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# Deformation Analysis of Mold Cavity with SLA Conformal Cooling Channel Insert

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## Abstract

Injection molding is the process of injection molten plastic into a mold to form desired shape of part and it's widely used process for mass production of plastics over the world. This process is not complete without the mold as it is the most critical part of the process. The cost of producing mold is huge due to manufacturing process and technique, tool material and cost of labor. The more effective the mold, the more efficient the process and the more profitable to the business. A critical factor is the cooling time, and a well-designed mold can achieve even cooling in the shortest period, which leads to increased productivity and higher quality of molded parts.

In this research, an alternative core design was employed, to achieve these goals during the molding process. The core has 2 parts: the core and core insert. The core insert was produced using SLA technology to achieve the conformal cooling while the core was machined, and the deflection was studied using finite element analysis.

## Introduction

Plastics are used in our everyday life and are employed in a every field due to its outstanding characteristics such as light weight, ease of fabrication, low cost of production, strength, chemical resistance, etc. There are different means of plastic production depending on the desired shape, production rate and the cost effectiveness amongst 3d printing, polymer casting, vacuum casting, injection molding, blow molding [1]

Injection molded plastic parts are produced by injecting molten plastic into a mold of intended shape. The molds are made from metals in order to withstand high temperature and pressure. The shape of product determines the method of production. Mold is design to form a desired shape. Aside the high set up cost, creating new molds takes time, thereafter production of parts only takes few seconds.

In injection molding process, the production time is divided into 3 major sections: filling, cooling, and ejection, which determine the production rate as well as the cost efficiency of the molding process. The reduction in production time is dependent on the cooling effectiveness in the mold [2].

Cooling time is the critical part and the longest period of the molding cycle. There are convectional method and the conformal methods of providing cooling in the mold to reduce the cooling time. Compared to the conventional means of cooling, conformal cooling has been proven to produce a higher heat absorption rate and improved part quality by using a 3D software to create a complex design, which is then printed [3] . It's called the conformal cooling because the coiling channels or coils are conformal to the core surface.

Additive manufacturing otherwise known as 3D printing is the layer-by-layer building of an object at a time, which differs from the subtraction method of production. It's used in to produce complex and intricated shapes. It's employed in the production of conformal cooling channels to accommodate irregular designs of the cooling channels. There are different types of 3D printers, which are classified by the technologies behind them. Some can print metal, rubber, or ceramics.

Furthermore, it also gives an opportunity to produce a mold with more than one material, as such using Fused Deposition Modelling (FDM) will give an opportunity to use a plastic component in mold over the conventional single metallic piece. It reduces material usage of the major metallic component.

Fabrication and analysis of conformal cooling channel inserts using Stereolithography (SLA) technology method investigates the cooling efficiency and heat transfer rate of conformal cooling channels while using it as a core insert. It also investigates the design efficiency of the mold and parameters that can be adopted for future designs.

## Literature Review

Several works have been done over years to improve plastic production using injection molding process. Firstly, Injection molding process is a method used to obtain molded products by injecting molten plastic materials into a mold, cooling and solidifying them. [4] The method is suitable for mass production and with complicated shapes.

There are different processes involved in creating a material using the injection molding process. It involves the clamping or closing of the mold chamber, thereafter the heated molten material is injected and allowed to cool for some time. The mold opens and the product is removed, and the cycle continues.

The injection molding machine is divided into 2 main parts, the clamping, and the injection unit. The basic function of the injection unit is to heat and inject the material into the mold. It's set in a way to feed the mold accurately with precise shot size at a calculated speed

The mold is the critical part of this process and at such, its required that for every new part to be produced a new mold is designed. Hong & Xuan [5] claimed mold serves as heat exchanger in which it absorbs heat from the molten plastic. A mold cooling system consists of temperature control unit, pump hoses, supply/cooling manifolds and cooling channels in the mold. There are different types of cooling layouts which are conventional straight-drilled cooling channels and conformal cooling channels.

The cooling channels in mold can be produced conventionally and be connected serially or parallelly to achieve optimal cooling. In parallel cooling channels, coolants flow from one manifold to another parallelly and in serial connection, are connected head to toe from with only one inlet and one outlet of the cooling channels [6].

In recent years, conformal cooling has been adopted as it provides efficient cooling performance [7]. Conformal cooling channels are conformal to the surface of the mold and the cooling channels are kept constantly to the mold surface, with the advent of 3D technology made it possible.

Conformal cooling channels has been proven to provide better performance compared to conventional cooling channels by using ANSYS to model and study the thermal performance and cycle time. Varying different cooling design such as pitch, diameter, and wall thickness to achieve optimal cooling [7]

Different cooling channel cross sections also provide different thermal performance, and reviewing the thermal performance using finite element analysis (FEA) to optimize different cross sections parameters [8]. Experimental results showed a square cross-sectional conformal cooling channel offered a better temperature distribution and reduced cycles in injection mold process compared to conventional straight cooling channel (CSCC) mold.

Not only conformal cooling can be in straight channels but also designs can be in the form of spiral designs to achieve optimal cooling. The spiral design cooling channels provide low pressure drop and a constant Reynolds number through the channels, and its' easy to locate the inlet and out of channels. Other design ranging from scaffold, zig zag and Voronoi had high pressure drop, long excessive cooling coil, unnecessary turnings, cannot support turbulent flow and difficulty in controlling the heat removal rate [5] .

Significant cooling time is reduced using conformal cooling channels when compared to conventional cooling channels, its proven that conformal cooling channels can achieve up to 20% reduction in cooling time and in turn increase productivity [9].

Although injection molding material has been significant in molding as it serves as the surface for heat exchanger [6]. Different materials have been used to improve the performance of mold base. The thermal conductivity of a Silicone rubber mold (SRM) was improved by 77.6% when compared with convectional Silicone rubber mold (SRM) by adding the recipe of aluminum powder, graphite powder and liquid silicon rubber with the 52.6 wt.%, 5.3 wt.%, and 42.1 wt.% respectively.

The internal cooling channel of coils was also lined with copper tube and after a significant cooling compared with the normal cooling channels, it established [10] that cooling channel design with copper tube insert can reduce cycle time by optimal and uniform heat transfer in the mold.

Moreover, during this research, a new approach will be reviewed to develop a core with a metallic part and check the deflection using a finite element analysis and the core insert with the cooling channel produced from the SLA technology.

## Research Methods

Mold design is dependent on the product, which is used to define and design the mold. A cup sample of 68mm diameter with 70mm height is show in Figure 1 the cup design was used to make the core and the cavity. The core is the immovable part of the mold.

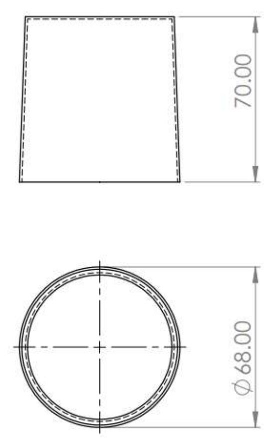



Figure 1: Dimension of Cup used.

In this research, the core is divided in to 2 pieces. The core is made from a metallic part and 3D printed core insert. The core is made from P20 steel tool and the insert made from SLA, its designed to contain the conformal cooling when inserted to complete the core.

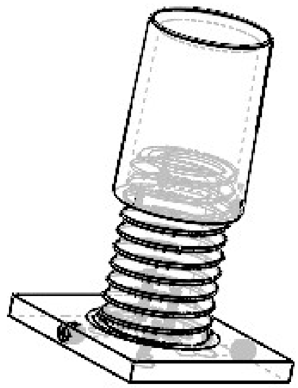


Figure 2: An assembled core

The core is divided segments and are coupled together with fasteners as shown in Figure 2. The thickness of the cover core is termed "t" the diameter of cooling channel is termed 'd' and the coil pitch is termed 'p' . These terms will be optimized in this work, and the thermal effects in absorbing heat of the melt plastic during injection molding will be reviewed. There are various combinations of the parameters to be considered to design the molding core to generate 3 samples as shown in Table 1.

Table 1: The 3 samples with varying thickness, pitch, and diameter.

| **Sample (mm)** | **1** | **2** | **3** |
|---|---|---|---|
| Thickness (t) | 5 | 7.5 | 10 |
| Pitch (p) | 7 | 9 | 12 |
| Diameter (d) | 4 | 6 | 8 |

There is a core insert which is attached to the rectangular base plate of 90mm x 90mm x 12.7mm. It serves as the support or base, where the conformal cooling design is mounted. The core is one end closed cylindrical shape with a diameter of 68mm, height of 70mm and a thickness 't' depending on the selected samples, all making one piece.

The core insert mounted on the base plate, is a diameter of – ('68 – 2t') mm and the also a height of -('70 – 2t') mm. The spiral flute is of selected diameter 'd' and pitch 'p'. Both the internal surface and the internal cooling core are tapered and given a draft angle to 2°, to ease removal. There are inlet and outlet channels which are located on the base plate, the base plate and the inner cooling core are of the same material printed as a single piece using SLA. Both the inlet and outlet ports are connected to the coolant flow via 1/8" NPT fittings.

The conformal cooling uses a coolant flow that conforms to the cooling surface. The internal cooling channel are designed such a way to have a flow path in the form of a helical coil around the peripheral of the part. It starts from base of the insert and travel across the surface and ended at the base as seen below Figure 3 and 4.

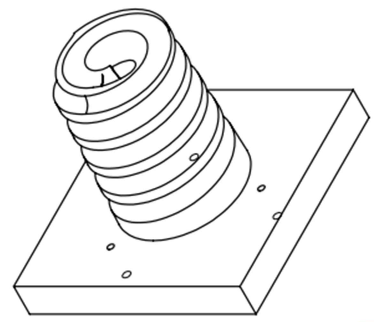


Figure 3: A drawing of a 3D printed core

The P20 steel tool was machined on the lathe by removing a chunk of materials in a cylindrical billet, thereby forming a cup like shape. The core is produced/machined and SLA insert are assembled as a single piece. Figure 4 shows both parts

Figure 4: Machined and printed core.

*Pressure determination*

In determining a safe injection pressure, various thickness of the cup samples were used. A cup thickness of 1.5mm, 2mm and 2.5mm, using simple setup on Autodesk Moldflow by placing the gate at the top (t) of the cup and at the bottom (b) of the cup as seen in Figure 5. A Polypropylene (PP) and a Polycarbonate (PC) material are selected with a melt flow rate of 15,10 and 5 g/10min for each material family and checked over cup thickness at different gate location.

The maximum pressure of 129.2 MPa was obtained from a PC under MFI of 5 g/10min with 1.5mm cup thickness.

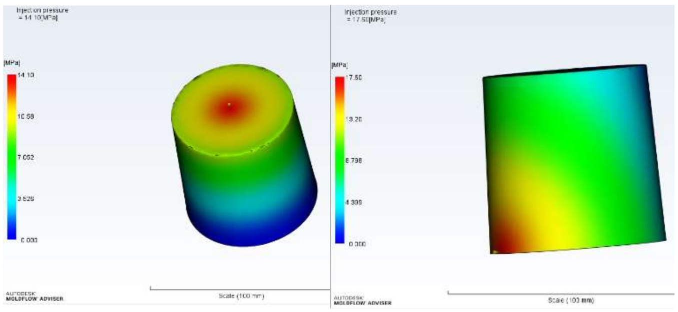


Figure 5: Injection pressure profiles with the gate location from the (a) top with wall thickness of 1.5mm using a PP plastic with MFI of 5 g/10min (b) bottom with wall thickness of 2mm using a PP plastic with MFI of 10g/10min

*Calculated Axial and Lateral Deflection*

The core is subjected to axial and lateral deflection under the applied pressure. Using the below formulae, the axial and lateral deflection is calculated.

$$\sigma_{lateral} = \frac{PD_2H^4}{8EI}$$

$$\delta_{axial} = \varepsilon_{vertical}.H_{core}$$

$$\varepsilon_{vertical} = \frac{\sigma_{wall}}{E}$$

$$A_{wall} = \frac{(D_2 - D_1)^2}{4}$$

Where $D_2$ = Core outer diameter; $D_1$ = Core internal diameter; P = Injection pressure; Hcore = Height of core; E – Elastic modulus of core; ε = Strain; δ = Vertical deflection; I – moment of inertia

*Finite Element Analysis of the Core.*

The deflection of the core is carefully reviewed using ABAQUS CAE to see the deflection of the core to an applied pressure. A simple core design was setup on ABAQUS software as show in Figure 6, and a P20 steel tool material was selected. The boundary conditions (-that the core base was fixed -) and the external surfaces were loaded according to the pressure obtained from a flow simulation software (Autodesk Adviser). The set was meshed asymmetrically.

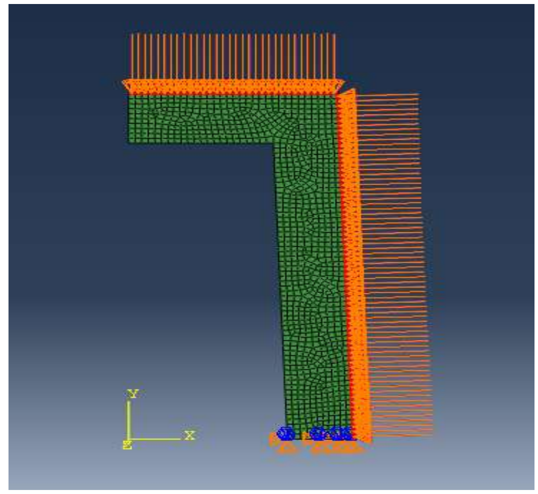


Figure 6: Core with applied boundary condition and pressure applied.

The tabulated deflection of both the FEA and calculated results is shown Table 2.

Table 2: Comparism between FEA and Calculated results

| Material | 5mm P20 | | FEA | | Calculated | |
|---|---|---|---|---|---|---|
| MFI | 15 g/10min | | Deflection (mm) | | Deflection (mm) | |
| Cup thickness (mm) | Gate Location | Injection Pressure (MPa) | x | y | x | y |
| 1.50 | Top (t) | 13.51 | 0.0082 | 0.00059 | 0.02722 | 0.14813 |
| 1.50 | Bottom (b) | 17.20 | 0.01044 | 0.00075 | 0.03465 | 0.18859 |
| 2.00 | Top (t) | 8.22 | 0.00499 | 0.00036 | 0.01656 | 0.09013 |
| 2.00 | Bottom (b) | 10.10 | 0.00613 | 0.02723 | 0.02035 | 0.11074 |
| 2.50 | Top (t) | 4.99 | 0.00302 | 0.0003 | 0.01005 | 0.05467 |
| 2.50 | Bottom (b) | 6.49 | 0.00394 | 0.00036 | 0.01308 | 0.07117 |

Table 2 shows an excerpt of 15g/min of 5mm P20 core thickness recorded from Moldflow software, as there is pressure recorded from 10 g/10min, 5 g/10min for the same 5mm P20 core thickness. The same data recorded for 7.5mm and 10mm P20 core thickness using plastic material of 15 g/10min, 10 g/10min, and 5 g/10min of PP and PC family

Moreover, Table 2 shows and compared simulated result to the formular results, there is a significant deflection under pressure application in both directions. The deflection in both methods increases as pressure increases. The calculated result is greater than the FEA results, which indicated that the calculated result is the maximum deflection obtainable under such pressure.

The difference in the data is traced to inability to model the idea injection process in the simulation software.

The results of axial and lateral displacement of the FEA are given in the below figures.

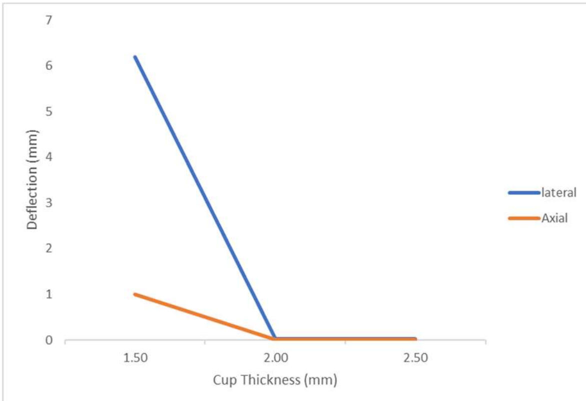



Figure 7: x and y- deflection on 5mm Core thickness using P20 tool steel vs Cup thickness using resin pressures for a PP & PC of 10 g/min MFI

Figure 7 shows deflection of 5mm P20 steel core with MFI of 10 g/min for both PP and PC pressures. It's recorded that the significant deflection in both x and y directions was experienced from 90MPa. As can be seen from Figure 7, the core failed under applied pressure. However, 7.5mm core thickness showed 0.02 mm of deflection under the applications of pressure as shown in Figure 7

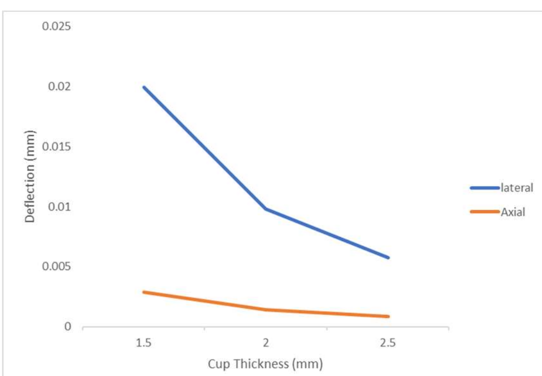



Figure 8: x and y - Deflection on 7.5mm Core thickness using P20 tool steel vs Cup thickness using a PP & PC of 5 g/min MFI pressure.

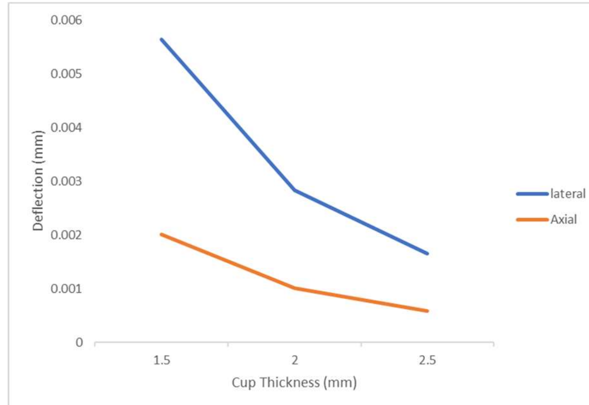


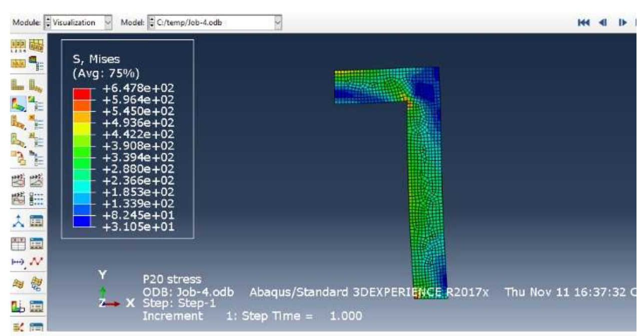

Figure 9: x and y - deflection on 10mm Core thickness using P20 tool steel vs Cup thickness using resin pressures for a PP & PC of 5 g/min MFI

Figure 9 shows deflection of metal core with 10mm thickness with MFI of 5 for both PP and PC. It showed maximum deflection of 0.0058mm with PC.

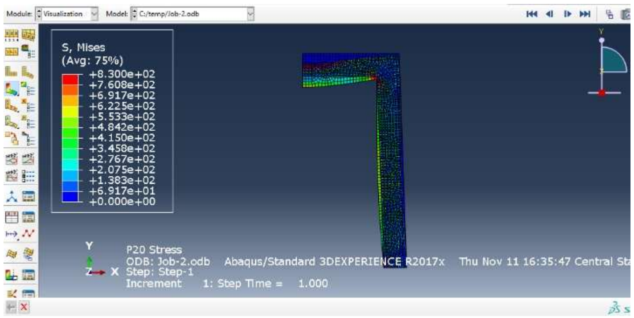
According to the cooling channel design guide, cooling channel depth is one to 4 times of cooling channel diameter and, cooling channels are located 25mm from the cavity surface. Therefore, this core design will be practically applicable for cooling channel designs.

*Stress Analysis*

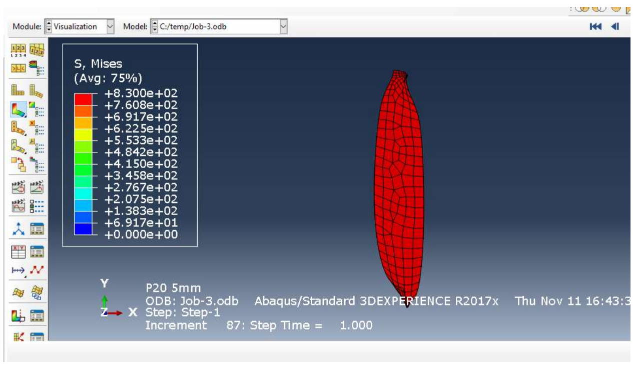
Stress is defined as force per unit area, in this study the ABAQUS CAE was used to observe the stress behavior of the samples, the contour of the maximum pressure was shown in Figure 10.




(a)




(b)




(c)

Figure 10 : Maximum stress obtain using the maximum injection pressure for (a) 10mm core thickness (b) 7.5mm core thickness (c) 5mm core thickness

The stress of the samples are also reviewed. Figure 10, showed the response of each sample to the maximum pressure is shown, a 647.8, 830 and 830MPa for 10mm, 7.5mm and 5mm core thickness respectively

Endurance failure stress of P20 is 456MPa [11] and stress analysis results showed that 7.5 mm and 10mm will with stand injection molding cyclic stresses at injection pressure less than 50 and 90 MPa respectively for safe applications. However, core thickness of 5mm failed with given injection molding conditions.

## Conclusions

Conformal cooling has proven to be very effective, however, adoption of conformal cooling was limited due to complexity, cost, and Selective Laser Meting(SLM) accessibility. In this research, we provide a stress analysis that shows possibility of using SLA conformal cooling insert for cooling channels. A core thickness of 7.5 mm and 10mm survived wide range of injection molding conditions from 0 to 50 MPa and 90 MPA (the highest pressure) respectively of injection molding pressure and give accommodable deflection and stress. Based on the results of this study, the proposed 2-piece core could be an alternative approach for inexpensive conformal cooling channel design. In continuation, the heat transfer rate and cooling efficiency will be reviewed in later works.

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