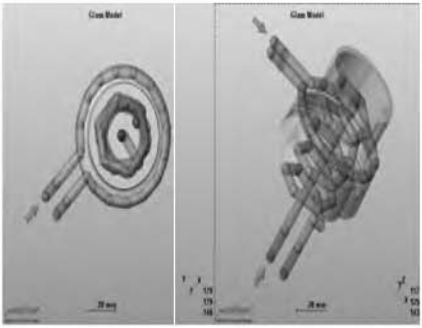


Figure 12: Inside spiral with outside ring

- Spiral inside the core/cavity insert

The spiral channel can be manufactured using LM methods. Such methods are used to create mould inserts that lend a great deal of freedom to the designer. Undercuts in the cooling design are not limiting and the cooling channels can follow complex shapes (Figure 13).

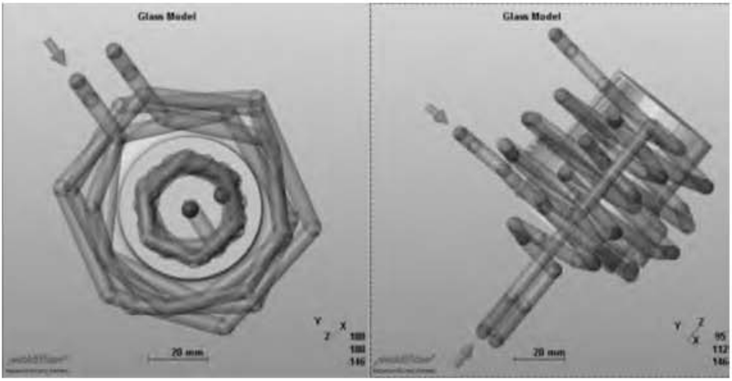


Figure 13: Inside spiral and outside spiral

3.4. Results of the simulation model

Figure 14 shows the impact that the five different cooling layouts have on the final cooling cycle time of the plastic cup. The mean values are compared with each other. There is a considerable improvement in mean cooling cycle time as the cooling layouts conform more to the part shape.

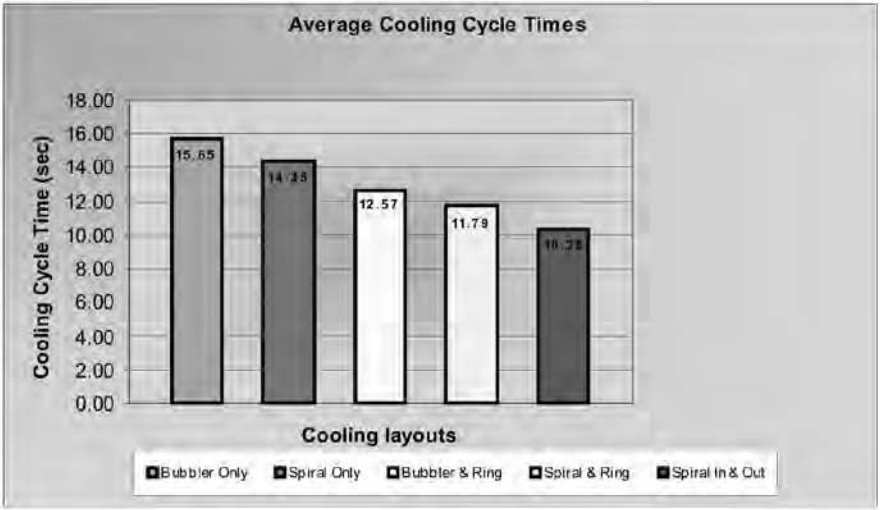


Figure 14: Average cooling cycle times of different cooling layouts

4. EXPERIMENTAL WORK

4.1. Mould design

Three different cooling channel layouts were chosen for this study: a conventional layout with straight channels using a bubbler (Figure 15), and two conformal cooling inserts using Direct Metal Laser Sintering (DMSL) with two different materials (Figure 16 and Figure 17). DirectMetal 20 is a very fine-grained bronze-based metal powder, and DirectSteel 20 is a very fine grained steel-based metal powder. In the case of DirectMetal 20 the material is suitable for most prototype injection moulding tooling applications (DirectTool) and for many functional metal prototype applications (DirectPart). It offers the highest building speed and thus is particularly suitable for larger parts. However, in this study it has shown water leakage, pointing at the porosity of the laser sintered insert.

A bubbler channel was created by fitting a tube in the centre of a drilled hole, forming an annular channel. Coolant flows up through the inner tube and flows down around the outside of the tube (Figure 15).

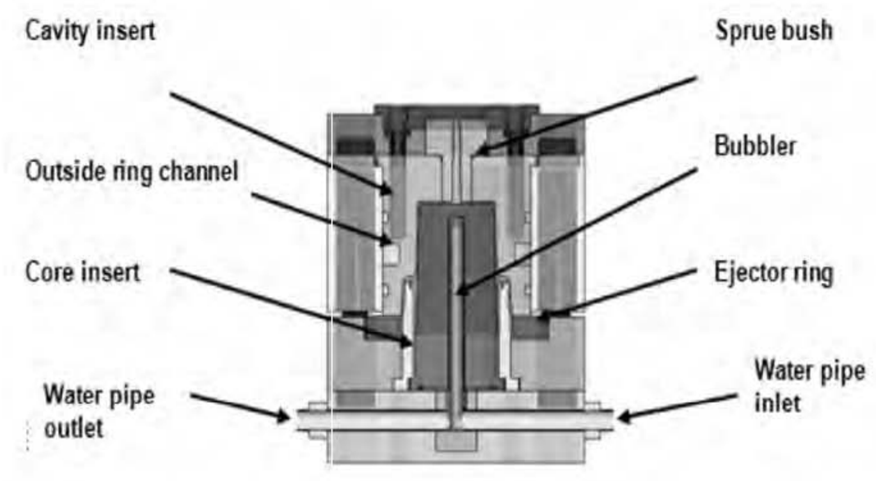
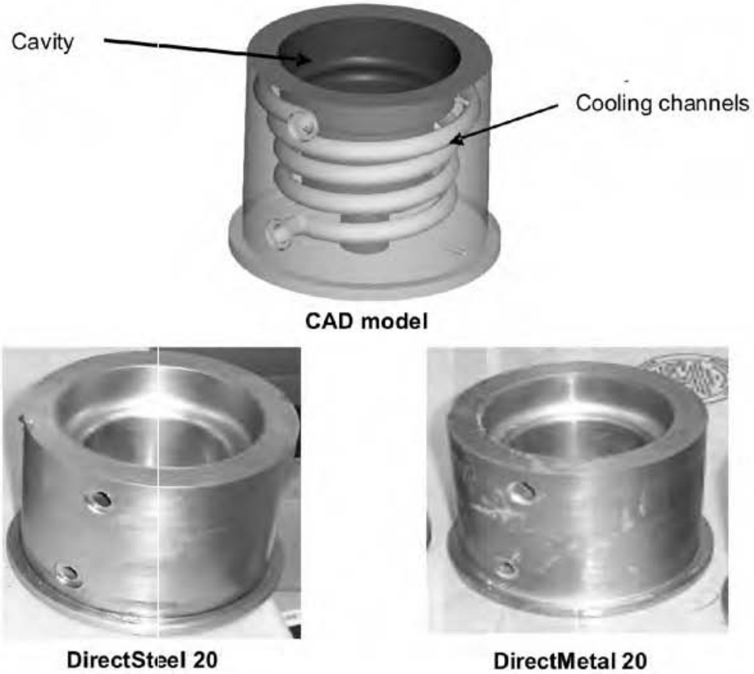


Figure 15: Bubbler channel cooling with outside ring



CAD model

DirectSteel 20

DirectMetal 20

Figure 16: Layer manufactured conformal channels

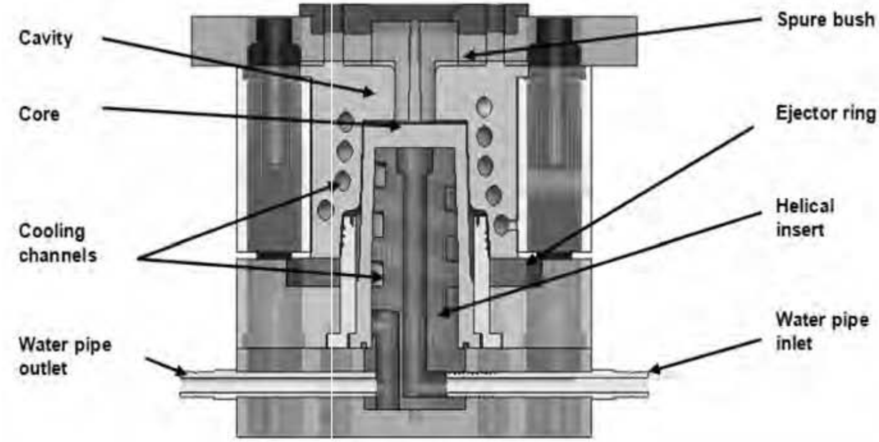


Figure 17: Mould of conformal cooling inside spiral and outside spiral

4.2. Results

The method used to determine the quality of the cups produced involved a comparison of the actual cups with the CAD model of the mould. The measurement points were done on a Mitutoyo Bright 710 Coordinate Measurement Machine (CMM). The CMM was programmed to measure approximately 480 points on each cup (some of the measurement points are shown in Figure 18).

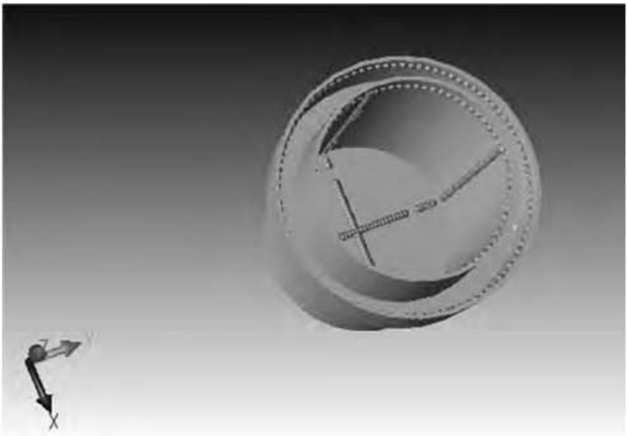


Figure 18: Selection of measured points on a sample cup

The data of the measurement points were analysed by two methods. The first was a Four-Way Factorial Analysis of Variance (ANOVA) [14] study with confidence intervals of 0.95 using STATISTICA. The ANOVA analysis was used with the factors method of cooling layouts (conventional and conformal), cycle times (14, 16, 19 and 22 seconds), mould temperatures (40, 50 and 60°C), and melt temperatures (200, 220 and 240°C). The difference between the mould temperatures against the cooling layout can be seen in Figure 19. It is clear that the mould temperature at 40°C with conformal cooling mould has less deviation than the others, and the conformal cooling layouts with different mould temperatures have fewer deviations than the conventional cooling layouts.

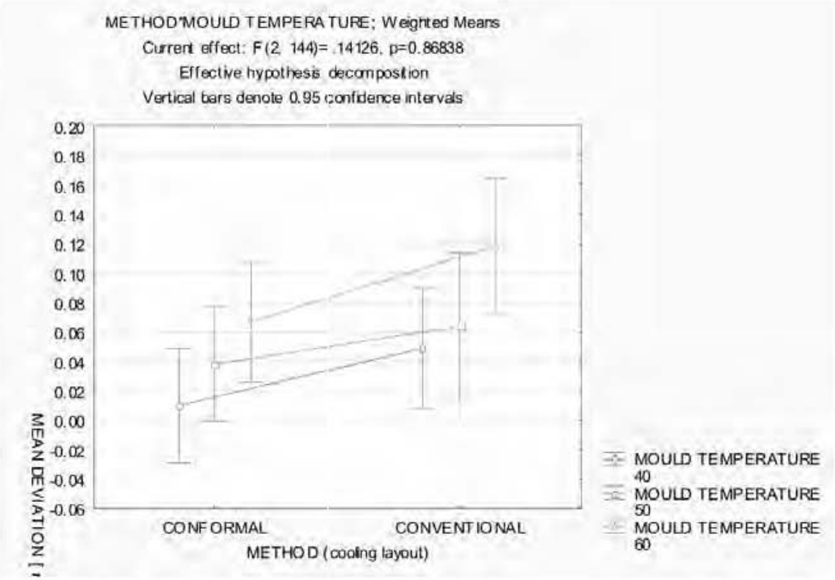


Figure 19: Statistical ANOVA result of cooling layouts against mould temperature

A comparison of the different cooling layouts in the mean deviation can be seen in Figure 20. It is noticeable that the conformal cooling layout has a smaller mean deviation (0.015 to 0.06) mm than that of the conventional cooling layout (0.05 to 0.15) mm. From a statistical point of view, the method with conformal cooling layout yields better quality parts than the method using conventional cooling layout.

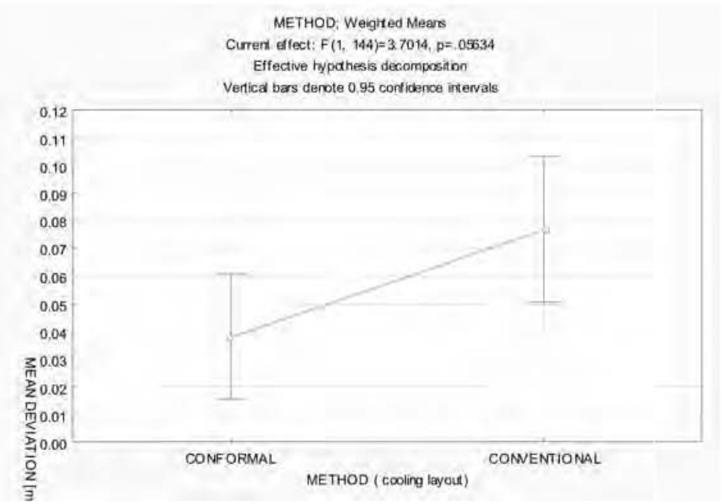


Figure 20: Statistical analysis of cooling layout

The residual is not normally distributed (Figure 21) because the points (dots) deviate substantially from the curve (red line). Consequently the Bootstrap test [15] was used to compare the interaction between methods and cycle times. Figure 22 shows a very interesting result: the sign *(ab)* on the figure indicates that there is no significant interaction between the conventional cooling method at cycle times of 16, 19, and 22 seconds and the conformal cooling method at cycle times of 14 and 16 seconds.

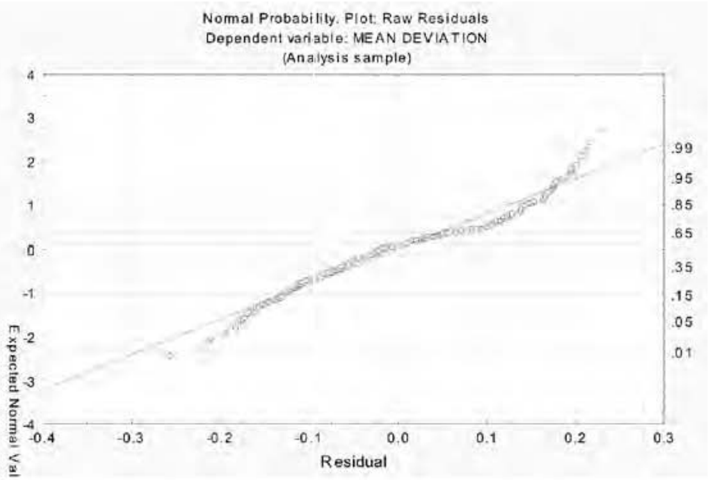


Figure 21: Normal probability plot

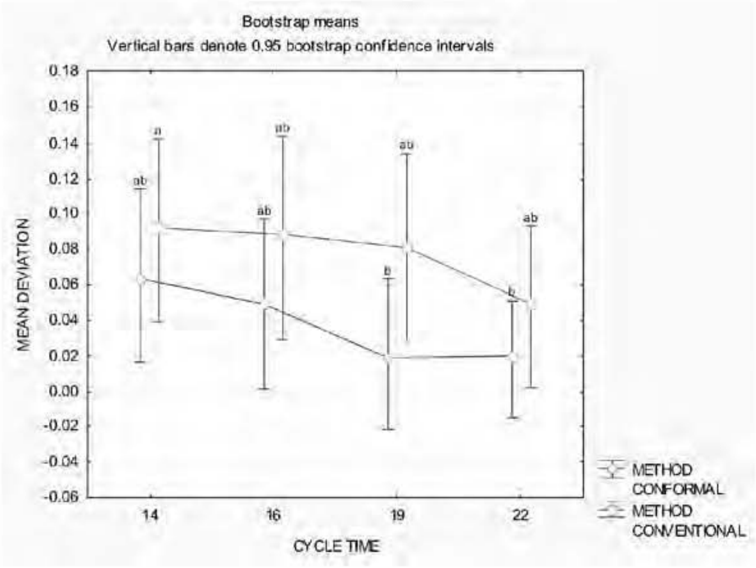


Figure 22: Statistical ANOVA result of bootstrap test on cycle time vs method of conventional/conformal cooling layouts

In the second method the data were arranged in histograms, showing the number of points in each error category. In Figure 23, a comparison of the measured deviations on cups with a conventional cooling layout, produced at different cycle times, can be seen. It is noticeable that all the deviations that were measured ranged between -0.8 mm and 1 mm. The minus sign indicates that the point measured on the actual cup is deeper (i.e. less material or inward material warpage) than the same point on the CAD model.

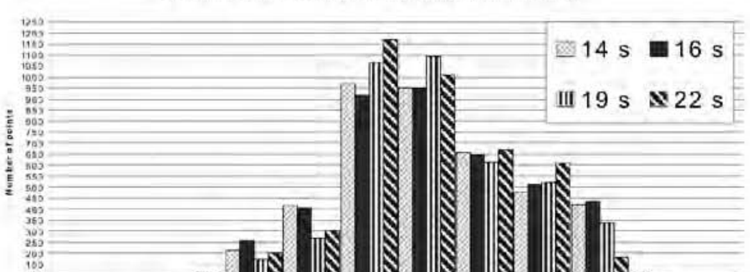


Figure 23: Histogram of measured points on cups produced from conventional mould

A similar comparison was done for the cups produced with the conformal cooling layout, and results are shown in Figure 24. In this case all the measured deviations ranged between -0.6 mm and 1 mm.

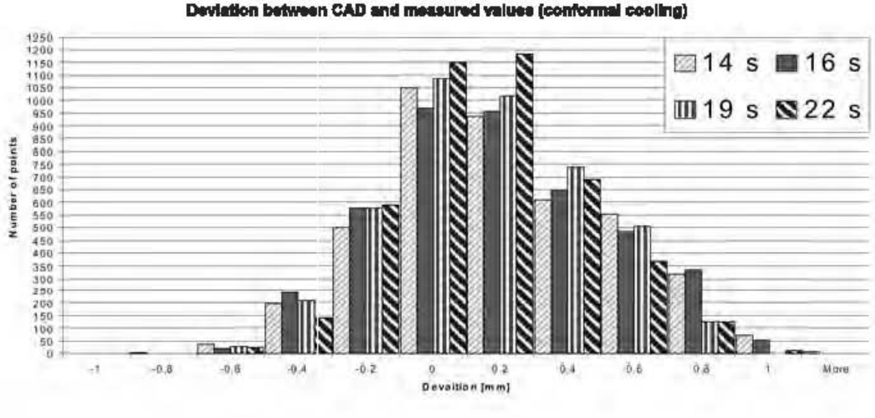


Figure 24: Histogram of measured points on cups produced from conformal mould

The extent of the deformation can be illustrated further by comparing the curves in Figure 25 to Figure 28. These figures are scatter plots of the total deviations between the CAD data and correlating measured points. The values on the Y-axis of each graph show the deviation from the CAD model in millimetres. If the value is negative, it indicates that the measured point is deeper than in the CAD model. It is obvious, by comparing the left hand side and right hand side of the graphs, in the region of the points number 251 to 301, which is the top of the cup, that a difference in deformation between the conventional/conformal cooling layout is noted. This means that the conformal cooling layout results in less deviation than the conventional cooling layout.

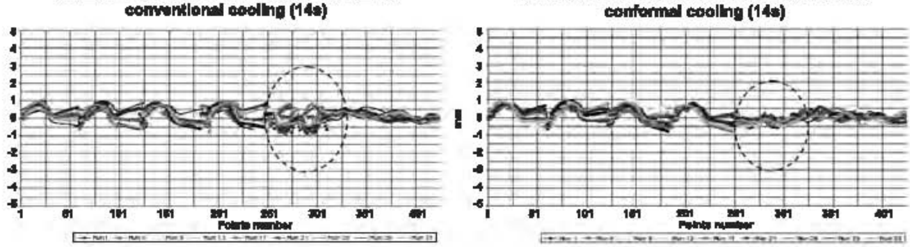


Figure 25: Deviation between CAD and measured values at 14 s on conventional/conformal moulds

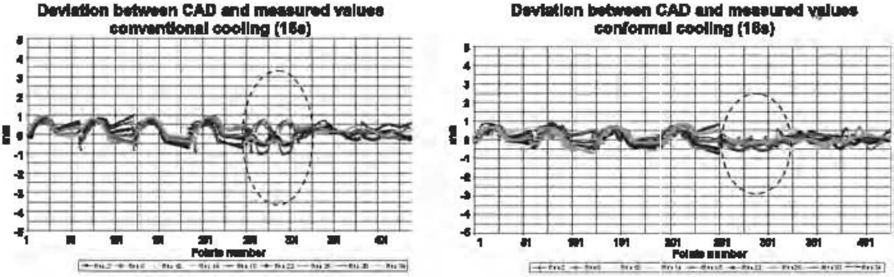


Figure 26: Deviation between CAD and measured values at 16s on conventional/conformal moulds

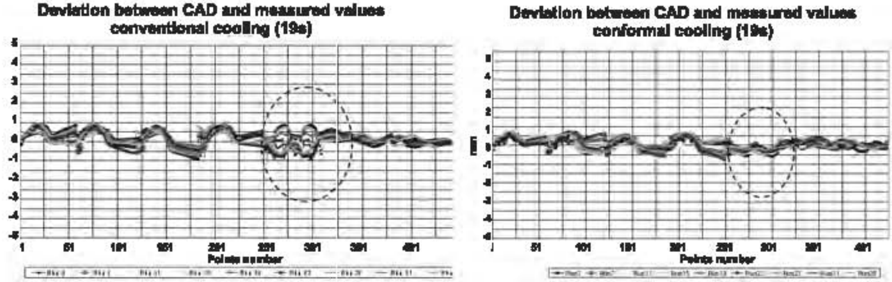


Figure 27: Deviation between CAD and measured values at 19 s on conventional/conformal moulds

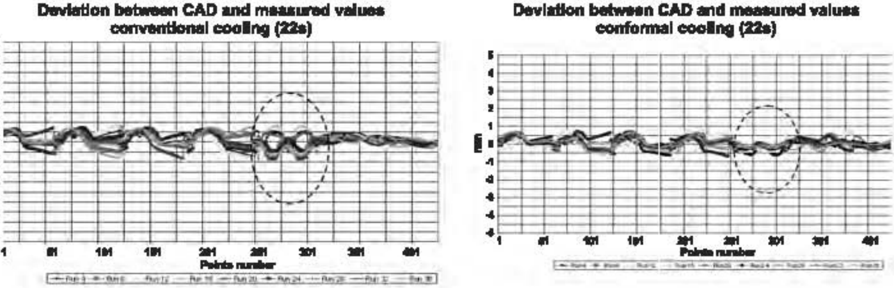


Figure 28: Deviation between CAD and measured values at 22 s on conventional/conformal moulds

5. ECONOMICS OF THE PROCESS

In order to see what cycle time reduction is achieved, Figure 29 shows a comparison between a cup produced by using the conventional mould at 19 seconds of cycle time and one produced by using the conformal mould at 14 seconds of cycle time at the same parameters of mould/melt temperatures (40, 220) °C. The cup produced by using the conventional mould (cycle time of

19 s) differs more from the CAD model than the cup produced by using the conformal mould (cycle time of 14 s). The improved design enables the production of cups with acceptable quality, at a cycle time reduced by 26% from the current cycle time.

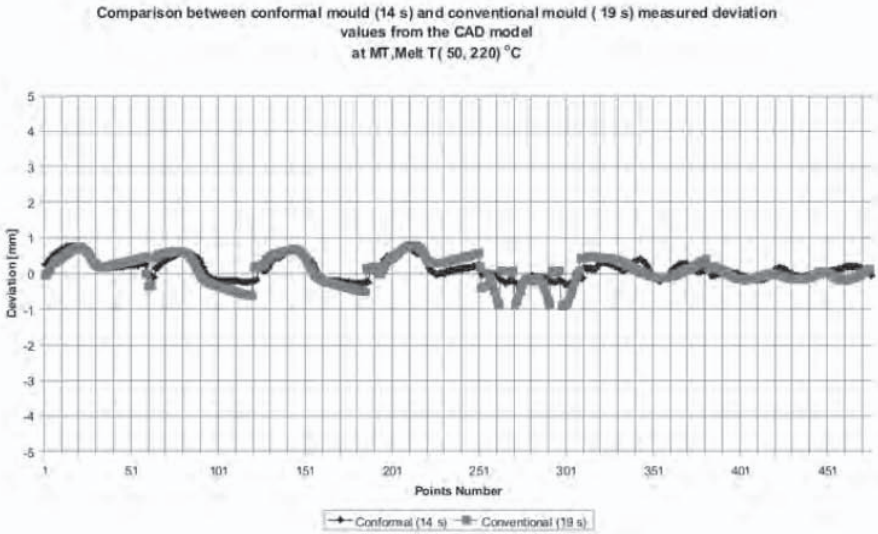


Figure 29: Cup quality comparison between conformal mould (14 s) and conventional mould (19 s) at mould and melt temperatures (50, 220) °C

Since the cavity insert manufactured by the LM technology is more expensive than that manufactured by the computer numerical control (CNC) technology, a calculation in terms of production hours ***h*** can be done in order to find out when the LM cavity insert will be amortised. Therefore, the chart below illustrates the break-even point for the LM/CNC cavity inserts (Figure 30). If the demand is expected to be more than 175 796 components [684 (hr) x 257 (units/hr)], then the LM cavity insert is a better option because it would result in lower total cost.

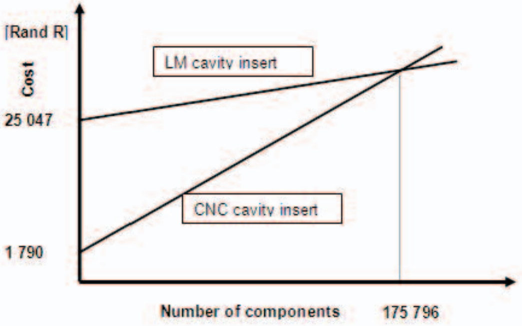


Figure 30: Break-even point chart

6. CONCLUSION AND FUTURE WORK

The results show that conformal cooling channels manufactured by the DMLS process constitute a viable method to improve quality and cooling time in comparison with cooling layouts manufactured by conventional machining. A cycle time reduction of 26% was experimentally proven. The LM process is the better option if the required production volume is higher than 175 800 components.

Simulation tools help designers to improve mould performance. At this time, however, the software does not have the possibility to simulate different conformal cooling layouts with complex parts shapes.

Further investigations in this area should aim at the development of a generic design methodology of the cooling layout, assuring an optimised thermal management of the mould. The additive manufacturing methods available today, such as Selective Laser Melting, which are able to process a large number of different materials, achieving a high density of the manufactured moulds/inserts, build a promising foundation for this research.

7. REFERENCES

Herbert, R., *Mould engineering*, 2nd Edition. Munich: Carl Hanser, 2002.

Boothroyd, G., Dewhurst, P. and Knight, W., *Product design for manufacture and assembly*. New York: Marcel Dekker, 2002.

Moldflow, "Moldflow plastics advisers training overview," Moldflow Corporation, 2005.

Rännar, L.E., Glad, A. and Gustafson, C.G., "Efficient cooling with tool inserts manufactured by electron beam melting," *Rapid Prototyping Journal*, vol. 13 (3), pp. 128-135, 2007.

Xu, X., Sachs, E. and Allen, S., "The design of conformal cooling channels in injection molding tooling," *Polymer Engineering and Science*, vol. 41 (7), pp. 1265-1279, 2001.

Sachs, E., Wylonis, E., Allen, S., Cima, M. and Guo, H., "Production of injection molding tooling with conformal cooling channels using the three dimensional printing process," *Polymer Engineering and Science*, vol. 40 (5), pp. 1232-1247, 2000.

Dormal, T., "Rapid tools for injection molding," presented at the 4th National Conference on Rapid and Virtual Prototyping and Applications, UK, 2003.

Karapatis, N.P., Van Griethuysen, J-P.S. and Glardon, R., "Direct rapid tooling: a review of current research," *Rapid Prototyping Journal*, vol. 4 (2), pp. 77-89, 1998.

Klocke, F., Celiker, T. and Song, Y-A., "Rapid metal tooling," *Rapid Prototyping Journal*, vol. 1 (3), pp. 32-42, 1995.

Kruth, J.P., Wang, X., Laoui, T. and Froyen, L., "Lasers and materials in selective laser sintering," *Assembly Automation*, vol. 23 (4), pp. 357-371, 2003.

Radstock, E., "Rapid tooling," *Rapid Prototyping Journal*, vol. 5, pp. 164-168, 1999.

Segal, J.I. and Campbell, R.I., "A review of research into the effects of rapid tooling on part properties," *Rapid Prototyping Journal*, vol. 7 (2), pp. 90-98, 2001.

Wimpenny, D., "Rapid tooling options compared," presented at Proceedings of the 4th National Conference on Rapid and Virtual Prototyping and Applications, UK, 2003.

Dunn, O.J. and Clarke, V.A., *Applied statistics: Analysis of variance and regression*. New York: John Wiley and Sons, 1974.

Efron, B. and Tibshirani, R., *An introduction to the bootstrap*. London: Chapman and Hall, 1993.